# Hydrological and Economical Aspects

# of

# Agronomically Productive Percolation Systems

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# HYDROLOGICAL AND ECONOMICAL ASPECTS

# OF

# AGRONOMICALLY PRODUCTIVE PERCOLATION SYSTEMS

by

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Diplom-Bauingenieur

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# E R K L Ä R U N G

Hiermit erkläre ich an Eides statt, daß ich die vorliegende Arbeit unter Verwendung der angegebenen Quellen selbständig verfaßt habe.

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## ABSTRACT

Extensive hydrological studies carried out in a semi-arid watershed in pensinsular India show that rice terraces constructed in lowlands have a significant impact on the water balance of a watershed. Low surface runoff and high ground water recharge indicate that rice terraces could be used as artificial ground water recharge basins.

Based on further field studies on the water balance in paddy fields a water management concept is suggested using rice terraces as agronomically productive percolation systems (APPS) for ground water recharge in upland areas. The evapotranspiration from the submerged area is agronomically productive (in terms of yields) in contrast to the evaporation from the common local percolation tanks. The ground water storage in a watershed is utilized more efficiently since the water recharged in the upland areas reaches the valley bottom after the end of the monsoon when the ground water level there is already declining.

A computer simulation model has been developed to validate the concept and study the feasibility of agronomically productive percolation systems under varying climatological and physical conditions. From a sensitivity analysis of the important parameters and from the results of model runs, recommendations are derived for the design of such systems. Favourable conditions for construction are defined.

## LIST OF ABBREVIATIONS

| | |
|---|---|
| APPS | Agronomically Productive Percolation Systems |
| APPT | Agronomically Productive Percolation Terraces |
| CN | Curve Number (US Soil Conservation Curve Number Method) |
| CWMP | Composite Water Management Project |
| ET | Evapotranspiration |
| FC | Field Capacity |
| FSRP | Farming Systems Research Programme at ICRISAT |
| GTZ | Deutsche Gesellschaft für Technische Zusammenarbeit, FRG |
| GW | Ground Water |
| ID-CROPS | Irrigated Dryland Crops |
| ICRISAT | International Crops Research Institute for the Semi-Arid Tropics, India |
| Mio | Million |
| NGRI | National Geophysical Research Institute, India |
| NRSA | National Remote Sensing Agency, India |
| PWP | Permanent Wilting Point |
| RMP | Resource Management Program |
| Rs | Indian Rupees |
| SAT | Semi-Arid Tropics |
| SCS | Soil Conservation Service |
| THD | Technical University of Darmstadt, FRG |
| TWA | Total Water Applied |
| USDA | United States Department of Agriculture |
| VLS | Village Level Studies |

LIST OF SYMBOLS

| | | |
|---|---|---|
| $A_{cr}$ | [$L^2$] | Area of crop |
| $A_{idc}$ | [$L^2$] | Area of irrigated dryland crop |
| $A_{pad}$ | [$L^2$] | Paddy area |
| $A_{sys}$ | [$L^2$] | System area |
| Av. | | Average value of parameter |
| | | |
| $B_{cr}$ | [Rs] | Benefit from crop |
| $B_j$ | [Rs] | Benefit at the end of j-th year |
| $BP_{cr}$ | [Rs] | Value of by-product for crop |
| | | |
| $c_{pump}$ | [Rs/T] | Hourly pump operation costs |
| $C_j$ | [Rs] | Costs at the end of j-th year |
| $C_v$ | [-] | Coefficient of variation |
| CN | [-] | Curve number used in US SCS curve number method |
| $CU_{pad}$ | [$L^3$] | Consumptive seasonal water use |
| | | |
| d | [T] | Days |
| $d_{crop}$ | [T] | Length of crop growing season in days |
| DI | [L/T] | Depth index |
| | | |
| $E_{act}$ | [L/T] | Actual soil evaporation |
| EC | [S/L] | Electrical conductivity |
| $E_{pan}$ | [L/T] | Pan class A evaporation |
| $E_{pan,act}$ | [L/T] | Actual $E_{pan}$ |
| $E_{pan,ltm}$ | [L/T] | Daily valve of long term mean of $E_{pan}$ |
| $E_{pan,norm}$ | [L/L] | Normalized pan class A evaporation |
| $E_{pot}$ | [L/T] | Potential soil evaporation |
| ET | [L/T] | Evapotranspiration |
| $E_{ta}$ | [L/T] | Evaporation from tank |
| $ET_{gw}$ | [L/T] | Evapotranspiration supplied by ground water |
| $ET_{max}$ | [L/T] | Maximum evapotranspiration |
| $ET_{pot}$ | [L/T] | Potential evapotranspiration |
| $ET_r$ | [L/T] | Evapotranspiration supplied by rain or runoff |
| | | |
| $f_{ind}$ | [-] | Precipitation reduction factor |
| $f_{red}$ | [-] | Pan evaporation reduction factor |
| | | |
| $GR_{cr}$ | [Rs] | Gross return of crop |
| | | |
| H | [L] | Delivery head, total potential head, saturated thickness |
| h | [T] | Hour |
| h | [L] | Head, pressure head |
| ha | [$L^2$] | Hectare [area] |
| $h_{ev}$ | [L] | Evaporation from tank |
| $H_{exp}$ | [L] | Expected original saturated thickness |
| $h_{gw,r,net}$ | [L] | Average height of irrigation per season |
| $h_o$ | [L] | Saturated thickness in well |
| $h_{perc}$ | [L] | Percolation through tank bed |
| $h_{seep}$ | [L] | Seepage through tank bund |
| $h_{surf}$ | [L] | Surface storage in paddy yield |

| | | |
|---|---|---|
| $I_a$ | [L] | Initial abstraction |
| $ID_{act}$ | [L/T] | Actual irrigation demand |
| $I_j$ | [Rs] | Investments |
| $IP_{cr}$ | [Rs] | Valve of input for crop |
| $IR_{crop}$ | [L³] | Irrigation requirement for season |
| $i_s$ | [L/T] | Uniform recharge |
| $IS_{act}$ | [L/T] | Actual irrigation supply |
| $IV_{act}$ | [L³] | Volume of irrigation demand |
| j | [-] | Number of year |
| k | [L/T] | Hydraulic conductivity |
| $k_{aq}$ | [L/T] | Hydraulic conductivity of aquifer |
| $k_{aw}$ | [L/T] | Conductivity in air water filled soil |
| $k_c$ | [-] | Crop factor |
| $k_c$ (GS) | [-] | Crop coefficient as a function of the growth stage |
| $k_{c,gn}$ | [-] | Crop factor groundnut |
| $k_{f,u}; k_{(\theta)}$ | [L/T] | Unsaturated hydraulic conductivity |
| $k_{gn}$ | [-] | Factor to consider the maximum ground water exploitation |
| $K_j$ | [Rs] | Capital costs |
| $k_{lake}$ | [-] | Lake evaporation coefficient |
| $k_m$ | [L] | Kilometers |
| $k_{pan}$ | [-] | Pan coefficient |
| $k_{red}$ | [-] | Yield reduction factor |
| $k_{rem}$ | [-] | Percentage of remaining growing season |
| $k_{risk}$ | [-] | Risk factor |
| $k_{root}$ | [-] | Root partitioning factor |
| $k_t$ | [-] | Factor to consider the critical time |
| $k_w$ | [-] | Weigthing factor to account for different yield response in each growth stage |
| $k_{yi}$ | [-] | Crop response factor |
| m | [L] | Month |
| m.a.s.l. | [L] | Meters above sea level |
| $M_j$ | [Rs] | Maintenance costs |
| n | [L/T] | Vertical ground water recharge or draft |
| n | | Number of observations, days, etc. |
| $n_{max}$ | [-] | Maximum number of days, etc. |
| NPV | [$R_s$] | Net present value of project |
| Oj | [Rs] | Costs of operation |
| $O_{well}$ | [Rs] | Operations costs of well |
| P | [L³/T] | Precipitation |
| p | [-] | Present worth factor, interest rate |
| $PAW_{act}$ | [L] | Actual plant available water |
| $PAW_{max}$ | [L] | Maximum plant available water |
| $P_{cr}$ | [Rs/M] | Farm gate price of crop |
| $P_{ind}$ | [L] | Rainfall index |
| $P_{ta}$ | [L³/T] | Precipitation on tank |
| Q | [L³/T] | Infiltration or evapotranspiration |
| Q | [L³/T] | Runoff |
| Q | [L³/T] | Discharge at delivery pipe of pump |
| $Q_{abs,gw}$ | [L³/T] | Ground water discharge from well |
| $Q_{abs,exp}$ | [L³/T] | Expected ground water discharge from well |
| $Q_{cons}$ | [L³/T] | Animal and human water consumption |

| | | |
|---|---|---|
| $Q_{drain,gw}$ | [$L^3/T$] | Ground water drainage |
| $Q_{in,gw}$ | [$L^3/T$] | Ground water inflow to tank |
| $Q_{gw,net}$ | [$L^3/T$] | Net ground water withdrawal |
| $Q_{gw,r}$ | [$L^3/T$] | Ground water recharge |
| $Q_{in}$ | [$L^3/T$] | Inflow to tank |
| $Q_{in,r}$ | [$L^3/T$] | Inflow to paddy fields (diversion of runoff) |
| $Q_{inf,r}$ | [$L^3/L$] | Cumulation rainfall infiltration in monsoon |
| $Q_{irr}$ | [$L^3/T$] | Irrigation outflow from tank |
| $Q_{irr,gw}$ | [$L^3/T$] | Ground water supplied to fields |
| $Q_{out}$ | [$L^3/T$] | Overflow or runoff from paddy |
| $Q_{over}$ | [$L^3/T$] | Overflow over spillway of tank |
| $Q_{perc}$ | [$L^3/T$] | Percolation |
| $Q_{perc,gw}$ | [$L^3/T$] | Percolation supplied by ground water |
| $Q_{perc,r}$ | [$L^3/T$] | Percolation supplied by rain or runnoff |
| $Q_{seep}$ | [$L^3/T$] | Seepage through tank bund |
| $Q_{seep,gw}$ | [$L^3/T$] | Seepage supplied by ground water |
| $Q_{seep,r}$ | [$L^3/T$] | Seepage supplied by rain or runoff |
| QS | [L/T] | Sink term to account for ET loss |
| $Q_{vis}$ | [$L^3/T$] | At surface visible seepage |
| | | |
| R | [-] | Correlation coefficient |
| R | [L] | Radius of cone of influence |
| RC | [L] | Deep percolation below root zone |
| RD | [L] | Rooting depth of plant |
| $r_o$ | [L] | Diameter of well |
| | | |
| S | [$L^3$] | Retention parameter |
| S | [-] | Storage coefficient |
| $S_a$ | [L/L] | Available soil water |
| SD | [L] | Submergance depth |
| SM | [L] | Soil moisture |
| $SM_{act}$ | [L] | Actual soil moisture |
| $SM_{max}$ | [L] | Soil moisture holding capacity |
| $SM_{pwp}$ | [L] | Soil moisture content at permanent wilting point |
| $SM_{sat}$ | [L] | Soil moisture content at 100 % saturation |
| $S_x$ | [-] | Standard deviation |
| $S_y$ | [-] | Specific yield of aquifer |
| $SY_{gwj}$ | [$Rs/L^3$] | Specific benefit of ground water |
| $SY_{owj}$ | [$Rs/L^3$] | Specific benefits (costs) of surface water |
| | | |
| T | [T] | Lifespan of project |
| T | [$L^2/T$] | Transmissivity |
| t | [M] | Tons |
| t | [T] | Time |
| $t_i$ | [T] | Duration of growth stage i |
| $T_{pot}$ | [L/T] | Potential transpiration |
| TWA | [L] | Total water applied to crop over the season |
| | | |
| $V_{abs,gw}$ | [$L^3$] | Annual ground water abstraction from well |
| $V_{dep}$ | [$L^3$] | Dependable resources |
| $V_{gw}$ | [$L^3$] | Ground water storage |
| $V_{gw,ab}$ | [$L^3$] | Net GW-abstraction |
| $V_{gw,exp}$ | [$L^3$] | Expected ground water storage |
| $V_{gw,r}$ | [$L^3$] | Net ground water recharge |
| $V_{gw,red}$ | [$L^3$] | Groundwater outflow during season |
| $V_{in,exp}$ | [$L^3$] | Effective expected inflow from catchment area (reduction of GW-storage) |
| $V_{ndep}$ | [$L^3$] | Non-dependable resources |
| $V_{p,exp}$ | [$L^3$] | Effective expected rainfall on terraces |
| $V_{prom}$ | [$L^3$] | Bound or promised resources |
| $V_{rc,exp}$ | [$L^3$] | Expected GW-recharge from dryland area |

| | | |
|---|---|---|
| $V_{ta}$ | [$L^3$] | Tank, farm pond storage |
| $V_{te}$ | [$L^3$] | Terrace storage |
| | | |
| y | [T] | Year |
| $Y;Y_{cr}$ | [$M/L^2$] | Crop yield |
| $Y_{max}$ | [$M/L^2$] | Maximum crop yield |
| | | |
| z | [L] | Depth below surface |
| $z_{gw}$ | [L] | Depth to ground water table |
| | | |
| $\beta$ | [-] | Fractional interception of radiation by crop canopy |
| | | |
| $\Delta BGW_j$ | [Rs] | Incremental net return due to increased GW-discharge |
| $\Delta CN$ | [-] | Range of curve number |
| $\Delta COW_j$ | [Rs] | Incremental costs due to reduced surface outflow |
| $\Delta GW_j$ | [$L^3$] | Increase of GW-discharge |
| $\Delta h$ | [L] | Change of water level |
| $\Delta OW_j$ | [$L^3$] | Reduction of surface outflow |
| $\Delta Q$ | [$L^3/T$] | Change of storage |
| $\Delta V_{gw}$ | [$L^3$] | Change of GW-storage |
| $\Delta Y_j$ | [Rs] | Incremental agricultural net returns due to APPT |
| | | |
| $\theta$ | [$L^3/L^3$] | Volumetric soil moisture content |
| | | |
| $\Psi$ | [L] | Capillary potential |

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# 1 INTRODUCTION

## 1.1 Motivation

Erratic and undependable rainfall is one of the major constraints limiting agricultural production in the Semi-Arid Tropics (SAT), especially in regions with alfisols (red soils) which have poor water retentivity (consult Map 1.1). The vagaries of the monsoon impose a high risk on traditional agricultural systems. Continued efforts in research are needed to enable small farmers to cope with drought, pests and diseases, and other stresses found in this harsh environment.

## 1.2 Introductory Remarks

The work for this thesis comprised 30 months of field work and data collection in two watersheds in south India. This part of the work was carried out in collaboration with the Resource Management Program (RMP) of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Patancheru, India and was funded by the "Deutsche Gesellschaft für Technische Zusammenarbeit" (GTZ). At ICRISAT the author participated in a project on "Composite Water Management on Red Soils in Semi-Arid India". The project aimed at combined or conjunctive use of surface and ground water resources, in a watershed as a physiographic unit, for stabilising and increasing agricultural production. The work was conducted by a team of junior and senior experts from the fields of economics, sociology, agricultural engineering, hydrogeology and civil engineering.

The findings of the author, derived from the field work in India, as well as data analysis and modelling at the "Institut für konstruktiven Wasserbau und Wasserwirtschaft", are presented below.

In chapter 1 the problem, the objectives of the study, and the methodology applied are explained. In chapter 2 the results and findings of the general hydrological studies in two watersheds are described. This section also introduces the reader to the hydrological, geological and socio-economic characteristics of the study region. Further investigations related to the impact of paddy fields on the water balance of a watershed are summarized in chapter 3. In chapter 4 a water management concept is formulated using rice terraces for artificial ground water recharge. In chapter 5 an attempt is made to validate the concept and investigate its feasibilty under the typical physical and social frameworks of semi-arid tropical India by adopting modelling techniques. Chapter 6 contains a summary of the important results of the data collection and modelling. Finally the main conclusions regarding management and design criteria of a terrace groundwater recharge system are presented.

## 1.3 The Problem

Irrigation tanks are the traditional element of water management in semi-arid tropical India. In the past they helped to stabilise crop production by providing water during dry spells and the post-monsoon season. Tanks consist of small earth dams built across local streams to collect rainwater running off the neighbouring region. The water collected is mainly used for irrigation and domestic purposes [247].

Many tanks date back centuries, for example the majority of tanks in Tamil Nadu were already in existence a century ago, some are even more than a thousand years old. In principle tank irrigation can be considered as an economically and socially profitable technology, however, tanks are often poorly maintained and inefficiently managed. They also incur high seepage, percolation and evaporation losses. Further problems are siltation of the tank bed and the submergence of valuable land that is reclaimed by farmers for irrigation by wells [169].

In India large scale canal irrigation has only developed over the past one hundred years. Massive investments into irrigated agriculture were made under British rule in the interest of increased exportation of goods, and after independence, out of the need to sustain self-sufficiency in food production. These large-scale projects, however, rarely achieved their targets [37]. A selection of common faults in large-scale irrigation projects are given below:

- Costs and duration of construction are underestimated
- The uptake of irrigation is slower than forecasted
- The economic rates of return are much lower than assumed
- Electric power requirements exceed supplies
- The systems are often poorly operated and maintained
- Designs are over-sophisticated

Well irrigation, although known of for a long time, remained relatively unimportant until the end of the sixties. However with the advance of small pumps and the availability of electricity in rural areas the use of ground water became economically feasible. The increase of the irrigated area was mainly due to the increase of the well irrigated area, while the tank irrigated area was stagnating. Nowadays well irrigation is already limited in many regions, where ground water tables are falling [170]. In some areas of Southern India the ground water table drops at a rate of one meter per year [228].

It is obvious that India is going to face great problems in the near future because of its fast growing population and therefore increasing demands for water, unless existing methods of water management are analysed and alternative concepts are developed and implemented.

Existing concepts:

The concept to increase the agricultural production of red soil areas at the farm level through construction and operation of farm ponds encountered problems due to the high seepage and percolation losses, unreliable water availability and the costs of water lifting [167]. Research at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) showed, that in spite of immense efforts to seal such ponds seepage and percolation losses of 20 to 30 mm/d could not be avoided.

The management and maintenance of the traditinal tanks could be improved by creating tank irrigation authorities run by elected farmers and government employees [169].

The idea to artificially recharge the ground water aquifer was already put to practice in India in the seventies. For instance in Maharashtra several hundreds of percolation tanks with capacities of below 150 000 $m^3$ were built under the "employment guarantee scheme". These tanks were identical to ordinary tanks apart from the absence of an irrigation outlet. Therefore, they presented the same problems as irrigation tanks. Since in a lot of cases socio-economic rather than hydrogeological factors dictated the location of tanks, the evaporation was often higher than the percolation. The benefits of percolation tanks are rarely questioned but virtually no monitoring or systematic research is being conducted to quantify the tank's technical and economical performance [57].

Engelhardt [57] suggested the concept of composite water management, which attempts to include the advantages of traditional surface structures such as tanks while avoiding their disadvantages.

Due to the many failures experienced with large-scale projects in contrast to the efficient operation of privately owned systems, small-scale structures were favoured in the above approach. It was proposed that the transition from tanks to well irrigation should be encouraged. Tanks submerging valuable agricultural land should disappear and be substituted by small ponds in the upper parts of the watershed. These ponds placed over geologically favourable formations should store runoff and overland flow for recharging the aquifer. Also wells below these percolation tanks benefit from the additional recharge. Further advantages would be that percolation ponds are less expensive, quickly built and easy to manage. Therefore, there is no need for sophisticated and costly administration. To be successful the above technology has to be supported by improved pricing policies for electricity and a legal framework to enable control of surface and ground water resources [57].

He also recognised the main drawbacks of the traditional irrigation systems [57]. His concept to encourage well irrigation and compensate increasing ground water abstraction by constructing small percolation tanks in the higher parts of a watershed appears to be a sensible form of water management. The subsurface storage of water for dry periods is more efficient, since there is no demand on agricultural land and no evaporation losses occur [51], [43]. Difficulties, however, lie in the details. Engelhardt [57] does not provide detailed information on design and construction of such tanks, but obviously envisages a design similar to tanks or farm ponds. Due to siltation these designs generally suffer from decreasing percolation and reduced storage capacity.

## 1.4 Objectives

In this thesis an attempt is made to tackle the above problems. The primary objective aims at the development of technologically sensible and socio-economically adapted structures, which efficiently transfer surface water underground. Design criteria for such structures need to be developed and strategies of management must be formulated. In addition the feasibility of such systems has to be studied under the different climatological, agronomical and hydrogeological conditions in semi-arid tropical India.

## 1.5 Methodology

A thorough understanding of the hydrological systems of red soil covered semi-arid watersheds was a prerequisite to systematically approach the problem. The hydrology of two representative watersheds displaying two sets of socio-economic and hydrological characteristics in peninsular India were studied. Extensive field studies were initiated to quantify the main parameters of the water balance of such watersheds. Within the limits of the financial resources and the manpower available appropriate data collection was considered feasible only in the two above mentioned watersheds.

A digital watershed model was developed to provide a better insight into the surface-subsurface interactions in the watersheds and to extrapolate measured results of three monsoon seasons for long term trends.

On the basis of the data collected, the modelling efforts and literature studies alternative ways of water management were formulated.

The concepts suggested were validated in an ex ante study by using modelling techniques.

As an additional step in the validation of such concepts pilot projects should be set up and monitored. However the last step is not covered in this study.

## 1.6 Selection of the Study Area

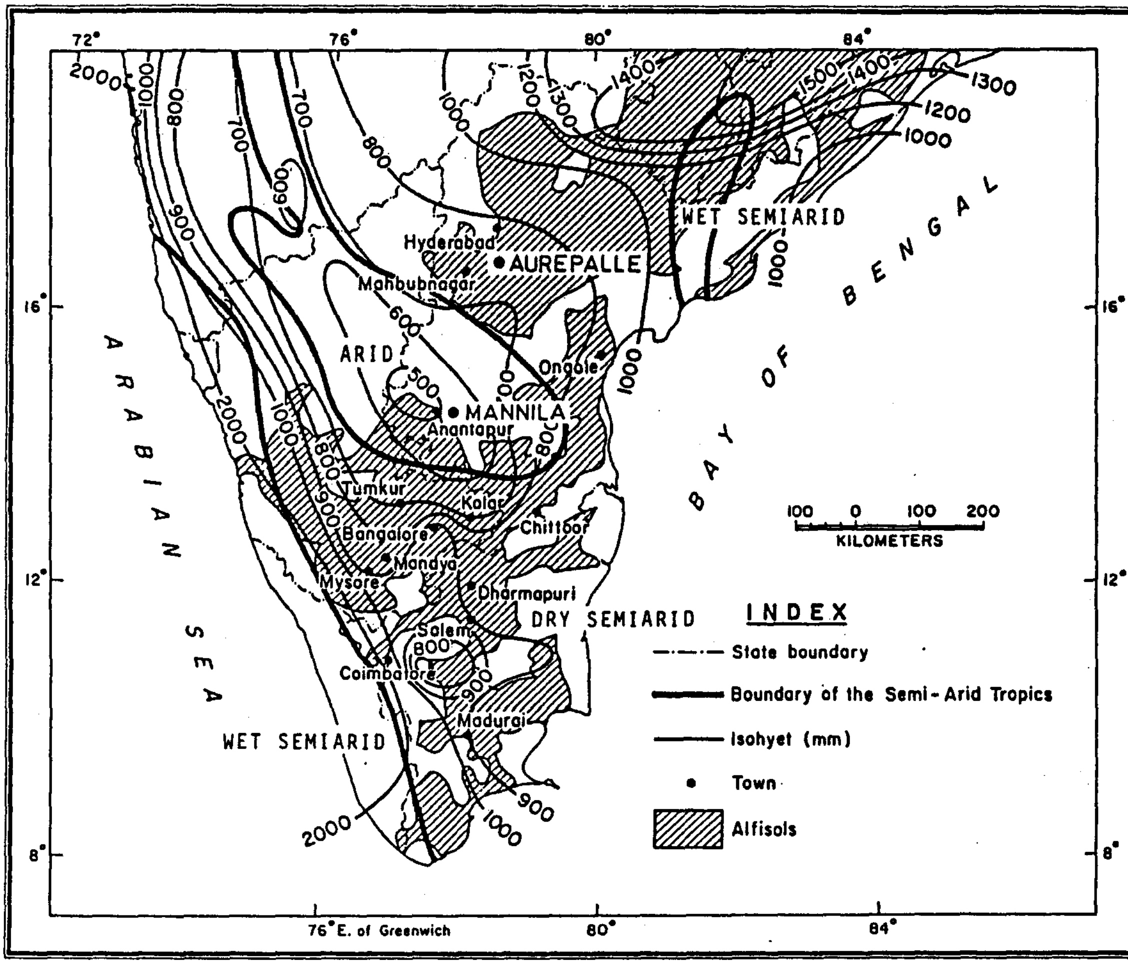
The Aurepalle watershed, located approximately 50 km south of Hyderabad in the Kalwakurthi Taluk of the Mahaboobnagar District (Map 1.1), was chosen as a study watershed because several studies had already been conducted there and information on socio-economic and hydrological issues was available. These studies included the 10 years village level study (VLS), a study on the optimization of small reservoires by Sharma [216] and a pilot study by Engelhardt [57] on the economics of traditional smallholder irrigation systems.

Of three other possible study watersheds namely the Bommenhalli watershed near Mysore, the Kolar watershed near Bangalore and the Mannila Watershed near Anantapur, the latter one was chosen for the following reasons:

- The Mannila watershed provides a good contrast to the Aurepalle watershed. It represents a low rainfall area with a long term mean of 560 mm/year and semi-arid to arid characteristics (Map 1.1). The soils are shallower than in the Aurepalle catchment and slopes are more gentle.

- An agricultural research station is located about 10 km from the watershed providing climatological data.

- In the choice of the Mannila watershed political reasons were also taken into consideration, since it lies in a drought prone area where good cooperation with government agencies could be anticipated.




Map 1.1: Isohyets of Annual Rainfall, Distribution of Alfisols (Red Soils) and Type of Climate in Peninsular India (Source: ICRISAT, Agroclimatology Group)

- One consideration of major importance was that the Mannila watershed was the most accessible allowing frequent control visits.

- The Bommenhalli watershed did not prove to be a watershed in the true hydrological sense, which could have lead to problems in measuring runoff and other hydrological parameters.

- In the Kolar watershed difficulties to assess the ground water resources were anticipated, because no open dugwells were found for observation.

# 2 AGRO-HYDROGEOLOGICAL INVENTORY OF THE STUDY REGION

## 2.1 General

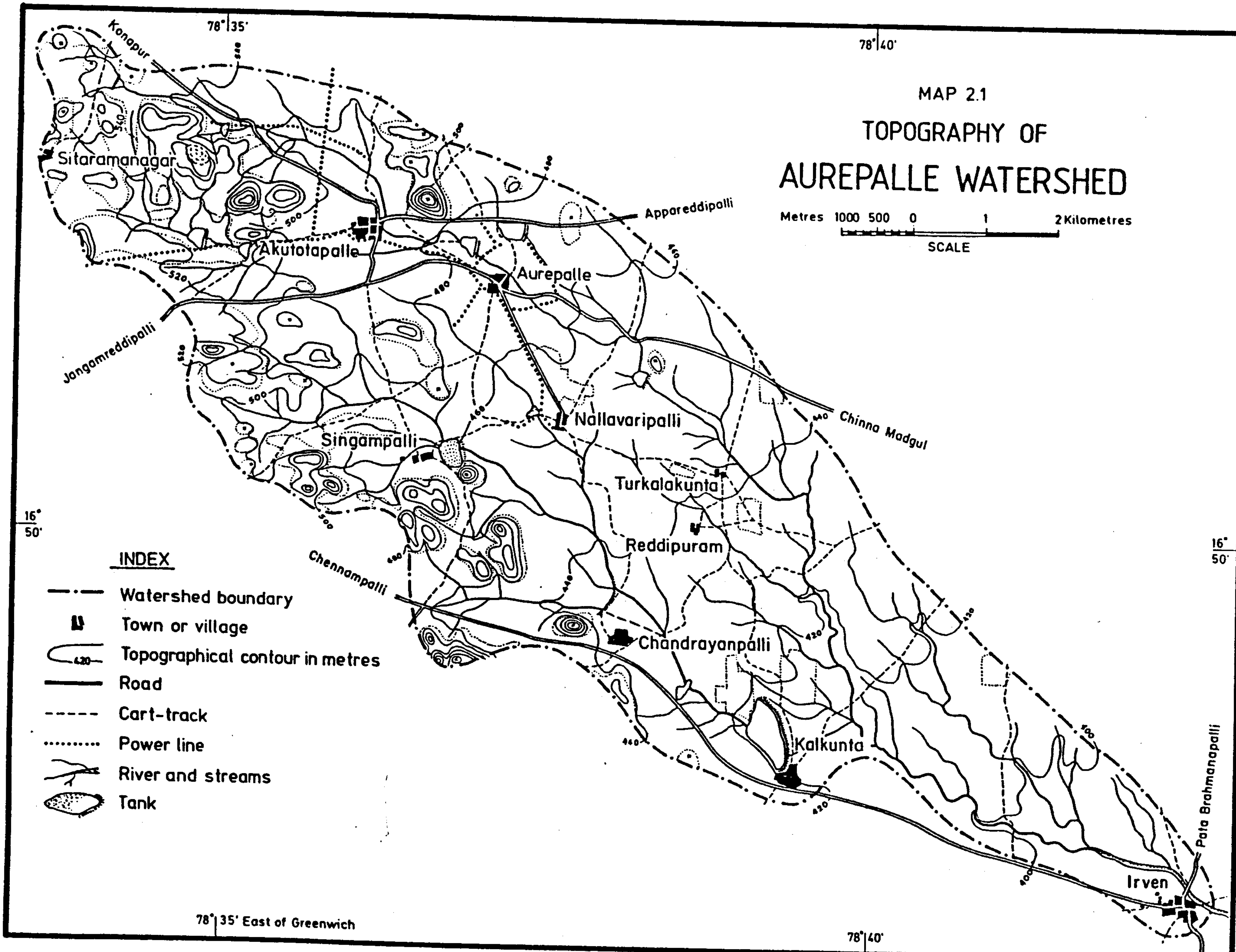
The inventory comprises a brief description of the physical and socio-economic characteristics of the study watershed collated in a review of projects previously carried out in the area and earlier work done by the author. This is followed by a detailed description of the hydrological features of the study watershed.

In this thesis emphasis is placed on describing the inventory of the Aurepalle watershed, because data mainly collected at Aurepalle was used for calibration of the simulation models presented below and similar methods of investigation were employed for both watersheds.

## 2.2 Description of the Study Area

The Aurepalle watershed, located 50 km south of Hyderabad in the Mahaboobnagar district of the state Andhra Pradesh at an elevation of 460 m.a.s.l., covers an area of roughly 70 $km^2$ (Map 2.1). A characteristic feature is the rocky outcrops which reach a height of about 150 m above the relatively flat land and which cover approximately 25 % of the total geographical area. About 70 % of the area is arable land and of this ca. 15 % are under irrigation. The main irrigated crop is rice covering 78 % of the irrigated land in the monsoon and 56 % in the post-monsoon season. Other important irrigated crops are sorghum, groundnut and castor [57]. The main dryland crops are sorghum, millet and castor. Agriculture is the main source of income supporting a population of about 170 inhabitants per $km^2$.

The soils of the watershed are loamy sands of shallow to medium depth with a low soil moisture holding capacity. They are derived from weathering of granites and can be classified as alfisols (red soils). The contents of organic matter is very small. In low lying areas the soils show a higher percentage of silt and clay. Patches of black soils also occur at a few places resulting from the weathering of dolorite dykes [154].




MAP 2.1
TOPOGRAPHY OF
AUREPALLE WATERSHED

Vast areas of India are covered by consolidated underground formations, usually referred to as hard rock areas. In the vicinity of the Aurepalle watershed granites prevail. The shallow ground water aquifer is constituted by a weathered mantle of granite covering the unaltered rock and by the fracture porosity of the unaltered rock itself. The thickness of the aquifer varies between 1 and 30 m, averaging roughly 12 m. The transmissivity values of the unconfined aquifer system are low, ranging from 16 $m^2/d$ to 159 $m^2/d$, with a mean value of 69 $m^2/d$. The specific yield lies between 0.3 % and 8 % averaging 2.1 % [155]. Dolorite dykes, quartz reefs, pegmatite, epidote and quartz veins traverse the water bearing formations. Due to their low porosity the dolorite dykes often act as subsurface dams forming barriers to the movement of ground water [136].

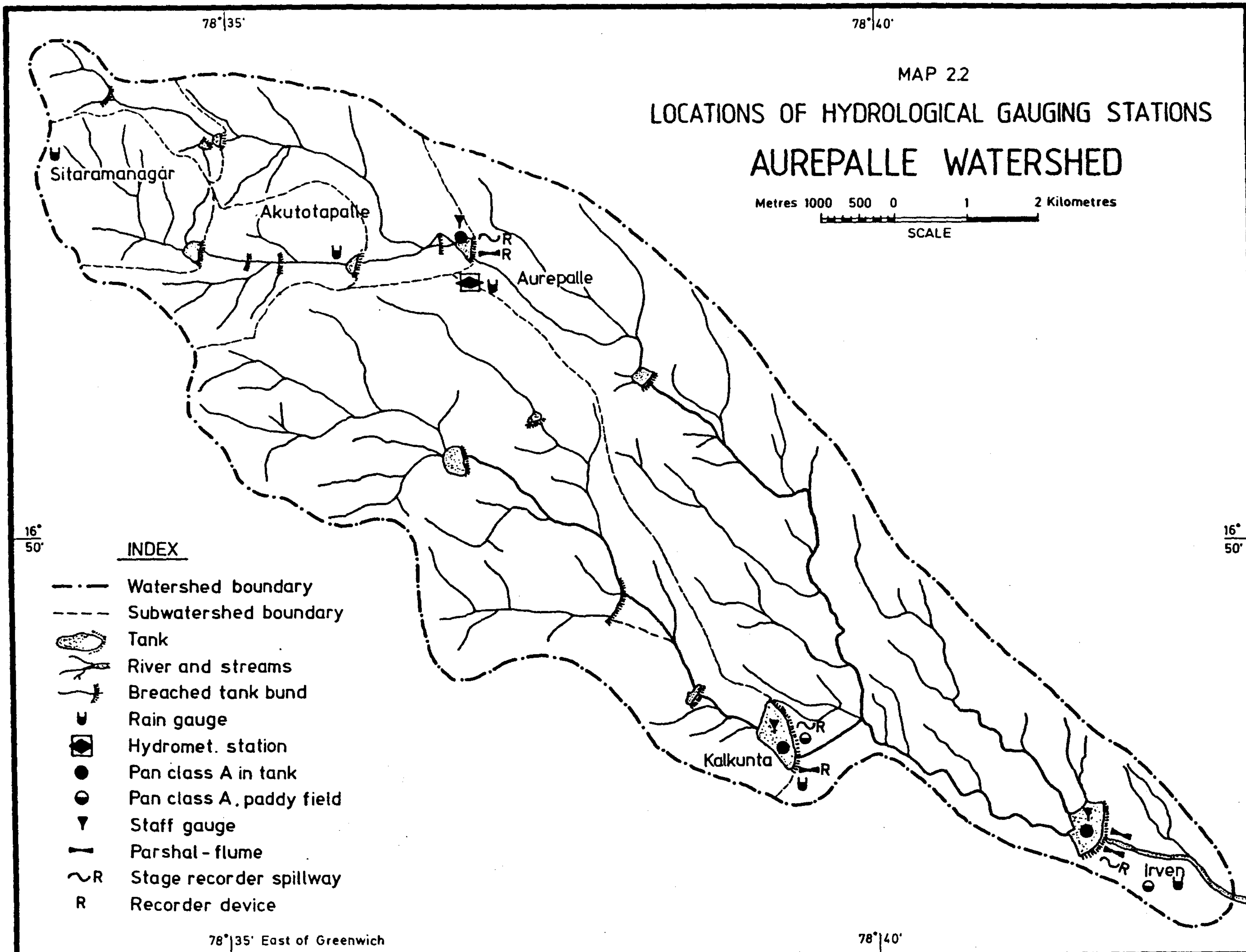
The drainage pattern of the watershed is of the subdentritic type and is aligned NW-SE. All the streams are ephemeral, bearing water only for short periods after heavy rainfall. The main stream leaving the watershed is the Bhimanapally vagu, a tributary of the river Dindi which joins the Krishna in the south east [154].

Irrigation is provided traditionally by tanks but also increasingly by wells. There are 11 tanks in the watershed with capacities of up to 600 000 $m^3$. The tanks are characterised by ratios of the command area (irrigated area) to tank bed area (submerged area) of between 1 and 2 [219], and have an average depth of 0.5 to 1.5 m, and daily evaporation and seepage losses of 5.2 mm/d and 9 mm/d, respectively [247], [115].

It is estimated that there are about 400 wells in the watershed, i.e., approximately 6 wells per $km^2$ [44]. Their interspacing is irregular but in the valley bottom some are only 20 m apart. Most of the wells are rectangular, unlined, shallow, open dugwells which differ greatly in size. In granitic terrain dugwells have certain advantages over borewells especially where the permeability of the aquifer is poor. The storage capacity in the dugwell can act as a buffer between hourly irrigation water demand and the low well yield. The average length, breadth, width, and depth are 10.76 m, 7.03 m and 9.77 m, respectively. The excavated volume amounts to almost 800 $m^3$ [57]. The majority of the wells in the watershed were built after Independance and construction was further encouraged when electricity was brought to the villages in the 1960's.

The area of wetland surrounding a well is a good indicator of the well yield. Depending on the well and the season the irrigated wetland ranges between 0.06 ha and 5.6 ha, which is roughly equivalent to a well yield of between 12.9 and 1042 $m^3/d$. Generally well yields are higher in the monsoon season. In the low lying areas wells are often recharged by tanks. In such cases well yields do not decrease so rapidly in the dry season.

Due to the falling ground water table the farmers have employed various methods to maintain or increase well yields. Apart from enlarging and deepening the wells, the use of in-well bores has become a common practice. In-well bores are drilled to intercept fractures, which are encountered at depths between 15 and 40 m. Water rises through the bore from the fractures under artesian conditions.


MAP 2.2
LOCATIONS OF HYDROLOGICAL GAUGING STATIONS
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
78°|35'
78°|40'
16° 50'
Sitaramanagar
Akutotapalle
Aurepalle
Kalkunta
Irven
R
INDEX
Watershed boundary
Subwatershed boundary
Tank
River and streams
Breached tank bund
Rain gauge
Hydromet. station
Pan class A in tank
Pan class A, paddy field
Staff gauge
Parshal - flume
Stage recorder spillway
Recorder device
78°|35' East of Greenwich

The quality of the ground water is generally good and suitable for irrigation. There is no immediate danger of salinity. However, there seems to be a deterioration of the ground water with increasing distance from the water divide [57], [183].

Detailed reviews can be found in [67], [44], [57], [99], [136], [154], [170], [184], [216].

The data covering the hydrological and meteorological characteristics of the study watershed is presented below.

## 2.3 Field Investigations

To quantify the main hydrological parameters of the water balance of the study watersheds the first stage of data collection was planned and launched at the beginning of the monsoon in 1984 and continued up to the end of the monsoon in 1986. It encompassed:

- Meteorological observations
- Monitoring of rainfall
- Monitoring of ground water levels
- Monitoring of tanks
- An inventory of wells and pump tests

The methods employed and results obtained for the above experiments are explained in detail below. Map 2.2 shows the locations of the hydrological gauging sites in the study watershed.

### 2.3.1 Meteorological Observations

A hydrometeorological station was set up near Aurepalle village in order to obtain information on the climate, especially on the evapotranspiration in the watershed. The station was equipped with both a standard and recording rain gauge; a Stevenson screen with a dry bulb, a wet bulb, a minimum and a maximum thermometer; a Class A evaporation pan; a wind vane; an anemometer; a sunshine recorder and a net radiation recorder.

### 2.3.2 Monitoring of Rainfall

In order to measure the input of water to the system a rainfall monitoring network was set up. Rainfall has been measured with a single non-recording rain gauge at Aurepalle village since 1975. In a watershed of roughly 70 $km^2$ and a length of about 15 km observations from only one rain gauge would mean a high uncertainty in the estimation of the average watershed rainfall, since the variability of rainfall is quite high in the study region. To improve the accuracy of recording of the watershed precipitation, four additional rain gauges were distributed over the watershed. The sites were selected according to the general norms of installation but the accessibility and availability of skilled personnel were also taken into account (Map. 2.1).

### 2.3.3 Monitoring of the Ground Water Level

Monitoring of ground water levels is one of several approaches to assess ground water recharge. A review of the literature shows that three main procedures are employed in Southern India to determine recharge:

- the so called "ad hoc" method
- the Tritium injection method
- the water level fluctuation approach

The "ad hoc" method can be considered a rule of thumb. Employing this method, only the order of magnitude can be determined and recharge is expressed as a percentage of rainfall. The percentage is usually taken from results of ground water projects carried out in areas with similar hydrogeological characteristics.

The Tritium injection method calculates recharge by the vertical displacement of a radioactive tracer which is introduced into the unsaturated soil zone just below the maximum rooting depth. Multiplying the displacement of the radioisotope with the percentage of soil moisture yields fairly good estimates of the natural ground water recharge.

The water level fluctuation approach requires measurements of the lowest pre-monsoon and the highest post-monsoon water levels as well as estimates of the specific yield of the aquifer and the amount of ground water draft. The basic formula to calculate net ground water recharge by this method is [239].

$$V_{gw,r} = \Delta V_{gw} + V_{gw,ab} \qquad (2.1)$$

where:

| | | | |
|---|---|---|---|
| $V_{gw,r}$ | = | Net ground water recharge | [$m^3$] |
| $\Delta V_{gw}$ | = | Change in ground water storage | [$m^3$] |
| $V_{gw,ab}$ | = | Ground water abstraction | [$m^3$] |

This method is only sound in gently sloping aquifers, where lateral ground water flow is negligible. Moreover determination of the specific yield is rather difficult especially for hard rock aquifers.

Each of the above mentioned techniques has major disadvantages, which lead to errors in results. Therefore, it is advisable to carry out at least two, preferably three, methods so that the results can be collated and their reliability improved.

So in addition to the water level fluctuation approach the Tritium injection method was employed. The latter approach was conducted in cooperation with a team of hydrogeologists of the National Geophysical Research Institute (NGRI). As a third method the ground water discharge method was adopted which is based on a subsurface-recharge-discharge comparison (Figure 2.1).

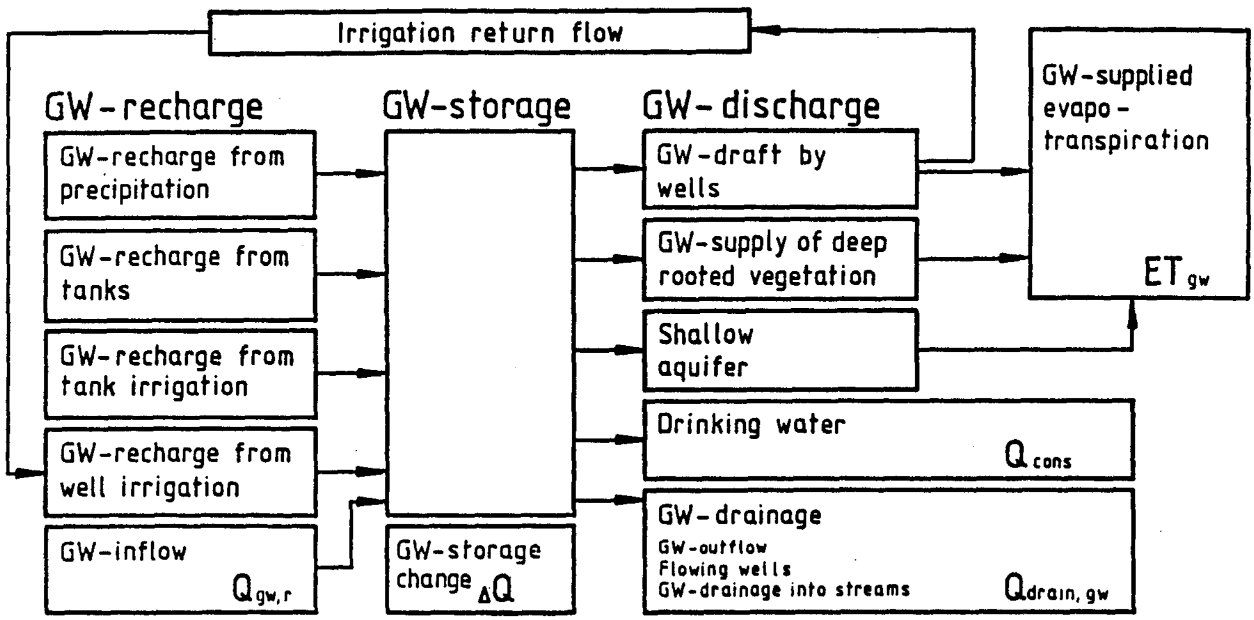



Figure 2.1: Model of the Components of Ground Water Recharge and Discharge

The model can be expessed in Equation 2.2:

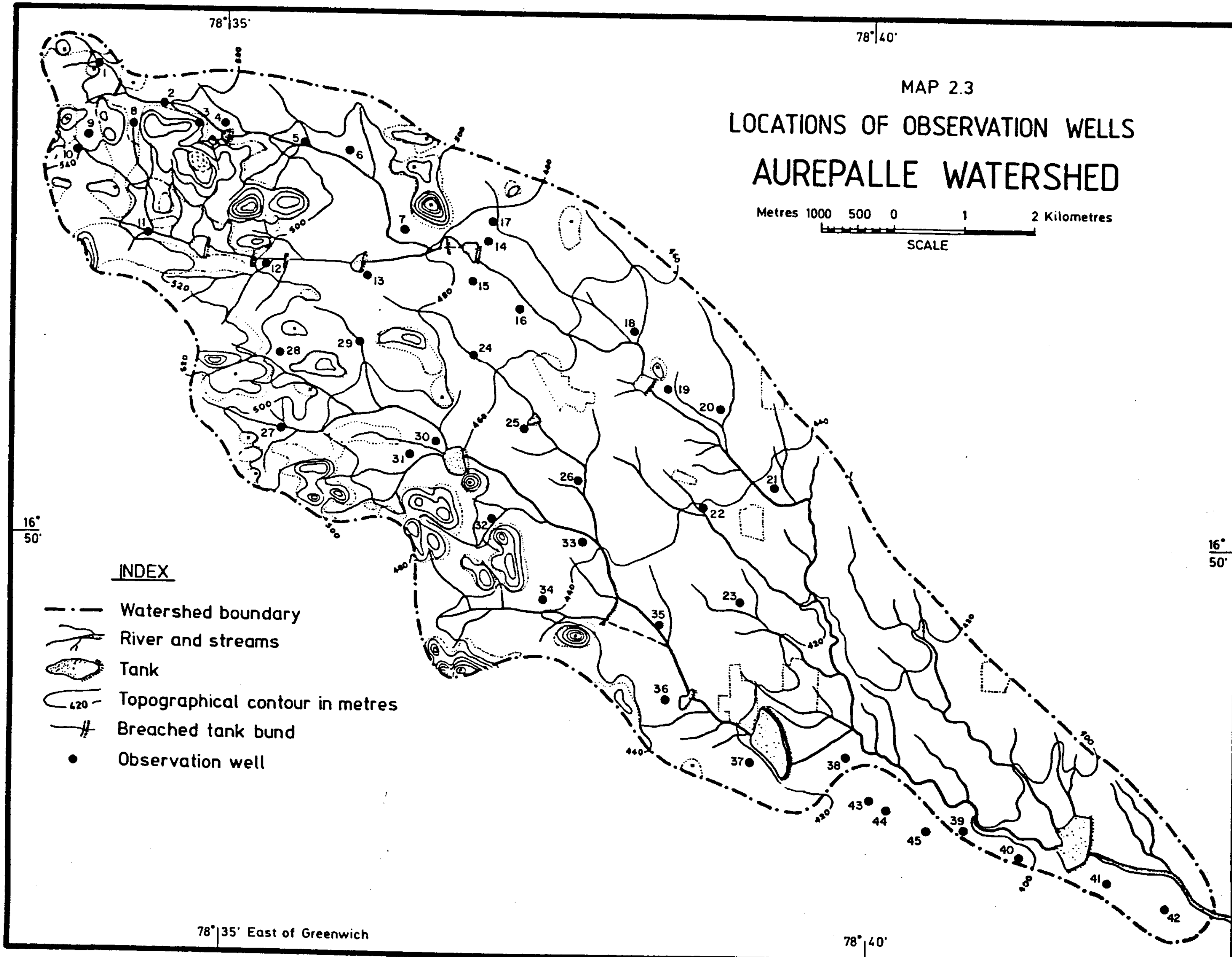
$$Q_{gw,r} = \Delta Q + Q_{cons} + Q_{drain,gw} + ET_{gw} \qquad (2.2)$$

where:

| | | |
|---|---|---|
| $Q_{gw,r}$ | = | Ground water recharge |
| $\Delta Q$ | = | Change in storage |
| $Q_{cons}$ | = | Animal and human water consumption |
| $Q_{drain,gw}$ | = | Ground water drainage |
| $ET_{gw}$ | = | Ground water supplied evapotranspiration |

Apart from specific yield, the water level fluctuation method and the ground water discharge method both require the determination of the change in ground water storage for the respective balance periods. Consequently over 40 observation wells were selected in the Aurepalle watershed in June 1984.

The selection criteria took into consideration the need to establish an evenly distributed network of wells, preferably consisting of a high percentage of unused dugwells or at least of mote operated wells (traditional way of lifting water in a leather bucket drawn by bullocks). Accessibility of wells, of course, was another important factor.




MAP 2.3

LOCATIONS OF OBSERVATION WELLS

AUREPALLE WATERSHED

During the dry season between December and April water levels were observed monthly, for the remaining part of the year, where rainfall was more likely fortnightly readings were taken.

The locations of the observation wells in the watershed are presented in Map 2.3.

### 2.3.4 Monitoring of the Tank Water Balance

Tank monitoring was planned in order to collect information on the runoff characteristics, the recharge induced and the losses due to evaporation. The tank water balance can be written as follows (Equation 2.3) (Figure 2.2):

$$P_{ta} + Q_{in} + Q_{in,gw} = E_{ta} + Q_{over} + Q_{irr} + Q_{perc} + Q_{seep} + Q_{vis} + \Delta Q \qquad (2.3)$$

where:

| | | | |
|---|---|---|---|
| $P_{ta}$ | = | Precipitation on tank | $[m^3/d]$ |
| $Q_{in}$ | = | Inflow to tank | $[m^3/d]$ |
| $Q_{in,gw}$ | = | Ground water inflow to tank | $[m^3/d]$ |
| $E_{ta}$ | = | Evaporation from tank | $[m^3/d]$ |
| $Q_{over}$ | = | Overflow over spillway | $[m^3/d]$ |
| $Q_{irr}$ | = | Irrigation outflow | $[m^3/d]$ |
| $Q_{perc}$ | = | Percolation through tank bed | $[m^3/d]$ |
| $Q_{seep}$ | = | Seepage through tank bund | $[m^3/d]$ |
| $Q_{vis}$ | = | At surface visible seepage | $[m^3/d]$ |
| $\Delta Q$ | = | Change in storage | $[m^3/d]$ |

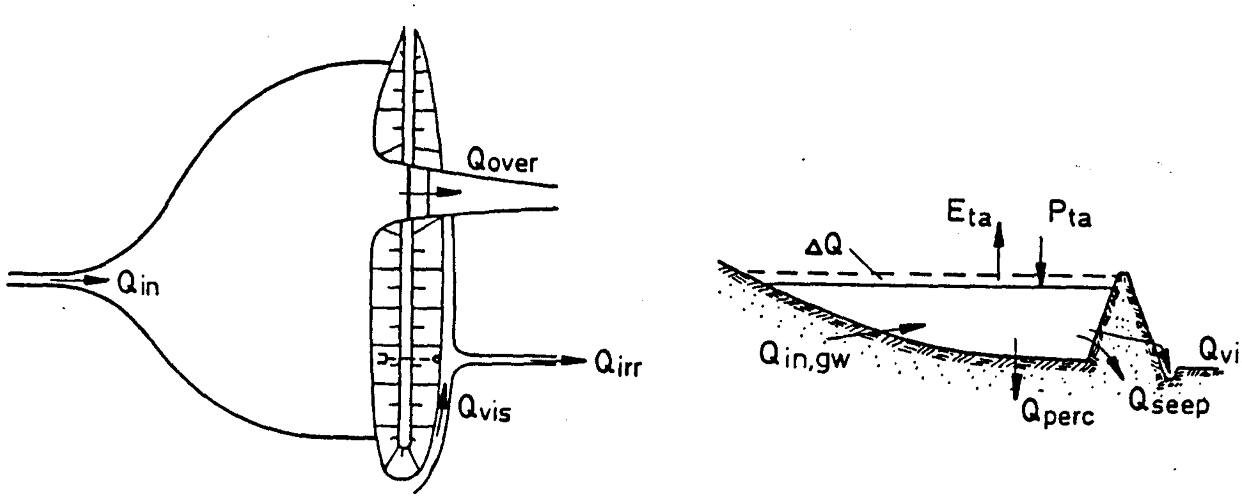



Figure 2.2: Parameters of the Tank Water Balance

During dry spells rainfall, inflow, overflow and often ground water inflow as well as visible seepage are negligible. For percolation tanks the term irrigation outflow can be ommitted. Thus equation 2.3 can be simplified to Equation 2.4:

$$\Delta h = h_{ev} + h_{seep} + h_{perc} \qquad (2.4)$$

where:

| | | | |
|---|---|---|---|
| $\Delta h$ | = | Change of water level | [m] |
| $h_{ev}$ | = | Evaporation from tank | [m] |
| $h_{seep}$ | = | Seepage through tank bund | [m] |
| $h_{perc}$ | = | Percolation through tank bed | [m] |

The sum of seepage and percolation ($h_{seep} + h_{perc}$) can be deduced, when the change of water level and evaporation are measured. This was achieved with a staff gauge and a pan class A installed in the tank.

To obtain a value for lake evaporation the pan values were multiplied with a monthly changing coefficient $k_{lake}$, which was interpolated from values published by Venkataraman and Krishnamurthy [250].

In addition irrigation outflow was monitored with the help of a Parshal flume, the head of the spillway discharge with a stage recorder, and the rain near the tank with a standard rain gauge. Stage capacity and stage area curves were used to convert rainfall and change in water level from millimeters into cubic meters.

The visible seepage is generally collected in ditches which divert the water into an irrigation channel. The terms visible seepage and irrigation outflow could therefore be combined. On days with inflow two unknown parameters, seepage and inflow, are left in Equation 2.3. On such days an average value of seepage plus percolation was adopted and the inflow to the tank could then be inferred.

In order to estimate the runoff in and from the catchment, the area was divided into several subwatersheds. The boundaries were drawn in such a way that all the runoff would drain into tanks at the bottom of each subwatershed. The resulting configuration is presented in Map 2.4.

The Aurepalle and Kalkunda tanks were monitored between July 1984 and November 1986. The fairly new Irven tank breached twice during the course of the experiments due to an improperly designed spillway. Thus, monitoring was abandoned there in 1985. However a rough assessment of the runoff in the lower part of the watershed was possible using the information gathered in 1984 and 1985.

The stage area and stage capacity curves of the Kalkunda tank had to be established by a levelling survey, since a plan of the tank was not available. The curves of the Irven tank were kindly provided by the Minor Irrigation Department, Mahaboobnagar District. The curves for the Aurepalle tank were taken from Sharma [216].

### 2.3.5 Well Inventory

A well inventory was carried out to quantify land use, the total ground water abstraction from the watershed and the ground water return flow from irrigated fields. A well questionnaire was designed to facilitate the collection of data. It comprised of questions concerning well identification, well design, the method of water lifting, well performance, soils, water quality and constraints. The inquires regarding the well performance included questions on type and area of irrigated crops, daily pumping hours, number of days of pumping and average water level in the well for all the three seasons in 1984 and 1985. A sample questionnaire is given in Appendix E. The quality of the information can be regarded as good, because the inquiry was conducted at the wells, where the answers could be checked. Wherever possible the answers were confirmed through measurements.

There are about 400 wells in the Aurepalle basin, which is too many to consider inventarisation of every one individually. Therefore only 98 wells, located in subwatersheds 3, 4, 5 and 6, were included in the questionnaire (Map 2.4).

### 2.3.6 Pumping Tests

Pump tests were conducted to establish delivery head - discharge relationships for the pump stations in dugwells. These relationships were required for the estimation of ground water draft and the total water applied to paddy and other irrigated crops.

The discharge was measured by using a portable 90 degree V-notch weir. The decreasing water level in the well was recorded with a well pipe at intervals of 5 to 15 min depending on the rate of drawdown, which varied because of the changing pump efficiency and the well geometry.

The wells for the pump tests were selected in such a way that data points were obtained with average delivery heads between 15 and 5 m.

## 2.4 Results of Field Investigations

### 2.4.1 Results of Meteorological Observation

Mean monthly values of the climatic data are depicted in Table 2.1. Rainfall appears to be negligible between December and March. During April and May pre-monsoon showers occasionally occur but in a normal year the monsoon starts in the second week of June. During this time the monthly rainfall increases to a peak of almost 150 mm in September and drops to levels of 68 and 30 mm/month in October and November, respectively. The coefficient of variation for the variability of monthly rainfall from year to year during the monsoon lies at approximately 60 %. The mean maximum temperature increases from 28.2 °C in December to 39.4 °C in May then drops in June to reach a level of about 31 °C during July, August and September. After a slight rise in October, the temperature decreases again to a low in December. The minimum temperature fluctuates far less but shows the same cycle apart from October, when the minimum temperature does not rise again. The daily range of temperature is highest in the dry season and lowest during monsoon. The relative humidity at 7.00 hours remains fairly constant at around 85 % between July and December. The lowest value is recorded in May with 54 %. The 14.00 hours relative humidity peaks in August with 61 % and drops in March and April to 23 %. The wind speed is feeble during the dry season and becomes stronger in May indicating the arriving monsoon. After a peak in June/July the wind drops again to the spring and winter values. The pan evaporation value follows the cycle of the maximum temperature with a main peak in May of 12.8 mm/d and a second peak in October of 6.4 mm/d. As little as 5.3 mm are evaporated in December. The sun shines for up to 9.5 hours in the dry season, in contrast to 4.6 hours in the middle of the monsoon.

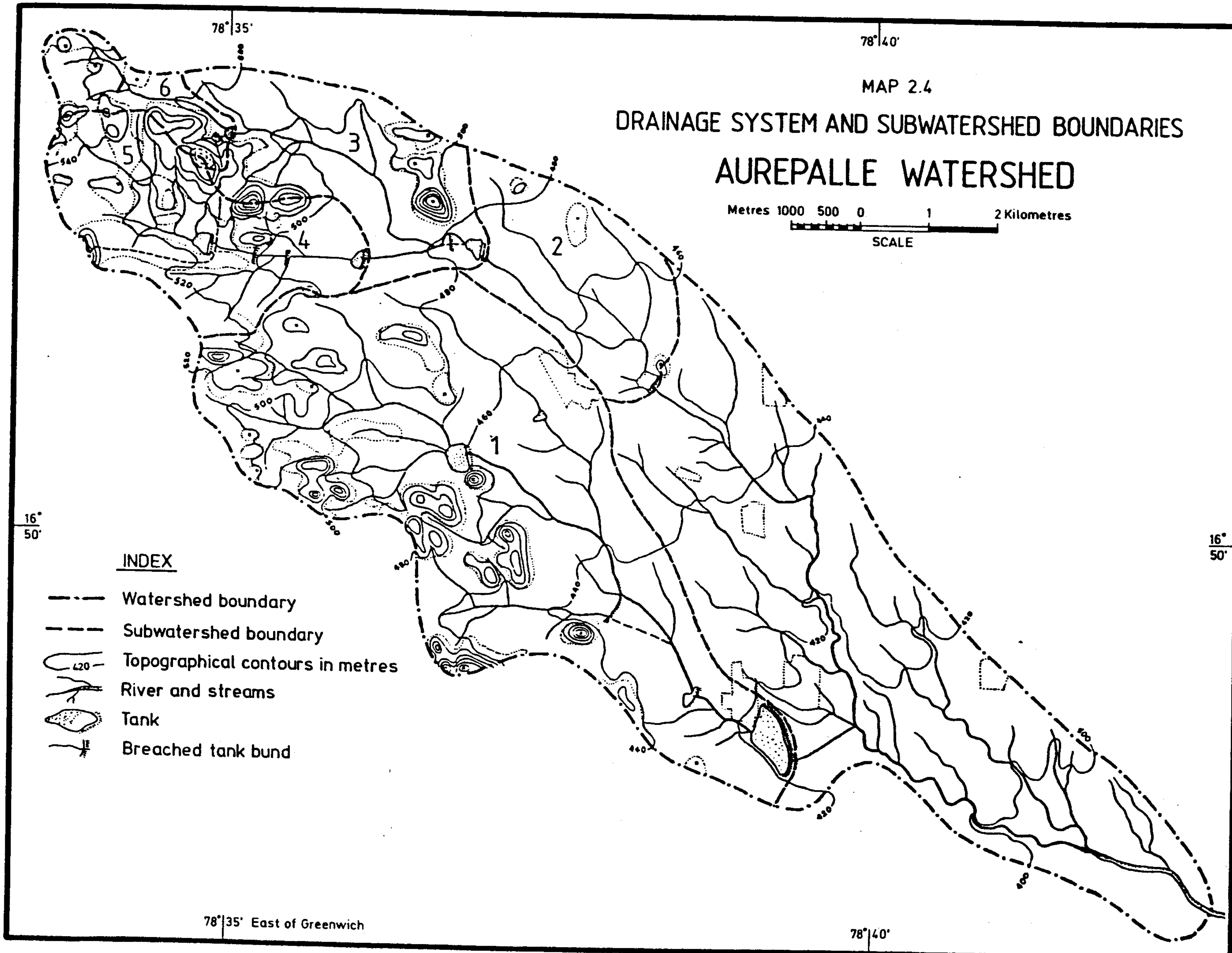

MAP 2.4
DRAINAGE SYSTEM AND SUBWATERSHED BOUNDARIES
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
INDEX
Watershed boundary
Subwatershed boundary
Topographical contours in metres
River and streams
Tank
Breached tank bund
78°35'
78°40'
78°35' East of Greenwich
16° 50'
1
2
3
4
5
6
420
440
460
480
500
520
540

Table 2.1: Monthly Means of Climate Data at Aurepalle Station (calculated from 1985 and 1986 data and corrected for long term trends with ICRISAT data, monthly totals of rainfall were determined from the 11 years rainfall record)

| Month | Rain | Temperature | | | Humidity | | Wind | Pan | Sun |
|---|---|---|---|---|---|---|---|---|---|
| | | Max | Min | Mean | 7 h | 14 h | | evap. | hours |
| | [mm] | [°C] | [°C] | [°C] | [%] | [%] | [km/h] | [mm/d] | [h/d] |
| January | 1.7 | 28.6 | 15.3 | 3.3 | 85 | 36 | 6.6 | 5.3 | 9.0 |
| February | 6.7 | 31.2 | 16.7 | 14.5 | 75 | 30 | 7.3 | 7.4 | 9.5 |
| March | 9.4 | 35.2 | 19.0 | 15.2 | 63 | 23 | 7.8 | 9.4 | 9.2 |
| April | 26.1 | 37.3 | 23.2 | 14.1 | 58 | 23 | 8.2 | 10.3 | 9.4 |
| May | 37.3 | 39.4 | 25.0 | 14.4 | 54 | 24 | 13.1 | 12.8 | 9.4 |
| June | 78.4 | 33.4 | 23.2 | 10.2 | 76 | 45 | 20.0 | 10.0 | 6.2 |
| July | 104.7 | 31.4 | 22.6 | 8.8 | 85 | 59 | 18.2 | 8.6 | 4.6 |
| August | 125.6 | 31.0 | 22.1 | 8.9 | 87 | 61 | 15.0 | 6.4 | 5.0 |
| September | 149.1 | 31.0 | 22.4 | 8.6 | 88 | 56 | 8.5 | 5.2 | 6.5 |
| October | 68.3 | 31.6 | 20.8 | 10.8 | 85 | 49 | 6.1 | 6.4 | 7.7 |
| November | 30.2 | 29.4 | 16.8 | 12.6 | 83 | 43 | 6.2 | 5.7 | 8.6 |
| December | 0.2 | 28.2 | 15.5 | 12.7 | 84 | 36 | 5.1 | 5.4 | 8.9 |

### 2.4.2 Results of Monitoring of Rainfall

Table 2.2 presents the annual rainfall received during the period of 1984 to 1986 for all stations monitored in the Aurepalle Watershed.

Table 2.2: Annual Rainfall in the Aurepalle Watershed at Different Stations from 1984 to 1986

| Year | Stations | | | | | |
|---|---|---|---|---|---|---|
| | Watershed Mean | Sitaraman. | Akutotap. | Aurepalle | Kalkunta | Irven |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] |
| 1984 | 490.0 | 519.0* | -- | 562.0 | 401.0* | 446.0* |
| 1985 | 640.0 | 519.0 | 514.0 | 583.0 | 767.0 | 761.0 |
| 1986 | 560.0 | 495.0 | 468.4 | 496.3 | 653.0 | 618.6 |

* extrapolated with Aurepalle rainfall for June and July

In the Aurepalle watershed there is considerable spatial variation in the annual rainfall. The rainfall at the two lower stations Kalkunta and Irven, differs markedly from that at the three stations in the upper, more hilly, part of the watershed. In contrast there are only small differences between stations located in the same half of the watershed. Orographical reasons may be responsible for these differences.

The average yearly precipitation at the Aurepalle station was 618.8 mm/y for the period from 1976 to 1986. In the study period from monsoon 1984 to monsoon 1986 the rainfall falls slightly below average twice and in 1986 markedly below average. However the two stations in the lower part of the watershed received nearly average rainfall during 1984 to 1986.

The monthly means calculated from the entire record of the Aurepalle station give the distribution of rainfall over the year (Table 2.3).

Table 2.3: Mean Monthly Totals of Rainfall at Aurepalle (observation period 1975 to 1986)

| | Rain [mm/month] | Sx [mm/month] | Cv [%] |
|---|---|---|---|
| January | 4.3 | 9.1 | 211.0 |
| February | 7.2 | 14.9 | 206.0 |
| March | 8.0 | 21.5 | 267.0 |
| April | 23.7 | 14.3 | 60.4 |
| May | 32.2 | 34.9 | 108.0 |
| June | 76.4 | 38.4 | 50.3 |
| July | 102.8 | 67.0 | 65.2 |
| August | 121.4 | 75.3 | 62.1 |
| September | 144.1 | 85.4 | 59.2 |
| October | 70.5 | 61.3 | 87.0 |
| November | 33.3 | 36.9 | 111.0 |
| December | 3.0 | 6.7 | 219.0 |

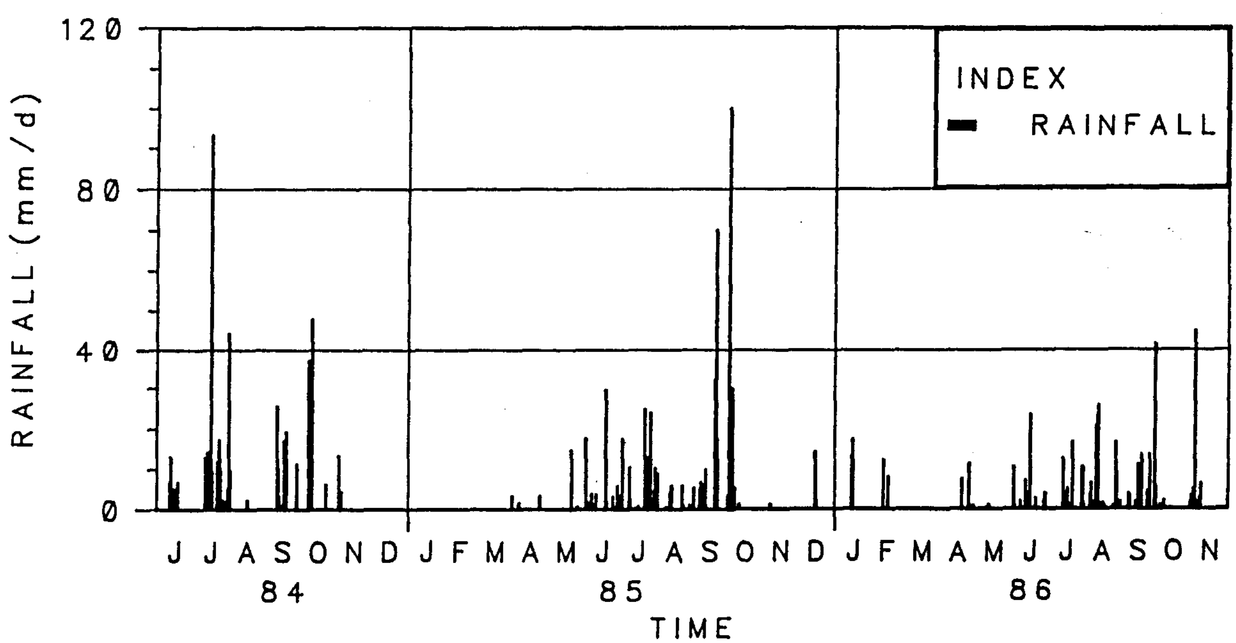



Figure 2.3: Distribution of Daily Rainfall during the Study Period at Aurepalle

Considerable variation in the rainfall pattern was observed between years. Whereas there was one day in monsoon 1984 with rainfall above 90 mm and two days in monsoon 1985 with rainfall above 70 mm, the highest rainfall in monsoon 1986 amounted to only 44 mm. However, in 1986 unusually high rainfall was received in the pre- and post-monsoon seasons (Figure 2.3). How these different distributions influenced runoff and ground water recharge is discussed later. Another extreme situation worth mentioning is the dry spell in August/September 1984 where only 2.5 mm of rainfall occurred in five weeks.

### 2.4.3 Results of Monitoring of Ground Water Level

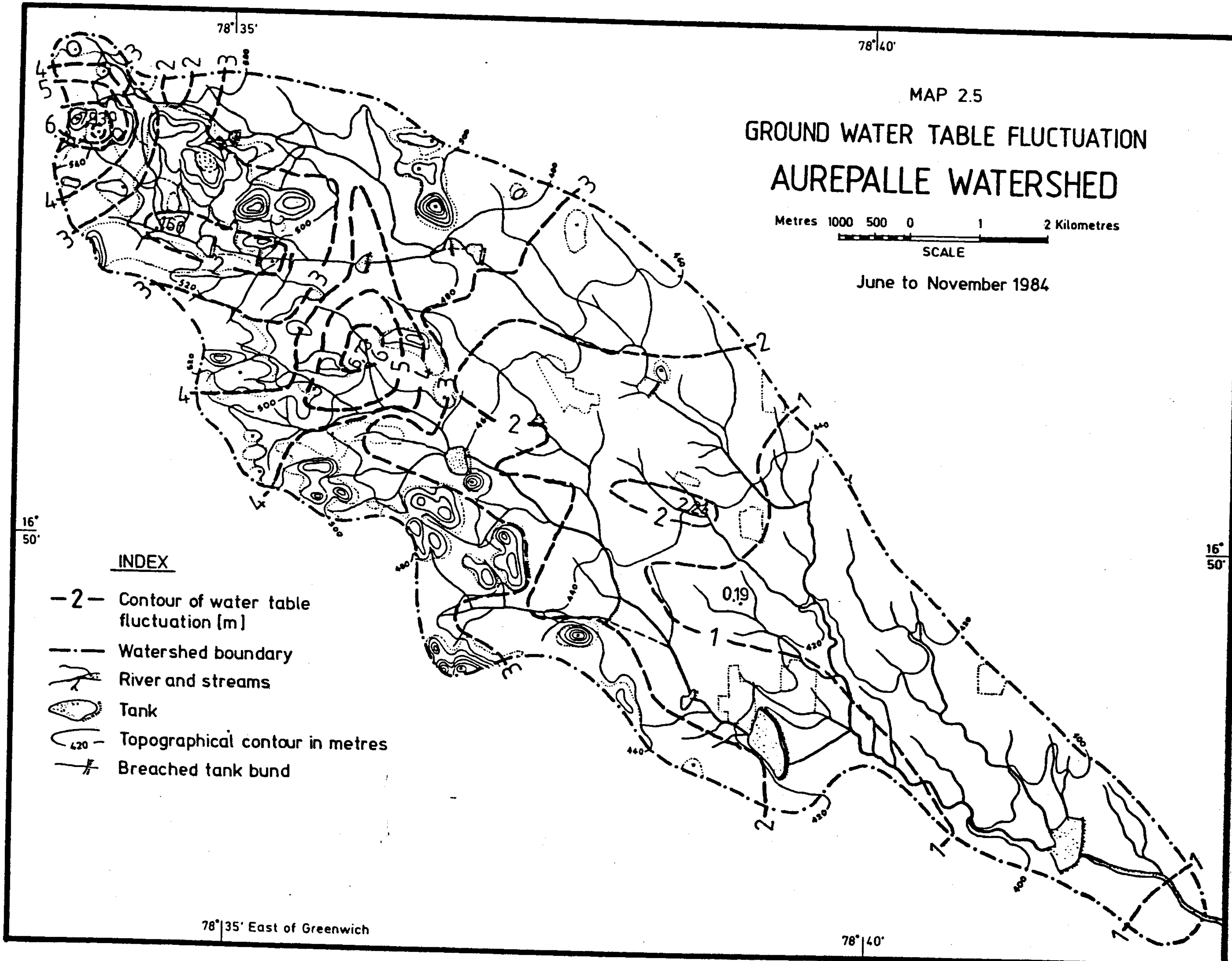
Water table fluctuations ranged between roughly 1 m in the lower part of the Aurepalle watershed and 9 m in the upper part. These large fluctuations can be partially attributed to changes in the specific yield of the aquifer, but large fluctuations were also observed below tanks (Maps 2.5 and 2.6).

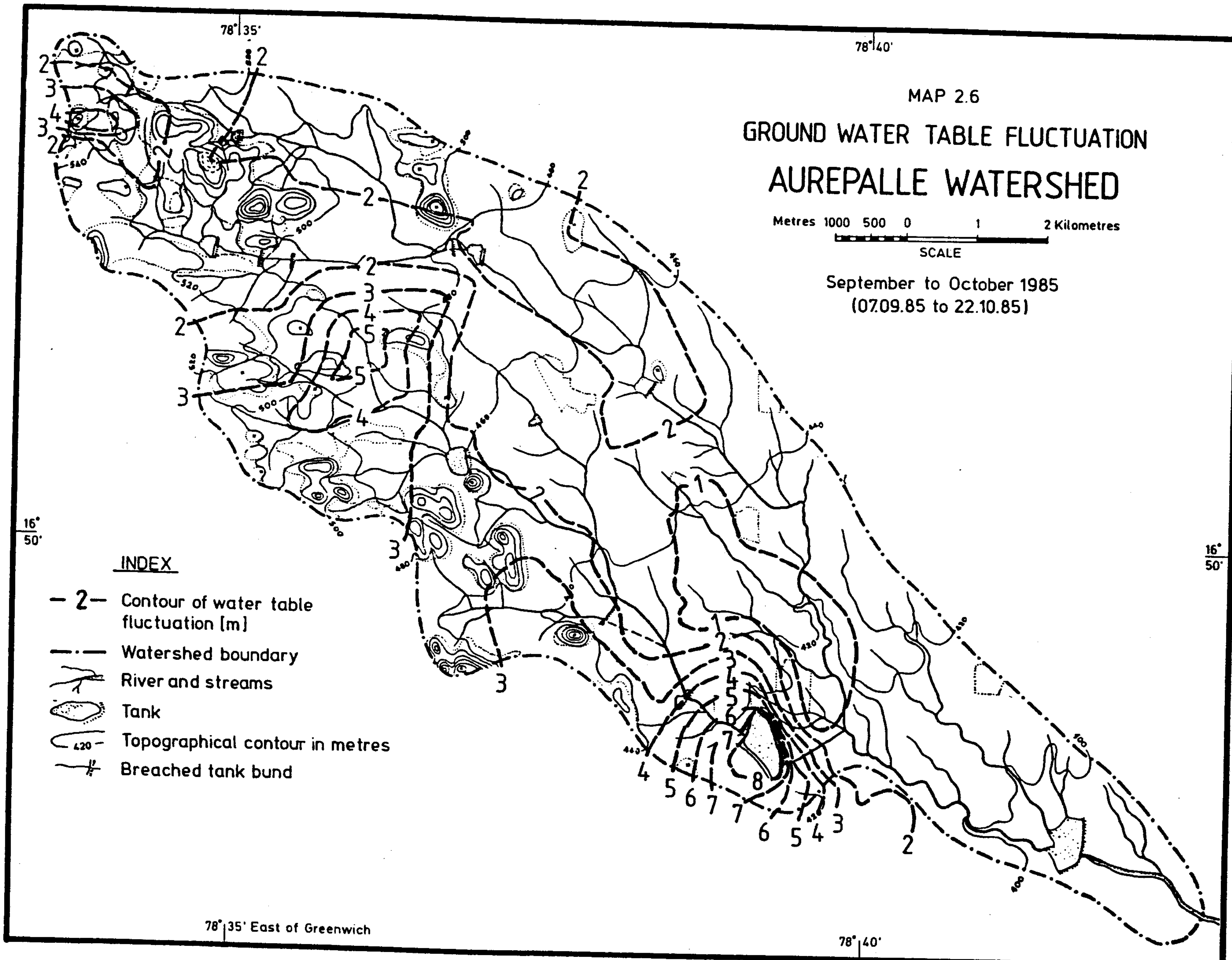
Well hydrographs were plotted from the water level data. Some selected hydrographs are given in Appendix F. A comparison of rainfall and well hydrographs shows that the distinctive peaks of weekly rainfall in 1984 and 1985 correspond to relative increases in the water table. In 1986, where weekly precipitation never exceeded 60.5 mm in the upper part of the watershed, the correlation is not so clear. However in the lower part, where rainfall was higher and reached a peak of 116.6 mm in the 39th. week, hydrographs showed a response with a rise of water levels (consult well hydrographs 37 and 44, Appendix F).

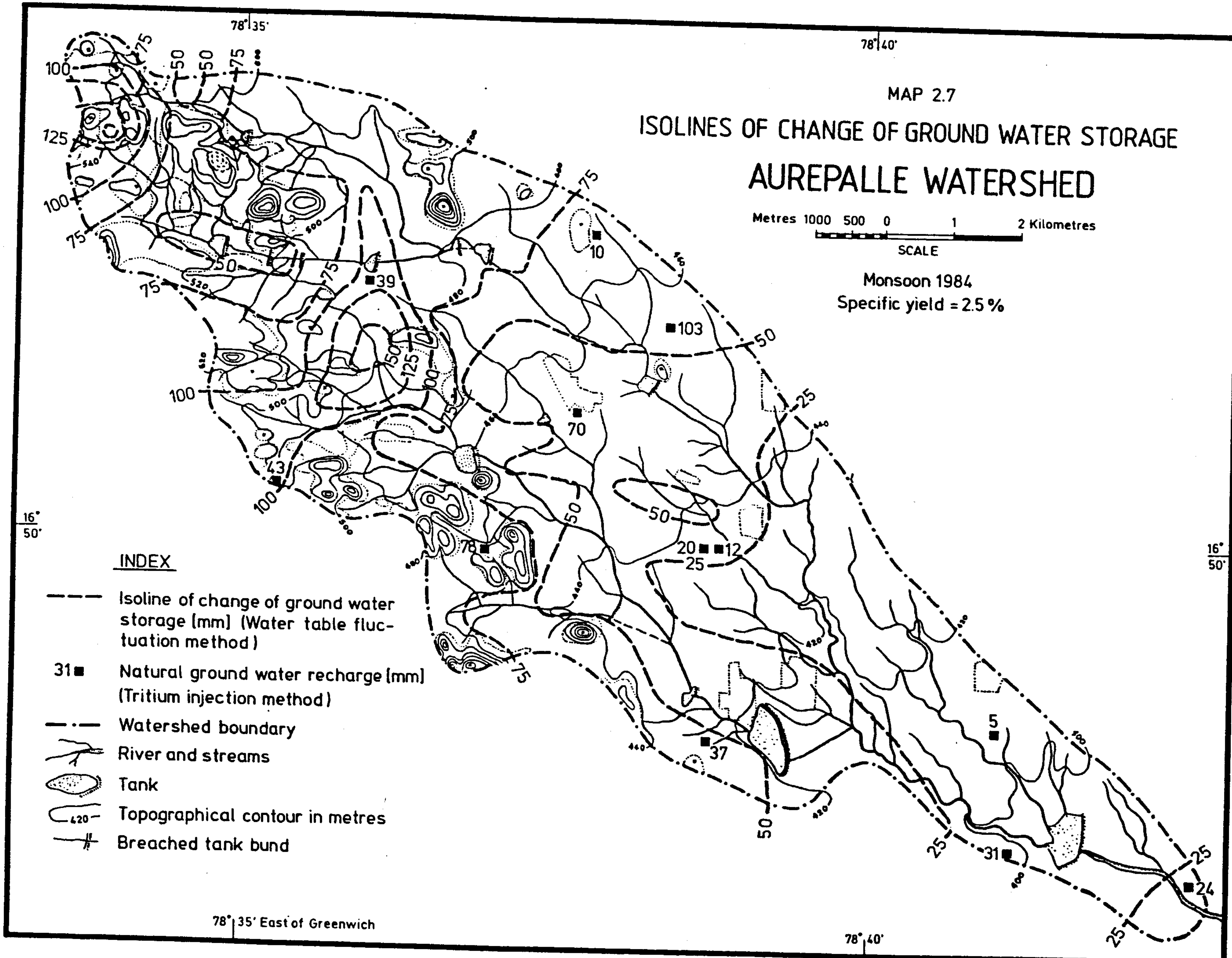
Average fluctuations in 1984 and 1985 worked out to be 1.85 m and 2.20 m, respectively. For the assessment of the change in ground water storage, information on the specific yield was required. A comparison of the results of the Tritium injection method and the water level data indicated a specific yield between 2.5 % and 3.0 %. This concurs with the results of the "Canadian Assisted Ground Water Project" [67] carried out in a geohydrologically similar region adjacent to the Aurepalle watershed. Muralidhasan et al [155] calculated a watershed average of 2.1 % from pump test data. The author determined a value of 2.7 % for subwatershed 3 by postulating that the decline of the water level in the dry season is roughly equal to the net ground water draft, which was estimated as 1.1 times the potential evapotranspiration of the total area under paddy cultivation. For further computations a value of 2.5 % was selected.

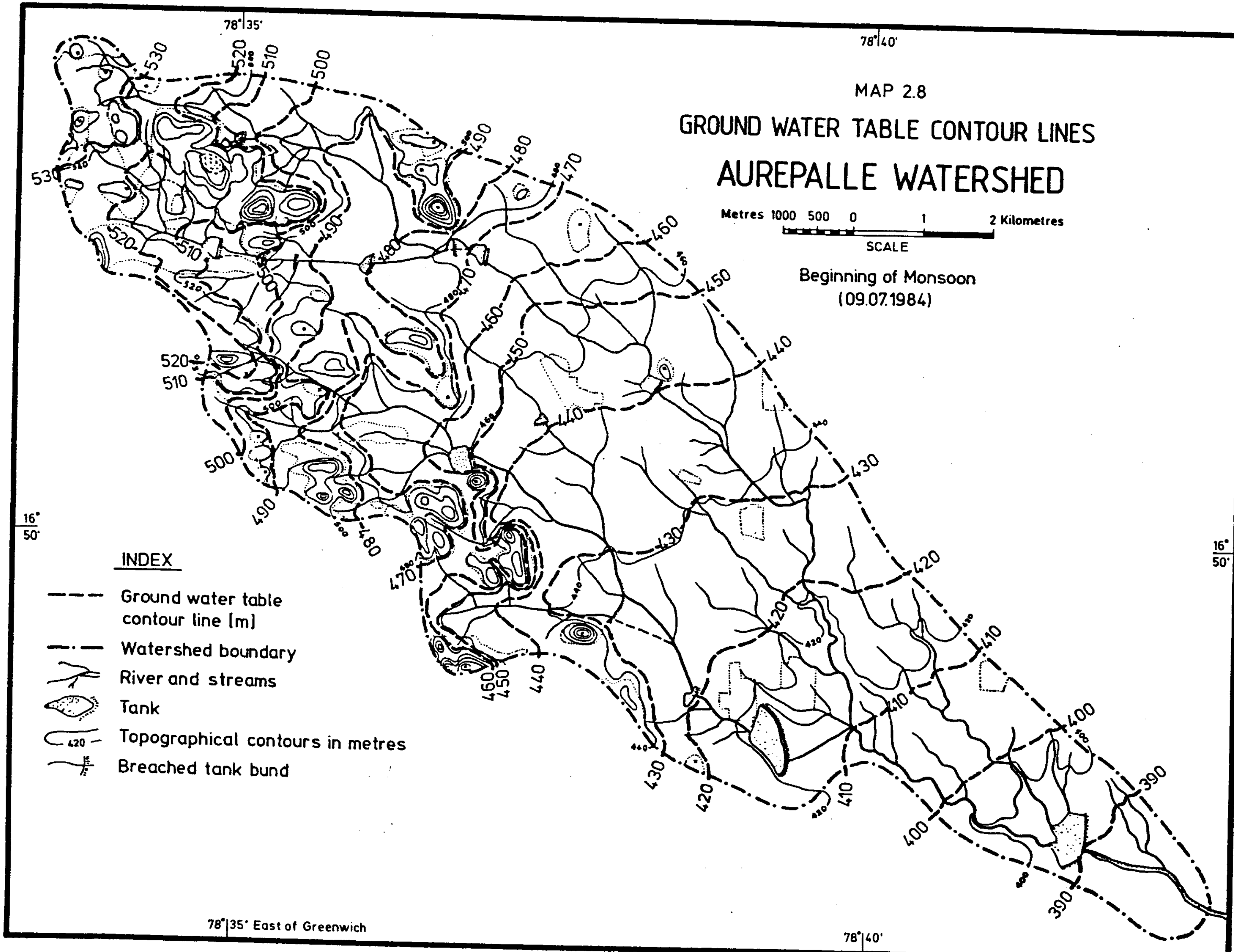
Taking into consideration a specific yield of 2.5 %, the change in storage thus became 46.3 mm in 1984 and 55.0 mm in 1985. Contours of the ground water storage change are depicted in Map 2.7.

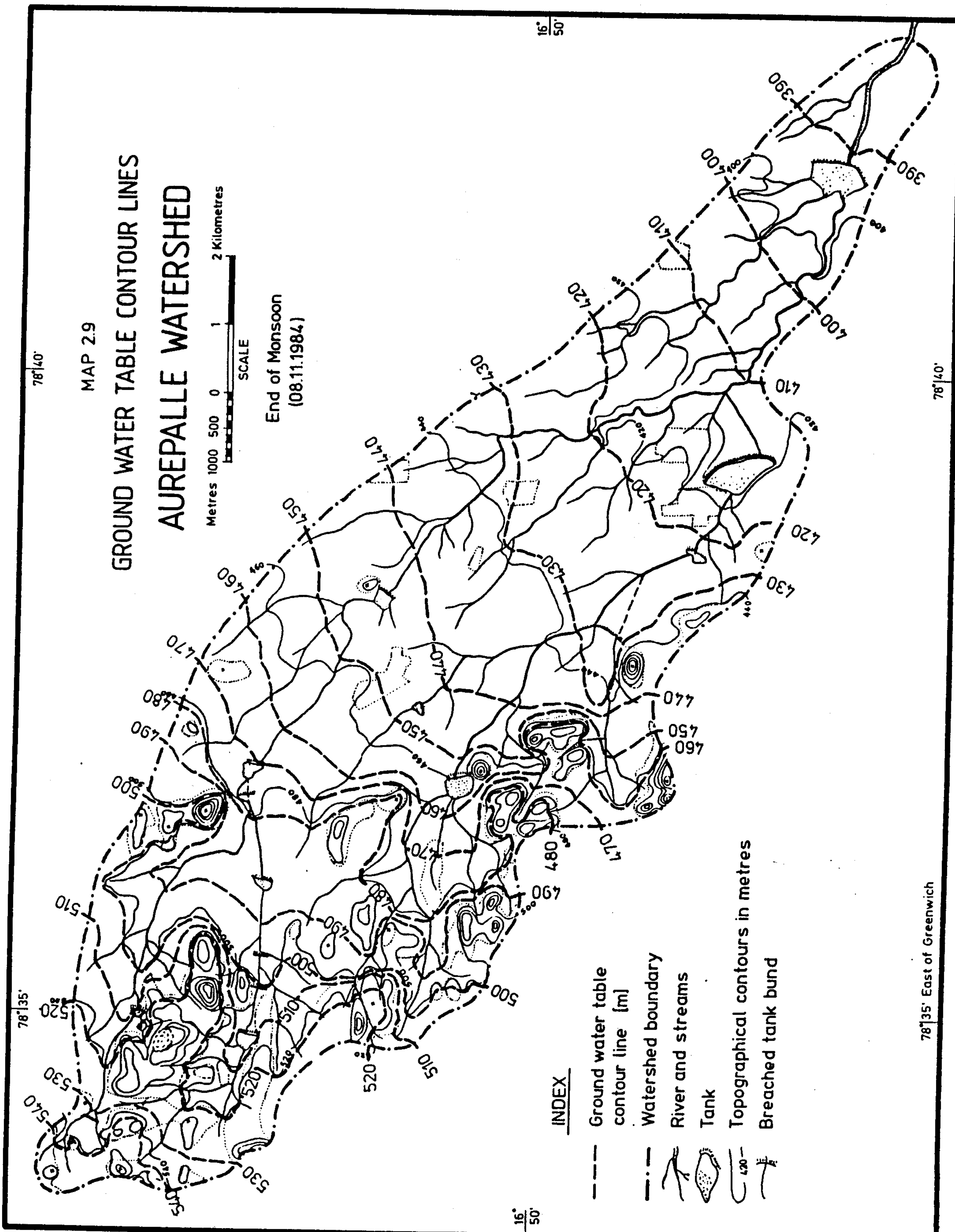
According to the results of a household census (Personal communication; Dangelmaier, 1984) the percentage of paddy area of the total geographical area was estimated to be 4 %. With this figure a net ground water draft of 22.2 mm for 1984 and 25.5 mm for 1985 was determined. Addition of storage change and net ground water draft yielded a net ground water recharge of 68.5 mm in 1984 and 80.5 mm in 1985.


MAP 2.5
GROUND WATER TABLE FLUCTUATION
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
June to November 1984
78°|35'
78°|40'
78°|35' East of Greenwich
78°|40'
16° 50'
16° 50'
INDEX
—2— Contour of water table fluctuation (m)
Watershed boundary
River and streams
Tank
420 — Topographical contour in metres
Breached tank bund


MAP 2.6
GROUND WATER TABLE FLUCTUATION
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
September to October 1985
(07.09.85 to 22.10.85)
INDEX
— 2 — Contour of water table fluctuation [m]
Watershed boundary
River and streams
Tank
Topographical contour in metres
Breached tank bund
78°|35'
78°|40'
16° 50'
78°|35' East of Greenwich
78°|40'
16° 50'


MAP 2.7
ISOLINES OF CHANGE OF GROUND WATER STORAGE
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
Monsoon 1984
Specific yield = 2.5 %
INDEX
Isoline of change of ground water storage (mm) (Water table fluctuation method)
31 Natural ground water recharge (mm) (Tritium injection method)
Watershed boundary
River and streams
Tank
420 Topographical contour in metres
Breached tank bund
78° 35' East of Greenwich
78° 40'
16° 50'


MAP 2.8
GROUND WATER TABLE CONTOUR LINES
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
Beginning of Monsoon
(09.07.1984)
INDEX
Ground water table contour line [m]
Watershed boundary
River and streams
Tank
Topographical contours in metres
Breached tank bund
78°35'
78°40'
16° 50'
78°35' East of Greenwich
530
520
510
500
490
480
470
460
450
440
430
420
410
400
390


MAP 2.9
GROUND WATER TABLE CONTOUR LINES
AUREPALLE WATERSHED
Metres 1000 500 0 1 2 Kilometres
SCALE
End of Monsoon
(08.11.1984)
INDEX
Ground water table contour line [m]
Watershed boundary
River and streams
Tank
Topographical contours in metres
Breached tank bund
78°40'
78°35'
78°35' East of Greenwich
16°50'
390
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540

The above calculations of the net ground water draft for the entire watershed are fairly rough, but better data was available for subwatershed 3 (Table 2.4). Table 2.5 summarizes the results of the water table monitoring.

Table 2.4: Ground Water Recharge Determination for Subwatershed 3

| | Unit | 1984 | 1985 |
|---|---|---|---|
| Av. rise of water table | [m] | 3.52 | 1.77 |
| Specific yield | [%] | 2.50 | 2.50 |
| GW-storage change | [mm] | 88.00 | 44.00 |
| Period of draft | [d] | 101.00 | 116.00 |
| Paddy area | [km²] | 0.57 | 0.57 |
| ET paddy | [mm/d] | 5.00 | 5.00 |
| Net GW-draft | [mm/d] | 5.50 | 5.50 |
| Watershed area | [km²] | 6.18 | 6.18 |
| Net GW-draft from basin | [mm] | 51.00 | 59.00 |
| Net ground water recharge | [mm] | 139.00 | 103.00 |

Table 2.5: Summary of Results of Water Table Monitoring

| | Unit | Aurepalle Watershed 1984 | Aurepalle Watershed 1985 | Subwatershed 3 1984 | Subwatershed 3 1985 |
|---|---|---|---|---|---|
| Precipitation | [mm] | 490.00 | 640.00 | 545.00 | 540.00 |
| | [Mio m³] | 34.30 | 44.80 | 3.37 | 3.34 |
| Net GW-recharge | [mm] | 68.50 | 80.50 | 139.2 | 103.1 |
| | [Mio m³] | 4.80 | 5.64 | 0.86 | 0.64 |
| Infiltration Factor | [%] | 14.00 | 12.60 | 25.50 | 19.10 |

A levelling survey was conducted in 1985 with the help of the Engineering Unit of the RMP, ICRISAT in order to determine the reduced levels of benchmarks at the observation wells. From the reduced levels the actual elevation of the water table was calculated and maps of the contours of the pre- and post-monsoon water table were prepared. Maps 2.8 and 2.9 provide an illustration of the direction of the ground water flow.

### 2.4.4 Results of Monitoring of Tank Water Balance

During the two years with annual rainfall of slightly below average (1984, 545 mm; 1985, 540 mm) the total inflow to the Aurepalle tank amounted to roughly 4 % of the annual watershed rainfall. During 1986 with an annual rainfall of 480 mm no inflow at all was observed (Table 2.6). The absence of inflow is not solely explained by the low annual rainfall, but also by the rainfall distribution with lower maximum rainfall intensities of about 40 mm/d (consult Figure 2.3). Another interesting fact is that the tank did not overflow during the study period. Also visible seepage was not observed, probably because the tank was never filled to full capacity. Since no water was released from the tank for irrigation and no overflow occurred, about 19 % of the collected water evaporated and 81 % were recharged into the aquifer.

Table 2.6: Summary of Results of Tank Monitoring at Aurepalle

| | Unit | Subwatershed 3 1984 | 1985 | 1986 |
|---|---|---|---|---|
| Precipitation | [mm] | 545.00 | 540.00 | 480.00 |
| | [1000 $m^3$] | 3368.10 | 3337.20 | 2966.40 |
| Total inflow | [mm] | 21.66 | 20.03 | 0.00 |
| | [1000 $m^3$] | 133.88 | 123.79 | 0.00 |
| | [%] | 3.98 * | 3.71 * | 0.00 * |
| Evaporation | [1000 $m^3$] | 30.43 | 18.15 | 0.00 |
| | [%] | 22.73 ** | 14.66 ** | 0.00 ** |
| Seepage + perc. | [1000 $m^3$] | 103.44 | 105.64 | 0.00 |
| | [%] | 77.27 ** | 85.34 ** | 0.00 ** |
| Visible seepage | [1000 $m^3$] | 0.00 | 0.00 | 0.00 |
| Irrig. outflow | [1000 $m^3$] | 0.00 | 0.00 | 0.00 |
| GW-inflow | [1000 $m^3$] | 0.00 | 0.00 | 0.00 |
| Tank overflow | [1000 $m^3$] | 0.00 | 0.00 | 0.00 |

* Percent of precipitation
** Percent of inflow

Table 2.7: Comparison of weekly Rainfall and Inflow to Aurepalle Tank

| Week | Year | Rainfall [mm] | Rainfall [m³] | Inflow [mm] | Inflow [m³] | Inflow [%] |
|---|---|---|---|---|---|---|
| 40 | 1985 | 149.9 | 926382 | 7.3 | 44820 | 4.84 |
| 41 | 1984 | 139.6 | 862728 | 12.2 | 75138 | 8.71 |
| 38 | 1985 | 119.9 | 740982 | 9.5 | 58829 | 7.94 |
| 29 | 1984 | 115.6 | 714408 | 7.2 | 44508 | 6.23 |
| 39 | 1986 | 60.5 | 373890 | 0.0 | 0 | 0.00 |
| 31 | 1984 | 59.6 | 368328 | 0.5 | 2926 | 0.01 |
| 44 | 1986 | 57.7 | 356586 | 0.0 | 0 | 0.00 |
| 32 | 1986 | 56.6 | 349788 | 0.0 | 0 | 0.00 |
| 38 | 1984 | 50.9 | 314562 | 0.0 | 16 | 0.00 |
| 37 | 1984 | 40.5 | 250290 | 0.1 | 498 | 0.00 |

More than 95 % of the inflow to the Aurepalle tank was generated during four rainy spells in three monsoon seasons. Precipitation of more than 60 mm/week needs to fall in subwatershed 3 before inflow occurs (Table 2.7). This is also illustrated in Figure 2.4.

It is not possible to present exact figures of total runoff for the entire Aurepalle watershed, since not all the tanks could be monitored. Therefore inflow percentages from monitored tanks were substituted for unmonitored tanks in the corresponding subwatershed.

The total inflow to the tanks worked out to be 2.0 Mio $m^3$ equal to 5.8 % or 28.6 mm in 1984, and to 3.0 Mio $m^3$ equal to 6.7 % or 42.9 mm in 1985. For 1986 only a rough estimation can be given, because the Irven tank was not monitored consistently. Total runoff in this year adds up to 1.1 Mio $m^3$ equal to 2.8 % or 15.7 mm. Most of the inflow was generated in subwatershed 0 (Map 2.4).

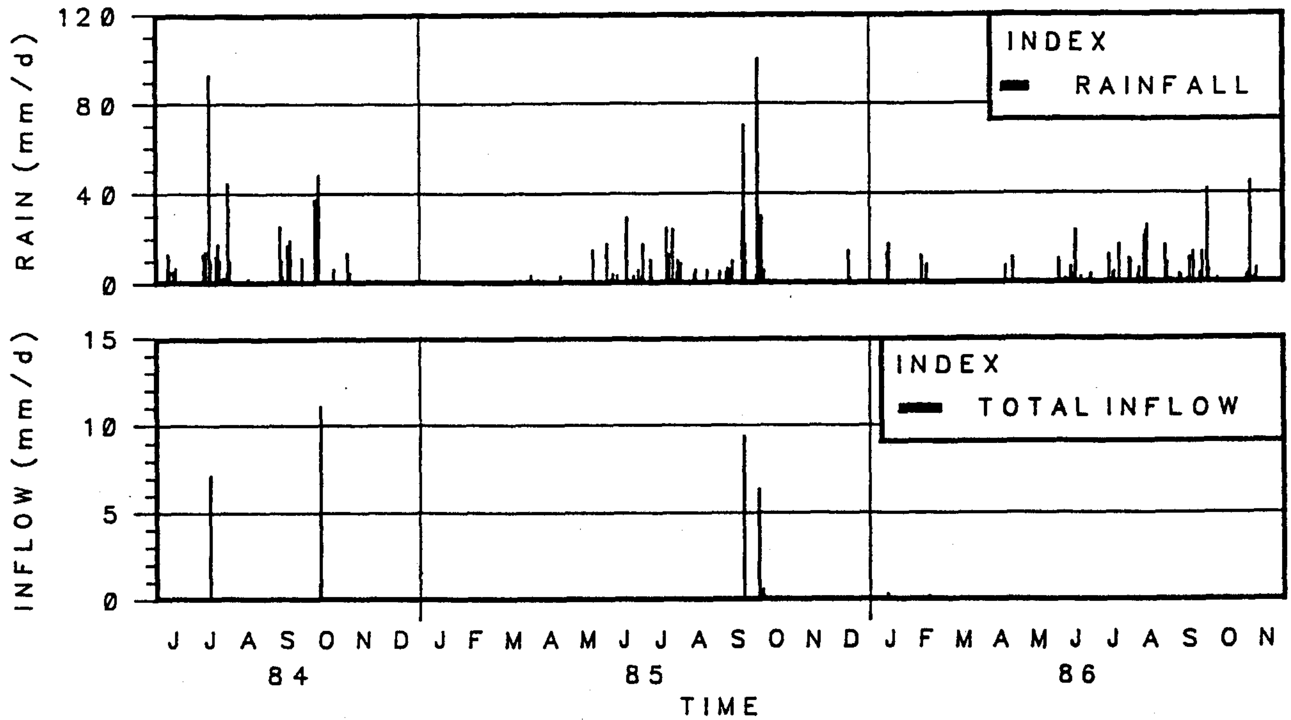



Figure 2.4: Rainfall and Inflow at the Aurepalle Tank

During the hydrological years 1984/85 and 1985/86 the level of weekly average evaporation at the Aurepalle tank remained fairly constant at a value between 4 and 6 mm/d. In both years the percolation plus seepage losses dropped after the first inflow from values of about 35 mm/d to values below 14 mm/d (Figure 2.5). The lower seepage plus percolation rates in 1984 may be due to the longer ponding period. It seems that the decline of these rates follows the typical negative exponential form of infiltration curves. After inflow the volume of the seepage plus percolation loss is over proportionally high for two reasons. Large areas are submerged and the rate of percolation in mm/d is increased, since water enters dry soil. Thus, in the weeks immediately after inflow, the major portion of seepage plus percolation loss occurs. These above observations indicate that too long ponding periods cause inefficiencies of percolation tanks, especially when the ponding period is extended into the summer season, when evaporation losses are high.

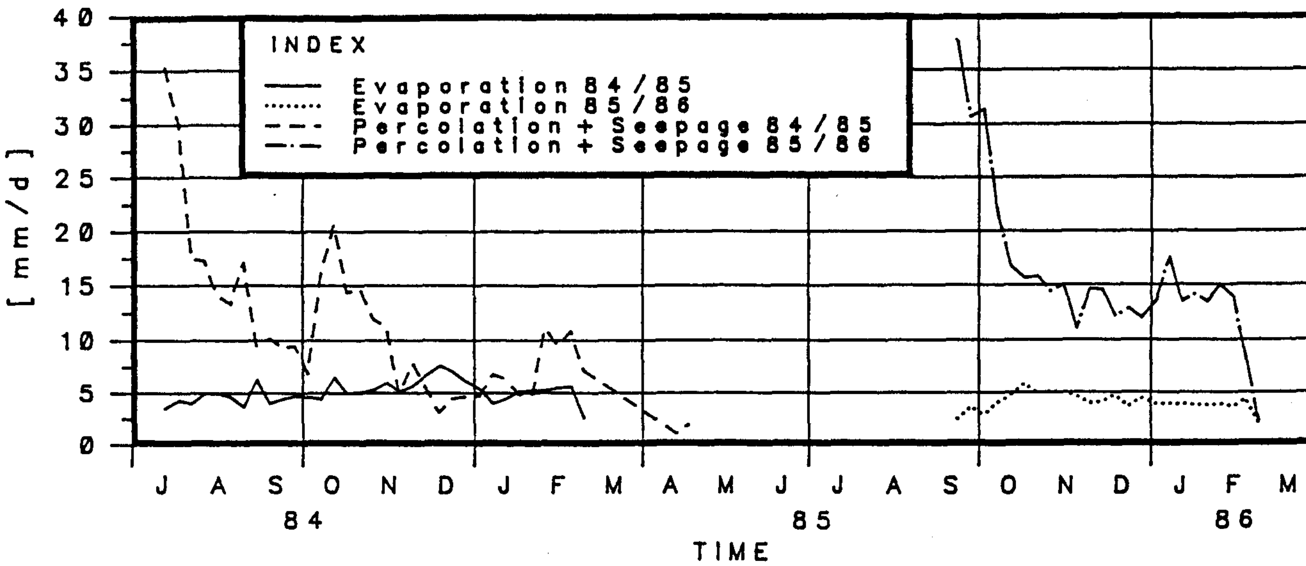



Figure 2.5: Evaporation and Percolation plus Seepage of the Aurepalle Tank

Sharma and Helweg [219] determined the permeability of the bed and bund of the Aurepalle tank. They found the permeability of the tank bed to be several orders of magnitude lower than that of the bund. The main loss from the tank is obviously seepage through the bund. After inflow a high water depth in the tank should be correlated with a high seepage loss. This could be another reason for the high initial loss.

Data on seepage plus percolation in the Kalkunta tank is only available for the weeks before and after the second major inflow in October 1984. The data indicate the same trend, but at a much lower level of 4.25 mm/d. The silted tank bed of the Kalkunta tank, where much finer material is deposited than in the Aurepalle tank, provides an explanation for the low values.

In the other study watershed two relatively new percolation tanks were monitored throughout the monsoons of 1985 and 1986. For these tanks the data collected indicated a seepage plus percolation rate of approximately 25 mm/d. A decline of this value due to siltation is likely. Tank monitoring at ICRISAT revealed that seepage plus percolation decreased from initial values of 90 mm/d down to 10 mm/d after a few years (Personal communication; Sachan, (ICRISAT), 1986).

### 2.4.5 Results of Well Inventory

The daily water application on paddy fields worked out to be 13.0, 18.6 and 21.5 mm/d in the monsoon, post-monsoon and summer season, respectively. Of these values 5.5 mm/d in the monsoon season, 6.0 mm/d in the post-monsoon and 9.0 mm/d in the summer season were lost by evapotranspiration, during conveyance and through seepage. The remaining portion of the water applied reaches the aquifer again by deep percolation. This flow is also called ground water return flow. It amounted to 7.5 mm/d equal to 57.7 %, 12.6 mm/d equal to 67.7 % and 12.5 mm/d equal to 58.1 % in the monsoon the post-monsoon and the summer season, respectively (Table 2.8). The lower value in the monsoon season can be explained by the fact that in addition to ground water, the water demand of the crops is met by rain and runoff.

Table 2.8: Results of Well Inventory in Subwatershed 3

| | Unit | Season Monsoon | Post-Monsoon | Summer |
|---|---|---|---|---|
| Total water pumped | [$m^3$/ha] | 14994.0 | 22525.0 | 20419.0 |
| Total pumping days | [d/season] | 115.0 | 120.0 | 95.0 |
| Daily water application | [mm/d] | 13.0 | 18.6 | 21.5 |
| Total paddy area | [ha] | 57.0 | 67.0 | 29.0 |
| Total GW-draft | [$m^3$] | 854658.0 | 1509175.0 | 592151.0 |
| Net GW-draft = ET·1.1 | [mm/d]<br>[$m^3$] | 5.5<br>361520.0 | 6.0<br>487464.0 | 9.0<br>248111.0 |
| GW-return flow | [mm/d]<br>[%] | 7.5<br>57.7 | 12.6<br>67.7 | 12.5<br>58.1 |

### 2.4.6 Results of Pumping Tests

Of the seven pump tests conducted, the results of the pump tests of wells No. 4 and No. 6 appeared to fall in a different range from the rest (Figure 2.6). Therefore, the two pumps were inspected. In one case a bump in the delivery pipe was found to be a possible reason for the discharge. In the other case consultation with the farmer showed that doubts existed over the HP-value of the pump. Consequently only five pump tests were included in the regression analysis. Equation 2.5 is valid for 5-HP pumps.

$$Q_{abs,gw} = 79.51 - 3.2091 \cdot H \qquad R^2 = 0.75 \qquad (2.5)$$

where:

$Q_{abs,gw}$ = discharge [$m^3$/h]
H = delivery head [m]
R = correlation coefficient

Equation 2.5 does not represent a standard delivery head-discharge curve. It is meant for estimations of discharges from an average well when information on average seasonal delivery heads is available.

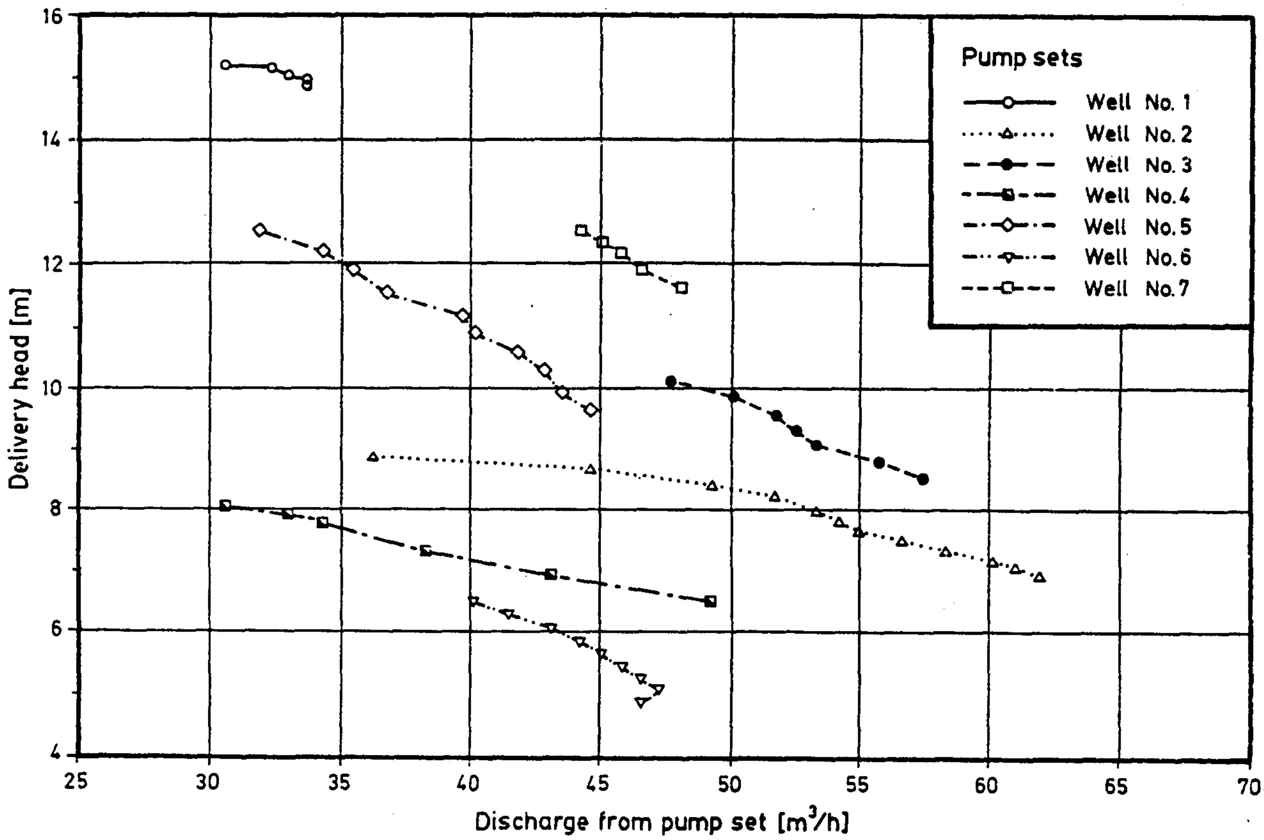



Figure 2.6: Delivery Head - Discharge Curves for 5-HP Pump Sets

## 2.5 Watershed Model

### 2.5.1 General

A computer simulation model was developed to extrapolate the measured results of the 30 month study period in combination with the more representative 11 year Aurepalle rainfall record. The modelling was begun after the literature review and field investigations of the agro-hydro-geological inventory had provided enough qualitative and quantitative information to allow sufficient understanding of the hydrology of the study area.

The Aurepalle subwatershed 3 (Map 2.4) was selected as a suitable area for calibration, since the largest and most reliable data base had been established there.

### 2.5.2 Type of Model

The type of model chosen was a discrete, physical, semi-distributed, continous watershed model. A time step of one day was considered a reasonable compromise between accuracy of prediction and running time of the programme. Furthermore, most of the data was available in daily units. An attempt was made to work as far as possible with parameters which have physical significance and can be measured in the field. The model is called semi-distributed, because it does not possess the complexity of a finite element model, but is distributed in different land use units and therefore not a lumped model. The attribute "continous" was assigned since the model simulates the water balance not only for a single rainfall-runoff event but continously for several years. It is a watershed model, because surface subsurface interactions are taken into account. Below the model is referred to as the "land use element watershed model". A flow chart of the programme is presented in Appendix S.

### 2.5.3 Model Concept

As a first step a model was designed to simulate the water balance of a small watershed consisting of a catchment area with the typical configuration of land use elements encountered in the study region. These elements or zones are rocky outcrops at the watershed boundaries, dryland areas, and paddy fields in the low lying region including a tank at the bottom of the watershed (Figure 2.7). A larger watershed could be modelled by combining several of these small watersheds.

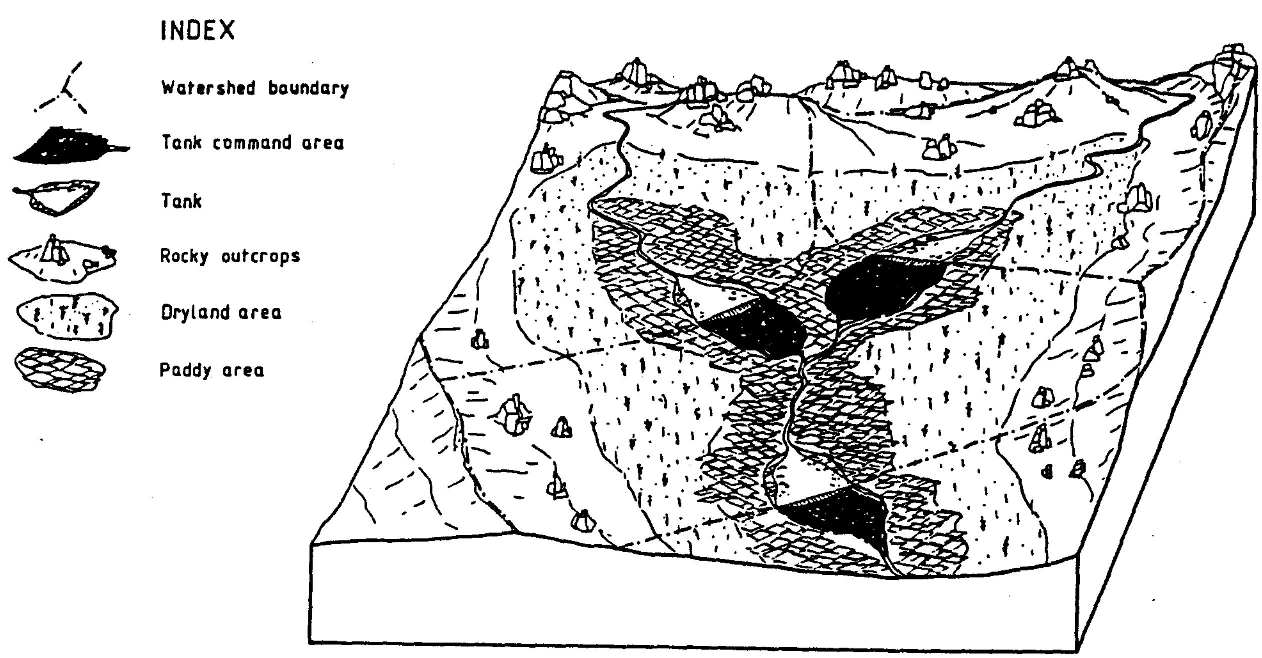



Figure 2.7: Land Use Units in a Typical Watershed (scheme)

The zones are entirely different in terms of their hydrological behaviour. The rocky outcrops generate relatively high runoff due to their low infiltration capacity and small depression storage. Their contribution to ground water recharge is also rather low. In contrast the dryland crop areas cover mostly sandy to loamy red soils, whose infiltration rate is high, resulting in low runoff. Paddy areas produce less runoff than both the other zones and in addition collect runoff generated in those zones. A major portion of the retained water is recharged. The water retention of paddy is highest when paddy fields are located along small streams, as is the case in parts of the Aurepalle watershed.

### 2.5.4 Model Structure

The presence of distinctive zones requires that each unit must be modelled separately and dictates the basic structure of the simulation model (Figure 2.8).

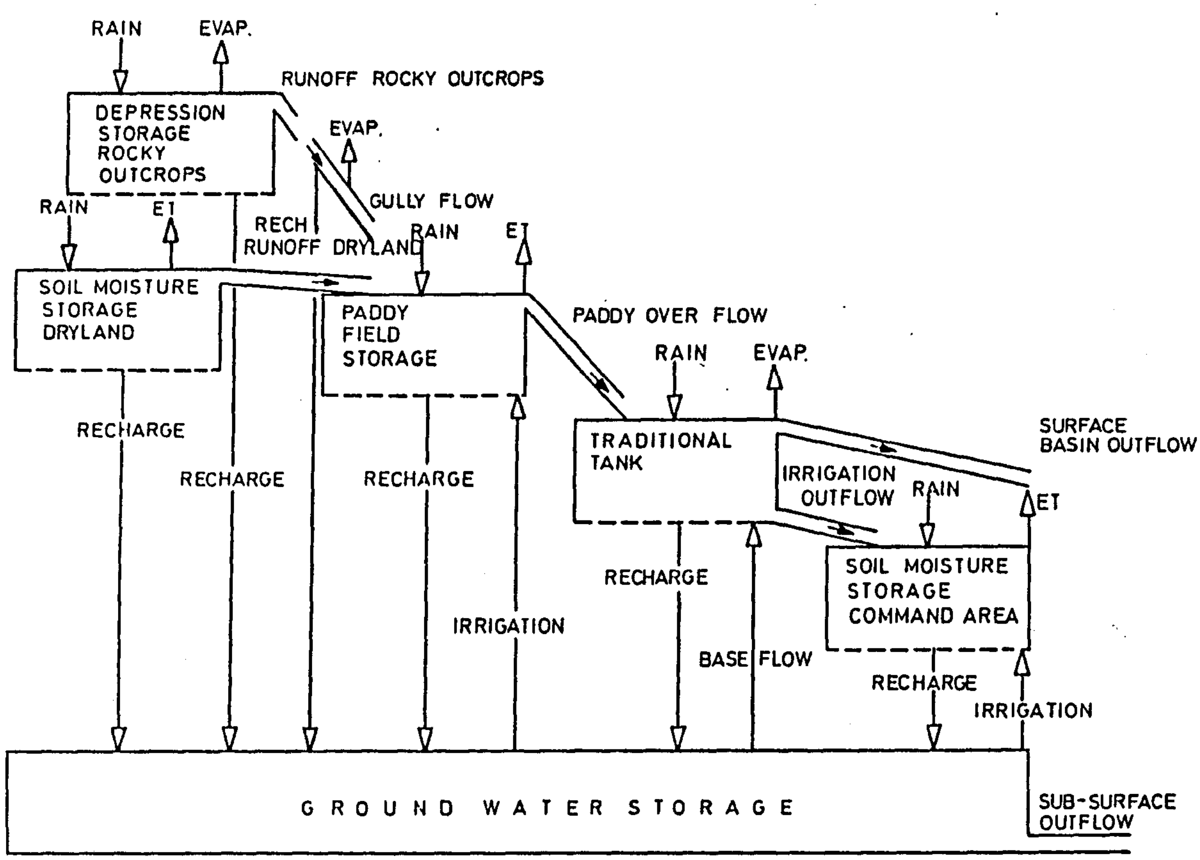



Figure 2.8: Model of the Water Flow in the Land Use Element Watershed Model

The model executes nine main subroutines:

1. Input data:
   Reading of general input data and daily rainfall.

2. Potential evapotranspiration:
   Computation of potential evapotranspiration.

3. Farmers decision making:
   Simulation of farmers decision making.

4. Rocky outcrop sub-model:
   Simulation of runoff and ground water recharge from rocky outcrops.

5. Dryland sub-model:
   Simulation of runoff, recharge and actual evapotranspiration in dryland areas.

6. Paddy sub-model:
   Simulation of runoff, recharge and actual evapotranspiration in paddy areas.

7. Tank sub-model:
   Simulation of tank inflow, storage, outflow, evaporation and seepage plus percolation.

8. Ground water sub-model:
   Simulation of ground water storage, ground water draft and baseflow.

9. Printing:
   Printing of results.

Since the subroutines used in this model are similar to the ones used in the model described in chapter 5, a detailed description of subroutines is not presented here (for details consult Appendix S).

### 2.5.5 Input Data

In the subroutine "input data" the parameters shown in table 2.9 are read for use in subsequent sub-models.

The water input to the model is daily rainfall and the climatic input is represented by average weekly pan class A evaporation. The pan evaporation is interpolated from monthly long term means. This input data combination was chosen, because daily rainfall and pan evaporation data are generally available in Southern India. For the potential evapotranspiration sub-model the above mentioned values of pan class A evaporation and a monthly changing pan coefficient $k_{pan}$ are required.

The rocky outcrop sub-model requires information on the extent of the area of the rocky zone, the depression storage and the infiltration characteristics expressed in a curve number according to the US Soil Conservation Service (SCS) curve number method [248].

The dryland model reqires data on the extent of the zone, its infiltration characteristics, the maximum soil moisture holding capacity of two soil layers, the average monthly percentage of light intercepted by the canopy of the crops grown, as well as monthly valves of the fraction of water available to the growing plant roots.

Crop coefficients, the average percolation rate, the maximum possible submergence depth, the area of paddy and the SCS curve number have to be supplied to the paddy model.

For the tank model the stage capacity and stage area curves are needed, as well as, the initial and minimum percolation plus seepage rate and also coefficients which relate the pan class A evaporation to lake evaporation.

The ground water model needs to be supplied with estimations of the maximum ground water storage, the specific yield and information on use of water by deep rooted vegetation as well as animal and human water consumption.

Table 2.9: Input Parameters Used in the Land Use Element Watershed Model

| Parameter | Value | Unit |
|---|---|---|
| Total watershed area (subwatershed 3) | 6.18 | [km²] |
| Rocky outcrops: | | |
| Area | 1.18 | [km²] |
| SCS curve number | 75.00 | |
| Depression storage | 30.00 | [mm] |
| Dryland area: | | |
| Area | changing | |
| SCS curve number | 60.00 | |
| Soil moisture storage upper layer | 35.00 | [mm] |
| Soil moisture storage lower layer | 75.00 | [mm] |
| Paddy area: | | |
| Area | changing | |
| SCS curve number | 75.00* | |
| Net maximum storage | 60.00 | [mm] |
| Maximum percolation rate | 21.00 | [mm/d] |
| Minimum percolation rate | 8.00 | [mm/d] |
| Tank: | | |
| Tank capacity | 177000.00 | [m³] |
| Initial percolation + seepage | 35.00 | [mm/d] |
| End value of percolation + seep. | 8.00 | [mm/d] |
| Recession factor of exp. equation | 0.0275 | |
| Ground water: | | |
| Maximum ground water storage | 650000.00 | [m³] |
| Specific yield | 0.0275 | |

*In the paddy model the SCS curve number is higher than in the dryland area, but in addition a surface storage of 60 mm is considered

### 2.5.6 Calibration of the Model

The field data collected represent the situation in the Aurepalle watershed for a sequence of three relatively dry years. Due to the dry conditions only four rainfall runoff events could be observed and used for calibration of the runoff sub-models. The data from a wet year would have improved the reliability of simulation of a wet year greatly. A better data base would also have been desirable for the development and calibration of the ground water recharge sub-models. Relatively good information was accumulated on evapotranspiration, seepage and percolation in tanks and paddy fields. For some factors only vague indications were available such as the estimation of the maximum ground water storage.

The calibration was executed by using the trial and error method. In the absence of long records of simulated and measured data a mathematical procedure to optimize parameters, such as the method of least squares of deviation, was disregarded. However a reasonable match of simulated and measured results was obtained with the parameters given in Table 2.9. Table 2.10 shows simulated results compared to measured, calculated or estimated results for subwatershed 3.

Table 2.10: Results of the Simulation, Compared to Results of the Data Collection for 1984/85 (Subwatershed 3)

| Parameter | Unit | 1984 Data Coll. | 1984 Simulat. | 1985 Data Coll. | 1985 Simulat. |
|---|---|---|---|---|---|
| Rainfall: | mm | 545.0 | 553.9 | 540.0 | 611.7 |
| Dryland area: | | | | | |
| Annual runoff | % | < 10.0 | 4.5 | < 10.0 | 7.0 |
| Annual recharge | % | 7.0 | 9.7 | 7.0 | 8.1 |
| | mm | 38.2 | 53.6 | 37.8 | 49.8 |
| Paddy: | | | | | |
| Annual infiltration | % | 66.0 | 70.9 | 66.0 | 70.3 |
| Tank: | | | | | |
| Evaporation | % | 22.7 | 19.1 | 14.7 | 19.8 |
| | $m^3$ | 30430.0 | 25978.0 | 18150.0 | 49008.0 |
| Infiltration | % | 77.3 | 80.9 | 85.3 | 72.0 |
| | $m^3$ | 103440.0 | 109974.0 | 105640.0 | 177986.0 |
| Watershed: | | | | | |
| Annual runoff | % | 4.0 | 4.0 | 3.7 | 6.5 |
| | $m^3$ | 133880.0 | 135951.9 | 123790.0 | 247231.0 |
| | mm | 21.7 | 22.0 | 20.0 | 40.0 |
| Annual recharge | % | 25.5 | 19.6 | 19.1 | 18.5 |
| | $m^3$ | 858900.0 | 670423.6 | 637630.0 | 698716.0 |
| | mm | 139.2 | 108.5 | 103.1 | 113.1 |
| Watershed outflow | % | 0.0 | 0.0 | 0.0 | 0.5 |

Simulated evaporation, infiltration losses and tank inflow agree quite well with the measured values in 1984.

In 1985 evaporation, infiltration and inflow are simulated as being much higher. The measured results are based on a watershed rainfall of 540 mm/y. In the model, however, the rainfall at the Aurepalle station was used (611.7 mm/y). A model run with daily watershed rainfall, computed from the daily rainfall of the three stations in and near the subwatershed by adopting the Thiessen polygon method, yielded much lower tank inflow.

The annual ground water recharge on dryland areas was estimated with the Tritium injection method to 7 % of the rainfall for the entire Aurepalle watershed [184]. Analysis of the report shows that only a few data points exist in subwatershed 3. The figure of 7 % applies more to the south-east part of the watershed. In subwatershed 3 the soils appear to be more sandy, consequently it was assumed that the parameter of recharge from drylands lies in the order of 9 %.

In view of the above considerations the match of deducted and simulated annual results appears to be satisfactory.

In Figures 2.9 and 2.10 the dryland water balance with the parameters rainfall, runoff, ground water recharge and soil moisture is plotted over standard weeks for the years 1984 and 1985. In addition the hydrograph of a representative well of subwatershed 3 and the one of the Aurepalle tank are presented in the same plots. The plots document that the simulated runoff and ground water recharge coincide with measured increases of well and tank water tables. The plot also shows that ground water recharge is only generated when the soil moisture storage was previously recharged to field capacity.

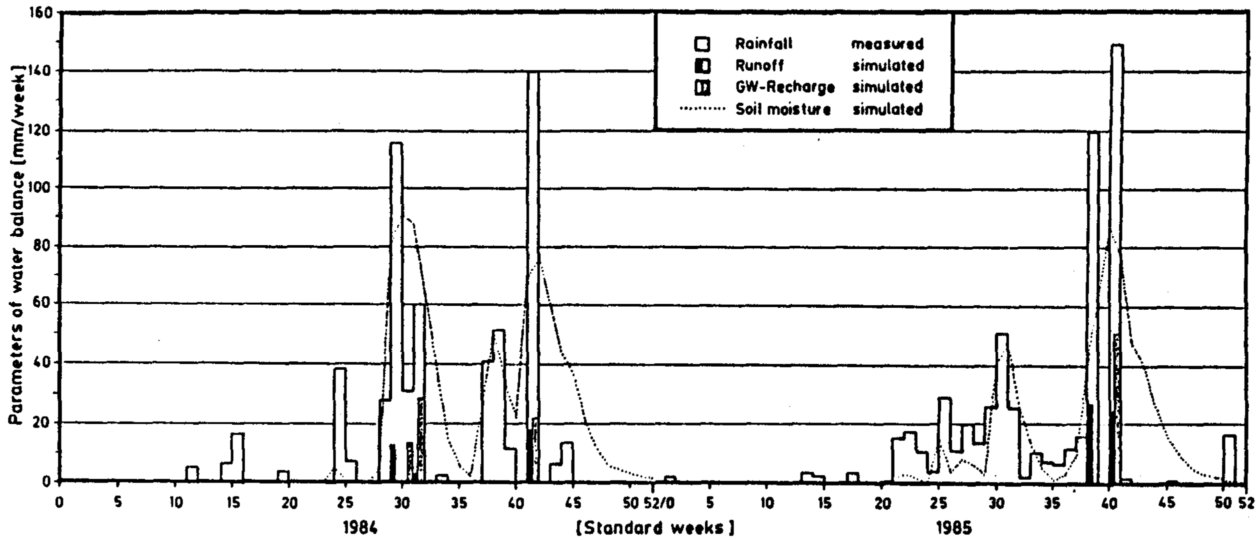



Fig. 2.9: Simulated Dryland Water Balance for Aurepalle 1984 and 1985

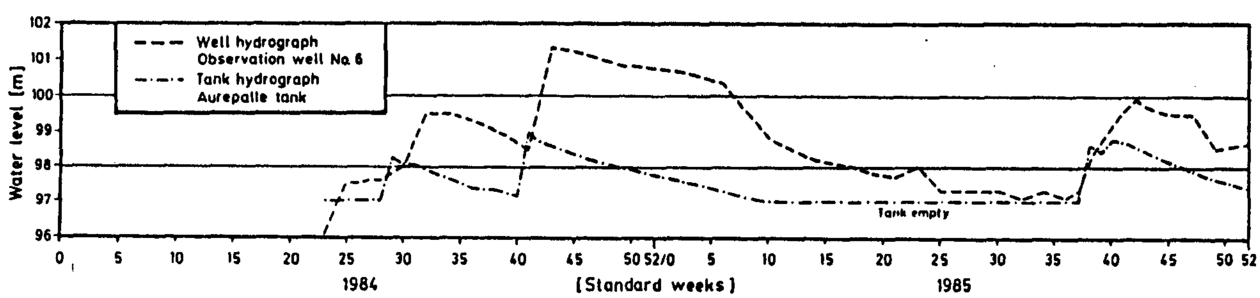



Fig. 2.10: Hydrograph of Aurepalle Tank (simulated) and Hydrograph of Observation Well No. 6 (measured)

### 2.5.7 Results of Modelling

After calibration, the model was run using the 11 years Aurepalle rainfall record including wet and dry years.

To study the effect of the infiltration characteristics on runoff and dryland recharge, a model run was executed with a SCS curve number of 63 for the dryland areas. This curve number applies to row crops and soils with good to very good infiltration potentials as is the case in Aurepalle subwatershed 3. Another model run was carried out with a curve number of 75 representing soils with good to medium infiltration. Most sandy loams fall into this category.

The results of these runs are depicted in Figures 2.11 and 2.12. For the two different soils, ground water recharge and runoff from dryland areas were plotted over the annual rainfall. The plot of the simulated ground water recharge indicates a linear relationship between annual recharge and annual precipitation. For coarse textured soils (CN 63) the recharge starts after approximately 440 mm of rain have fallen. Rainfall of 750 mm results in a ground water recharge of 115 mm. In case of the finer textured soil (CN 75), on average about 460 mm of rainfall must fall for recharge to occur; 750 mm of rain lead to only half of the recharge of the coarse soil type.

Figure 2.11 shows a quadratic relationship between runoff and annual rainfall. The distance between the curve for the coarser and the one for the finer textured soil illustrates the effect of infiltration characteristics of soils on runoff from drylands.

The simulation results show clearly that low runoff and relatively high recharge in the Aurepalle watershed can be partially attributed to the sandy soils.

For subwatershed 3 annual results of the simulation of hydrological parameters are given in Appendix T. The results document the different response of dryland-, paddy- and tank-recharge to varying rainfall patterns.

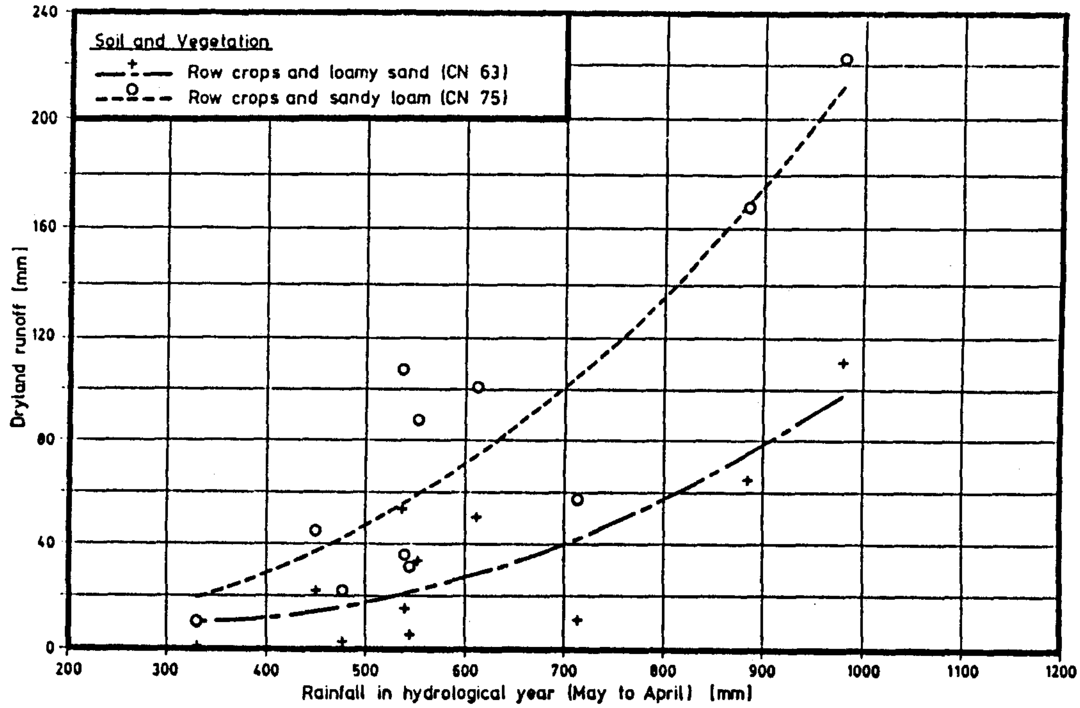



Figure 2.11: Simulated Dryland Runoff for Aurepalle Subwatershed 3, (1976/77 to 1986/87)

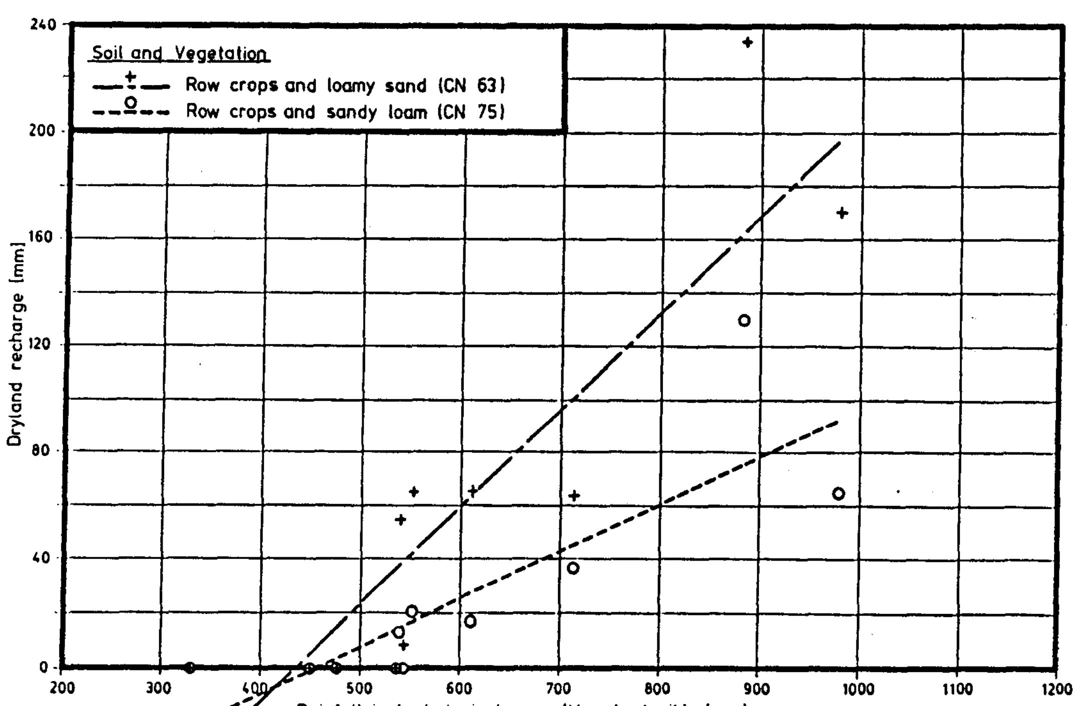



Figure 2.12 : Simulated Dryland Ground Water Recharge for Aurepalle Subwatershed 3, (1976/77 to 1986/87)

Recharge on dryland areas occurs generally late in the monsoon season because after the dry season the soil moisture has to be filled to field capacity first. Depending on the rainfall pattern dryland or natural recharge values fluctuate greatly. The coefficient of the annual variation of natural recharge worked out to be 91 %. Recharge can be negligible when rainfall is average but uniformly distributed . Dryland recharge is likely to be generated when large quantities of rain fall in short periods of time.

Due to irrigation the soil moisture in paddy fields is always near to field capacity and about two-thirds of the rainfall are converted into recharge at almost any time of the year. Therefore, for paddy fields the coefficient of the annual variation of ground water recharge was found to be only 58 %.

Recharge from tanks of course only starts when runoff has been collected in tanks and depends on the length of the ponding period. During a year with excessive rains well distributed throughout the monsoon, high tank recharge can be expected.

The values of annual rainfall (hydrological year), of simulated annual watershed runoff and of simulated annual net ground water recharge were arranged in ascending order in Figure 2.13. An additional high rainfall year was added to the 11 simulated years, in order to raise the average rainfall closer to the level of the long term mean of the annual precipitation in the study region.

Whereas the rainfall shows a variation of 33 %, the variation of watershed runoff amounts to 133 %. Only three wet years generate approximately three-quarters of the entire runoff. In nine out of twelve years runoff was found to be below the average value of 50.8 mm (Figure 2.13).

The net ground water recharge is less variable than the runoff. The coefficient of variation works out to 59 %. In wet years the gross recharge is reduced due to baseflow. Only the net recharge is availabe for irrigation. This leads to seven years with recharge slightly to moderately above the mean of 86 mm and five years with recharge markedly below.

The lower fluctuations of ground water recharge explain the trend away from surface water towards the use of ground water which seems to be a much more dependable source for irrigation.

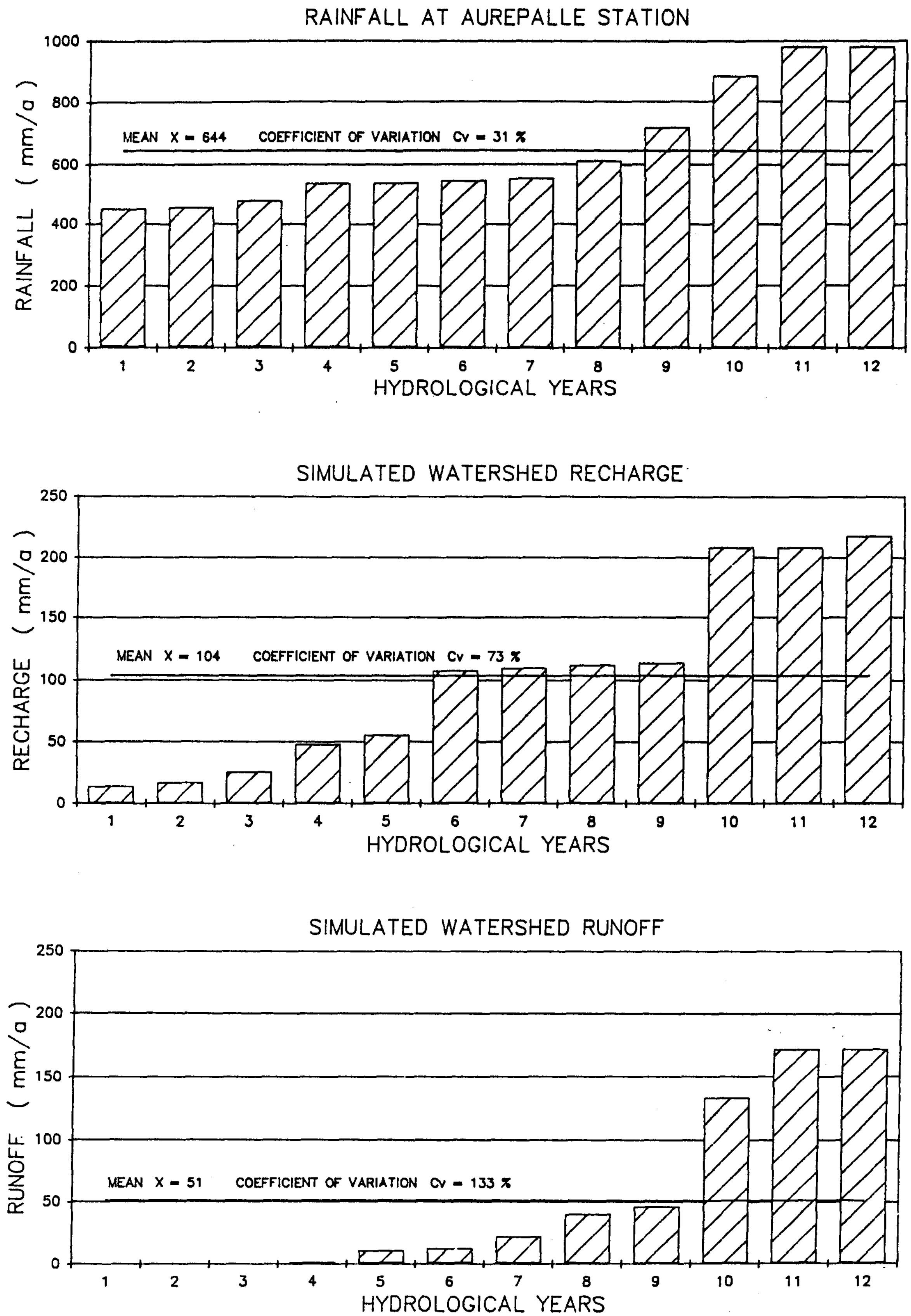



Figure 2.13: Variability of Rainfall, Simulated Recharge and Runoff in Aurepalle Watershed, Hydrological Years 1976/77 to 1987/88

## 2.6 Summary and Conclusions

The agro-hydrogeological inventory, as well as, the modelling provided quite a number of results describing the hydrology of watersheds similar to the ones in the study region. The important observations are summarized briefly below.

Of a simulated mean annual precipitation of 640 mm, on average 51 mm or 8 % are collected as inflow in tanks and only 2 % of the precipitation leave subwatershed 3 over the surplus weir. The ground water recharge, as determined by the ground water level fluctuation approach, amounts to about 86 mm; equal to an infiltration factor of 13 %. With the Tritium injection method a natural ground water recharge of 6 % was measured [184]. In the study period the ground water abstraction exceeded the ground water recharge. Only major rainfall events of the order of more than 60 mm/week lead to runoff and a rise of ground water levels.

Runoff from dryland crop areas with sandy to sandy-loamy soils ranges between 0.1 and 9.3 % of the rainfall and ground water recharge between 0.0 and 192 mm/a.

In the tanks of the study area between 50 % to 78 % of the inflow infiltrate; 20 % to 48 % are lost by evaporation. The daily seepage plus percolation rates decrease after the first inflow from 15 to 40 mm/d down to 5 to 10 mm/d at the end of the monsoon.

As per the well questionnaire the daily water application for paddy in the rainy, post-rainy and summer season are 13.0 mm/d, 18.6 mm/d and 21.5 mm/d, respectively. Ground water return flow in paddy areas worked out to about 7.5 mm/d in the rainy season and 12.6 mm/d and 12.5 mm/d in the post-monsoon and summer season, respectively.

The most surprising result proved to be the low inflow, of only 8 %, into tanks in subwatershed 3. In the above mentioned pilot study by Engelhardt [57] a value of 20 % was estimated. He obtained this figure by analysing data from the hydrological year 1984/1985 where rainfall was about 50 % above the long term annual mean.

The low runoff in subwatershed 3 can be partially attributed to the red sandy-loamy soils encountered in the watershed. Another reason seems to be the high percentage (10 %) of paddy area. This is a much higher percentage than in the other parts of the Aurepalle watershed. Runoff from levelled terraces such as paddy terraces is usually very low, because farmers store rain water within the field bunds [173].

In the lower lying areas of the watershed, where huge areas are uncultivated and where only 4 % of the geographical area are under paddy cultivation, higher runoff was observed.

Based on the well questionnaire the ground water return flow due to irrigation was determined to be 58 % of the water applied in the monsoon season (Table 2.8). Therefore ground water recharge due to rainfall and runoff can be assumed to be of the same order of magnitude. However the rainfall infiltration factor of about 6 % for dryland areas, as determined with the Tritium injection method [184], proves to be an order of magnitude lower than that of paddy.

These figures illustrate the hydrologically different behaviour of dryland and wetland areas. An alteration of the land use by reducing the paddy area would increase runoff and reduce ground water recharge. The water harvesting efficiency of a watershed would decrease unless additional harvesting structures are introduced.

The infiltration factor of 13 % measured with the water level fluctuation method appears to be a plausible result, since the natural recharge on drylands plus the sum of recharge from paddy fields, streams and tanks are included in this figure.

Not only the meagre inflow to tanks but also the high percentage of ground water return flow indicate that paddy fields play an important role in the hydrology of a watershed. Recharge from paddy fields proves to be a major and dependable portion of the total ground water recharge. The infiltration from paddy fields is high enough to consider use of paddy fields for artificial recharge.

# 3 HYDROLOGICAL ASPECTS OF PADDY IRRIGATION

## 3.1 General

In the previous chapter the high ground water recharge and low runoff in the study watershed was partially attributed to the water retaining effect of rice terraces. The data suggestes that the impact of rice terraces on the overall water balance of a watershed is not negligible. In order to entirely understand the hydrology of a typical watershed in south India it is necessary to quantify the water conserving effect of paddy fields. Since the information obtained up to this point was mostly only derived from water budget computations at the watershed level, more detailed studies were initiated.

The collection of data commenced in early 1986 and was continued up to November 1986. The work encompassed a questionnaire to obtain a general idea on water harvesting and irrigation practices adopted by the farmers and measurements to quantify the water balance of paddy fields. The methods employed and the results obtained are presented in detail below.

## 3.2 Questionnaire on Irrigation Practices

### 3.2.1 General

The rain water harvesting questionnaire was designed and conducted with the aim to obtain primary information on:

- The irrigation and water harvesting practices adopted by the farmers.

- The infiltration characteristics in paddy fields.

- The feasibility of alternatives in the water management of wells.

- The costs of establishment and maintenance of rice terraces

and the order of magnitude of:

- Yields and net returns per hectare and season for the important crops.

During a field visit to Aurepalle in December 1985 a total of 30 randomly selected farmers were interviewed. The entire catalogue of questions asked is given in Appendix E.

### 3.2.2 Results of Questionnaire

According to the information provided by the farmers, precipitation is harvested in paddy fields by 100 % of the respondents through closure of outlets and repairing or levelling of field bunds. About 73 % of the farmers harvest runoff collected from more elevated areas but only 10 % divert water from gullies to their fields. In the monsoon 1985 none of the respondents could retain all the rain and runoff. 26.7 % could not retain runoff at all, because diversion was not possible, the bunds obstructed in-flow, the fields were located on elevated areas or because catchment

The practice of storing rain water and runoff in fields cultivated with irrigated dryland crops is not common. Most of the respondents fear a detrimental effect of excess or stagnating water on crop yields. However, for paddy varieties planted in the study area the average maximum permissible depth of submergence, where yields are not influenced, worked out to be about 90 mm (Table 3.1). This is the maximum level up to which farmers retain rain and runoff in there fields. With this harvesting practice, the farmers create a storage of about 60 mm in the terraces. Taking into account the infiltration during a rain storm, it can be assumed that rainfall with intensities lower than 80 mm/d does not generate runoff from rice terraces unless there is strong rainfall on previous days. On average the harvested water infiltrates within one to two days.

The cumulative infiltration of rainfall in paddy fields can be estimated for the monsoon season (June to October) with the following model:

$$Q_{inf,r} = \sum_{n=0}^{n=153} (P - ET) \quad \text{for } P <= 80 \text{ mm/d and } P >= ET \qquad (3.1)$$

where:

| | | |
|---|---|---|
| $Q_{inf,r}$ | = Cumulative rainfall infiltration in monsoon season | [mm/seas] |
| P | = Precipitation < = 80 mm/d | [mm/d] |
| ET | = Evapotranspiration of rice crop | [mm/d] |
| n | = Number of days | [d] |

For Aurepalle conditions the rainfall infiltration for a dry and a wet year worked out to be 313.1 and 477.9 mm, respectively. In both cases the infiltration is close to 60 % of the monsoon rainfall. Where overland flow or runoff is collected in the paddy fields much higher values can be expected.

The quantitative information regarding infiltration and harvesting practices is depicted in Table 3.1.

Table 3.1: Results of Water Harvesting Questionnaire

| | early monsoon | | | monsoon | | |
|---|---|---|---|---|---|---|
| | Av. [mm] | n | $C_v$ [%] | Av. [mm] | n | $C_v$ [%] |
| Maximum permissible depth of submergence during water harvest. | 88.4 | 30 | 23 | 88.4 | 30 | 23 |
| | **early monsoon** | | | **monsoon** | | |
| | [d] | n | [%] | [d] | n | [%] |
| Average period of infiltration | 1.2 | 25 | 34 | 1.6 | 29 | 32 |
| Runoff harvested | 1.4 | 26 | 63 | 3.3 | 29 | 44 |
| Pump not operated due to rainfall | 2.2 | 26 | 52 | 8.7 | 29 | 111 |
| Reduced pumping due to rainfall | 4.5 | 26 | 55 | 11.7 | 29 | 62 |

n = number of respondents

Questions concerning different alternatives of water management were answered as follows:

Only 6.7 % of the farmers believed that it was advisable to increase the height of field bunds higher than the normal measure of about 10 cm. 46.7 % agreed that water retained in uncultivated terraces could be used for irrigation and one-third believed that water could be stored in unused terraces to recharge the well.

## 3.3 Water Balance Studies in Paddy Fields

### 3.3.1 General

The well questionnaire and the water harvesting questionnaire provided a semi-quantitative idea of the role of paddy not only as a water consuming, but also a water retaining and conserving element in a watershed. However, it was felt that this information was not sufficient to develop a model of runoff and infiltration in paddy fields which could be included in the digital simulation model planned. Therefore the following experiments were initiated:

- Water balance experiments

- Drum culture experiments

- Ponding tests

- Infiltrometer tests

- Soil sampling

### 3.3.2 Water Balance of Paddy Fields

Before going into details it is necessary to explain several terms in the water balance of paddy fields. The water balance differs depending on the various ways a paddy based irrigation system is operated. There are four general ways:

(1) Only rainfed.

(2) Rainfed and irrigated through tanks, farm ponds or diversion channels (rainfed and irrigated with surface water).

(3) Rainfed and irrigated with ground water.

(4) Rainfed and irrigated with ground and surface water.

The water balance of case (4) is illustrated in Figure 3.1

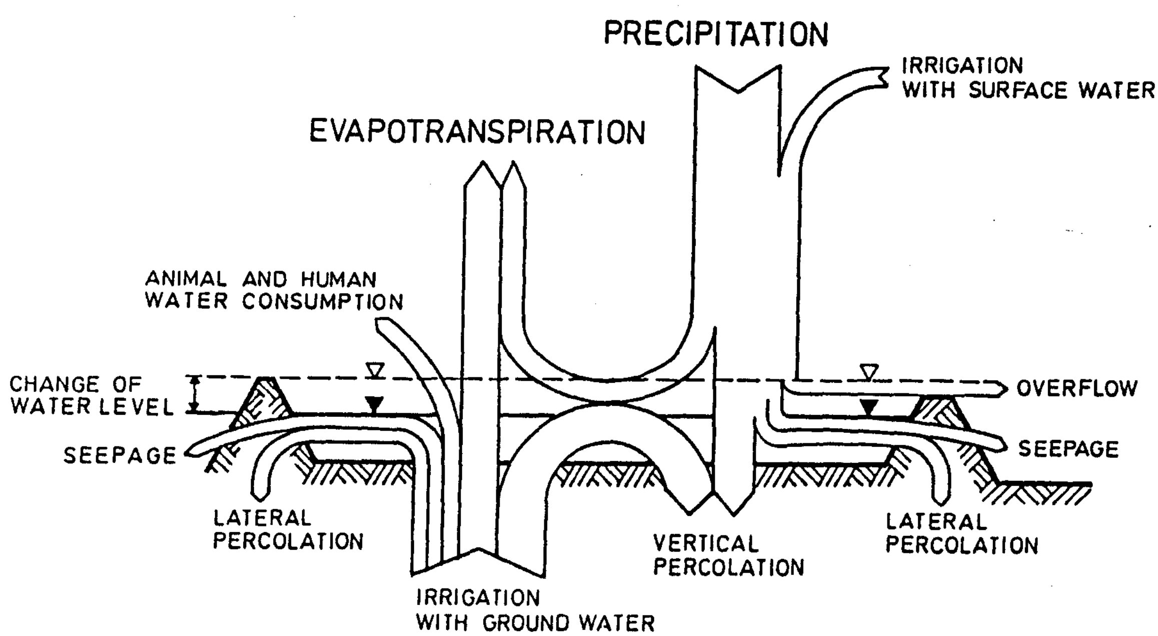



Figure 3.1: Water Balance of a Paddy Field (qualitatively)

For the "only rainfed" case (1) the water balance can be written as:

$$P = ET_r + Q_{perc,r} + Q_{seep,r} + Q_{out} + Q_{cons} + \Delta Q \qquad (3.2)$$

where:

| | | |
|---|---|---|
| $P$ | = Precipitation | [$m^3/d$] |
| $ET_r$ | = Evapotranspiration | [$m^3/d$] |
| $Q_{perc,r}$ | = Percolation | [$m^3/d$] |
| $Q_{seep,r}$ | = Seepage | [$m^3/d$] |
| $Q_{out}$ | = Overflow or runoff from plot | [$m^3/d$] |
| $Q_{cons}$ | = Animal and human water consumption | [$m^3/d$] |
| $\Delta Q$ | = Change of storage | [$m^3/d$] |

In this case the net ground water recharge is equal to the percolated water. Computation of net ground water recharge is similar for the irrigation option "rainfed plus surface water" (2). Only the term $Q_{in,r}$ = Inflow due to diversion of runoff has to be added on the left side. Thus Equation 3.2 becomes:

$$P + Q_{in,r} = ET_r + Q_{perc,r} + Q_{seep,r} + Q_{out} + Q_{cons} + \Delta Q \qquad (3.3)$$

In the other two cases (3 and 4) where ground water is also used for irrigation, net ground water recharge is not equal to the total percolation, since the fraction of the percolation that comes from the lifted ground water is only a return flow moving in an internal cycle (consult Figure 2.1). In order to distinguish the net percolation from the total percolation, the terms in the water balance equation were assigned indices describing the source of water (r: source is rainfall or runoff, gw: source is ground water):

$$P + Q_{in,r} + Q_{irr,gw} = Q_{perc,r} + Q_{perc,gw} + Q_{seep,r} + Q_{seep,gw} + ET_r + ET_{gw} + Q_{out} + Q_{cons} + \Delta Q \qquad (3.4)$$

where:

| | | |
|---|---|---|
| $Q_{irr,gw}$ | = Ground water supplied to fields | [$m^3/d$] |
| $Q_{perc,gw}$ | = Ground water return flow | [$m^3/d$] |
| $Q_{seep,gw}$ | = Fraction of ground water seeping through outer field bunds | [$m^3/d$] [$m^3/d$] |
| $ET_{gw}$ | = Fraction of ground water lost by evapotranspiration | [$m^3/d$] |

### 3.3.3 Methods Applied

The water balance studies were carried out at three sites in the Aurepalle watershed. These three sites were selected in order to cover different soil types, slopes, catchment properties and irrigation practices. Two different methods were applied to quantify the important terms of the water balance, the Drum Culture Method and the Water Balance Method.

#### 3.3.3.1 Water Balance Method

In the Gopal Reddy Plot, the Muralidar Rao Plot and the Irven Plot the components of the water balance were measured or estimated as follows:

- Rainfall (P) was measured with standard rain gauges. In the Muralidar Rao and Kalkunda Plots the gauges were located within 300 m of the plot, whereas at the Gopal Reddy Plot the gauge was situated directly in the plot.

- The amount of ground water drawn from the well and supplied to the fields ($Q_{irr,gw}$) was estimated by using the delivery head - discharge relationships given in chapter 2. In addition to this procedure the ground water application was measured at the Gopal Reddy Plot with a 6 inch Parshal flume. At the Muralidar Rao Plot a 90 degree V-notch weir was used.

- Actual evapotranspiration (ET) or consumptive use was quantified with the help of a small lysimeter, the ET-drums (explained below) and the U.S.D.A. pan class A installed in each plot.

- The change in surface storage ($\Delta Q$) was recorded with hook gauges.

- The order of magnitude of seepage ($Q_{seep}$) was estimated from the evapotranspiration of the wetted area adjacent to the outer field bunds.

- Animal and home consumption ($Q_{cons}$) was considered negligible.

- Inflow ($Q_{in,r}$) was not measured because the investment of time and material was considered to high. Instead inflow was simulated on the basis of rainfall and infiltration measurements and investigations on soils.

- Runoff can only be diverted during a few days in a season and overflow ($Q_{out}$) occurs even less frequently. Therefore, most of the time the water balance equation can be solved for the percolation parameter.

- During days with inflow and overflow, the overflow ($Q_{out}$) can be assessed with simulated inflow and average values of percolation.

It is possible to split evapotranspiration, seepage and percolation into the fractions $ET_{gw}$, $Q_{seep,gw}$, $Q_{perc,gw}$ and $ET_r$, $Q_{seep,r}$, $Q_{perc,r}$, respectively, if the source of irrigation, either precipitation and diverted runoff or ground water is recorded. On days where irrigation was provided from different sources, the fractions of the above parameters can be calculated by multiplication with the percentages of the amount of irrigation from each source.

### 3.3.3.2 Drum Culture Studies

The Drum Culture Method described by Dastane in [252] has been successfully used in the past for the measurement of evapotranspiration- and percolation losses in paddy fields. The technique employs two drums, one (A) with a bottom and (B) without a bottom, which are installed in the rice field as shown in Figure 3.2. The water level in the drums is maintained at a certain height. The difference in water levels on two consecutive days in drum A yields the values of consumptive use, while the difference in water levels in drum B gives values of the total water needs.

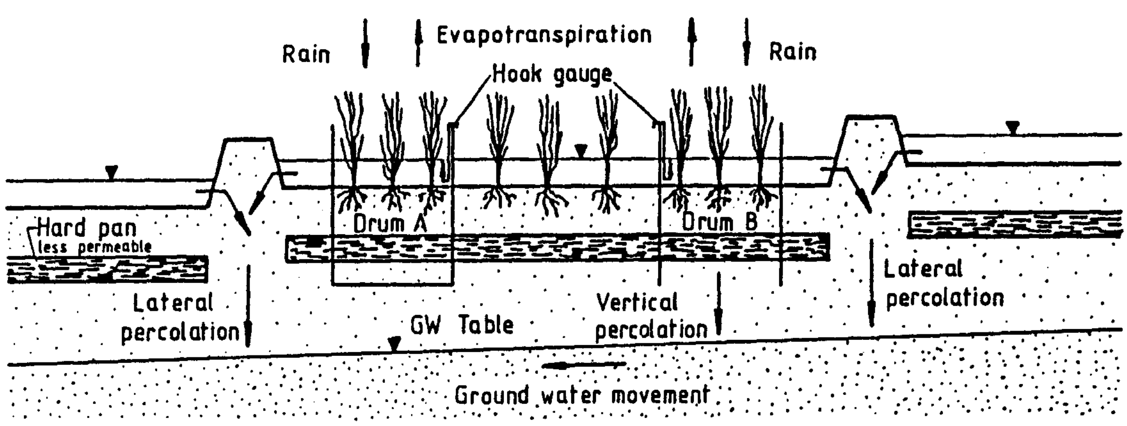



Figure 3.2: Drum Culture Method after Dastane in [252]

The percolation losses can be calculated from the difference between the readings in drum B and A . This method was used in the Gopal Reddy Plot, where red soils, black soils and intermediate soils are encountered. Two sets of drums were installed in both red and black soils and an additional one in the intermediate soil plot. In addition a rain gauge, a small lysimeter and a U.S.D.A. pan class A were placed in the plot, so that a pan coefficient for calculation of consumptive use could be worked out. The experimental set up of the Gopal Reddy Plot is presented in Figure 3.3.

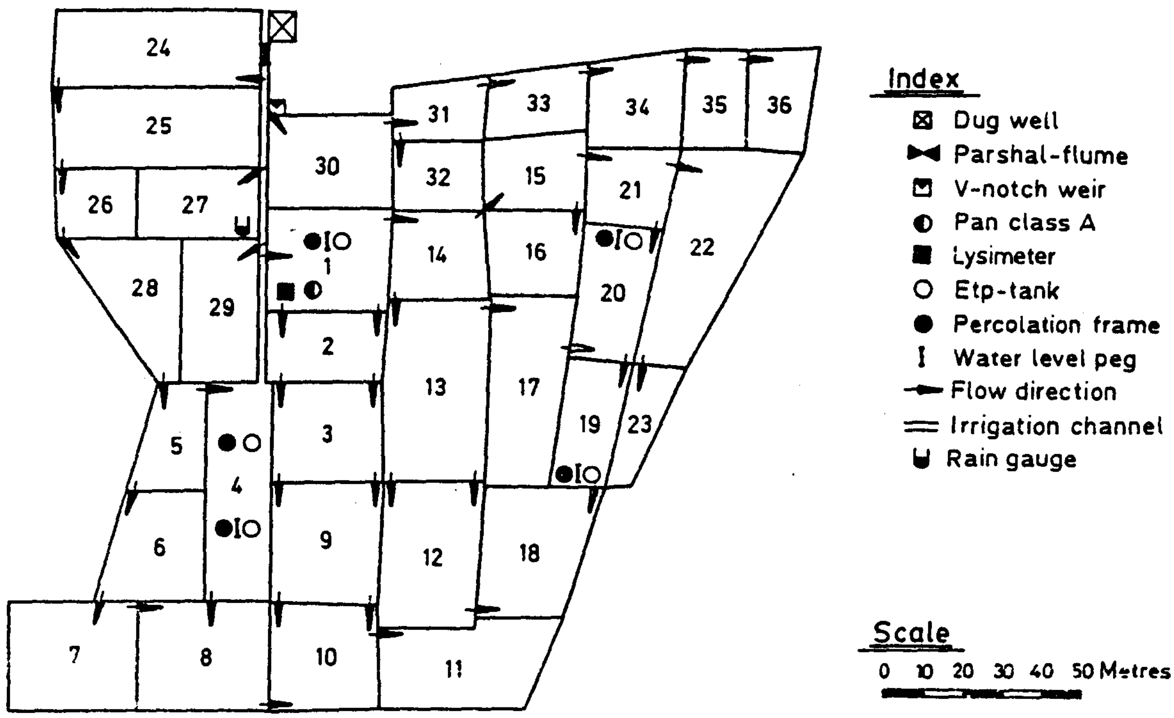



Figure 3.3: Plot Layout of the Well Terrace Irrigation System, Gopal Reddy

### 3.3.3.3 Ponding Tests

To support the results obtained in the water balance and drum culture experiments, and in order to estimate the potential percolation rates in paddy fields, three ponding tests were carried out. The procedure adopted was to fill the test plot and the surrounding fields to a submergence depth of about 3 to 5 cm (Figure 3.4). Leaks in the field bunds were sealed and inlets and outlets closed. The drop in the water level due to percolation, seepage and evapotranspiration was monitored.

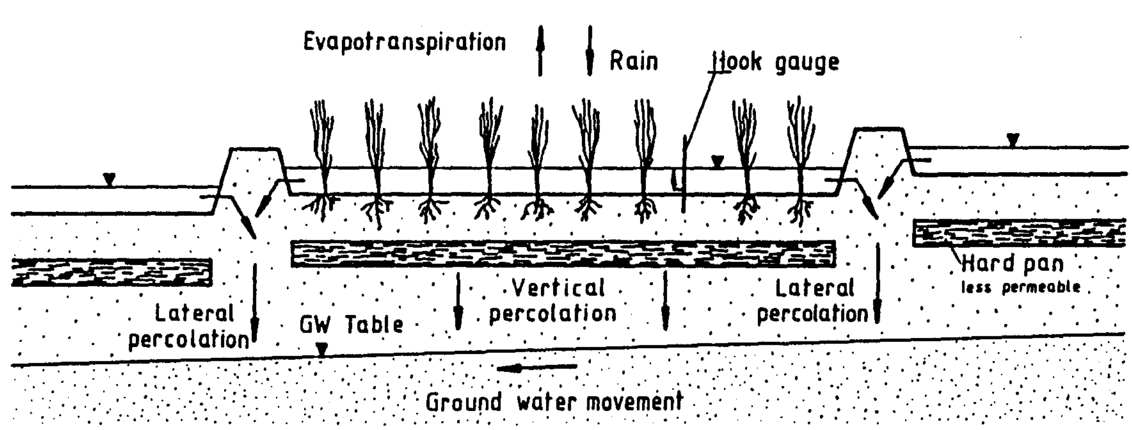



Figure 3.4: Ponding Test after Walker and Rushton [258]

#### 3.3.3.4 Infiltrometer Tests

Infiltration tests were conducted with the aim of assessing infiltration characteristics in the catchment area of the Gopal Reddy Plot, to study infiltration in an uncultivated paddy terrace, to complement the ponding tests and to investigate possible lateral seepage losses through inner field bunds of irrigated rice fields.

In the experiments a double ring infiltrometer was used. The water level was maintained at a depth of 30 mm. In paddy fields the initial soil moisture content was near saturation, in the dryland soil near the permanent wilting point, and in the uncultivated paddy terrace near field capacity.

#### 3.3.3.5 Soil Sampling

Soil samples were collected for physical and chemical analysis with the objective of classifying the soils of the sub-plots where ponding and infiltration tests were executed.

Initially, holes were excavated in each subplot to determine the depth of the puddled layers. Then four samples from the puddled layer, which varied in depth from 16 to 28 cm, were taken from each subplot. Another four samples per subplot were collected at depths of 0 to 15 cm below the puddled layer. Samples taken at the same depth from each subplot were bulked together and their physical and chemical properties analysed with help from FSRP Soil Physics and Chemistry staff.

### 3.3.4 Results

#### 3.3.4.1 Results of Water Balance Method

The results of the water balance studies on the Muralidar Rao Plot, where black soils predominate, are shown in Figure 3.5. Total water use, evapotranspiration and percolation including seepage are plotted over the growth period after transplantation. Percolation plus seepage declined from an initial value of 9 mm/d to below 2 mm/d shortly before harvest. The evapotranspiration increased over time due to rising temperatures in March and April. Part of the increase of ET also has to be attributed to higher transpiration of the growing plants. The total water use, which is the sum of ET and percolation plus seepage, dropped from close to 14 mm /d to a constant 10 mm/d.

The results obtained in the Gopal Reddy Plot are presented in Table 3.2. In the early monsoon season the total water applied was one-third higher than in the late monsoon season. During early monsoon evapotranspiration amounted to 892.5 mm falling to 577.0 mm in late monsoon. Seepage losses were considered to be lower than 5 % of the total water applied. Soil moisture changes were estimated to be in the order of 100 mm. As a result of this, the seasonal percolation loss worked out to be 2095.9 mm in early monsoon and 1653.0 mm in late monsoon. In both cases approximately two-thirds of the water applied percolated. The average percolation for the period between transplanting and harvest amounted to 21.0 mm/d in early monsoon and 18.2 mm/d in late monsoon, and the average daily applied water to 30.4 and 25.7 mm/d.

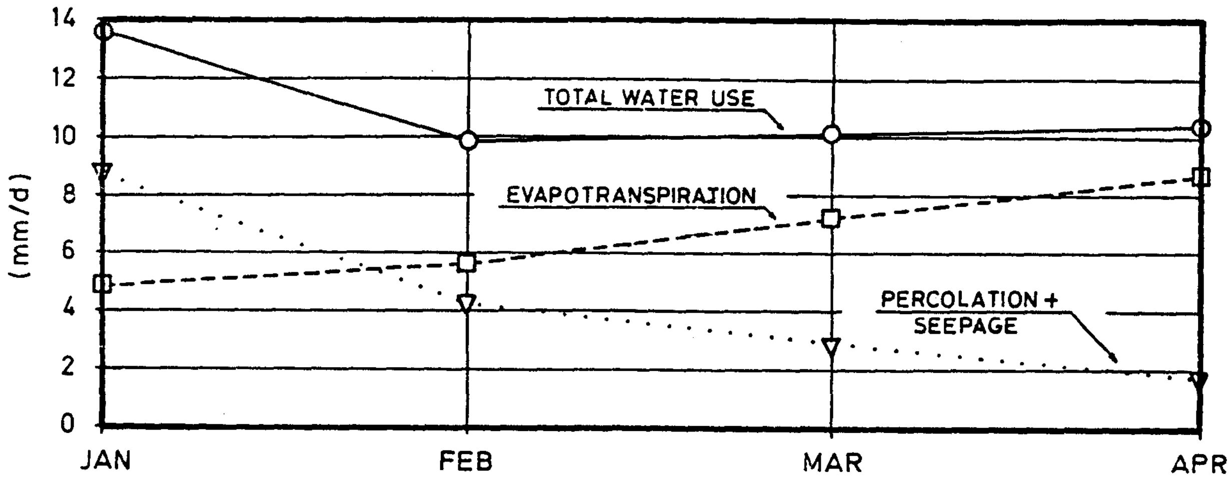



Figure 3.5: Results of Water Balance Studies on Black Soils in the Muralidar Rao Plot

Table 3.2: Results of Water Balance Studies, Gopal Reddy Plot

| Stage of crop | Dur. [d] | TWA [mm] | Rain [mm] | ET [mm] | Seep. [mm] | ΔSM [mm] | Perc. [mm] |
|---|---|---|---|---|---|---|---|
| **Early monsoon season 1986:** | | | | | | | |
| Nursery puddling | 6 | 50.3 | 0.3 | 6.3 | | | |
| Nursery | 25 | 179.3 | 1.5 | 37.2 | | | |
| Puddling | 22 | 445.6 | 10.1 | 150.0 | 5 % of | | |
| After transpl. | 84 | 2554.7 | 228.1 | 662.4 | TWA | | |
| Before harvest | 9 | 21.0 | 21.0 | 36.6 | | | |
| | | 3250.9 | - | 892.5 | - 163 | - 100 | = 2095 = 64.4 % of TWA |
| **Monsoon season 1986:** | | | | | | | |
| Nursery puddling | 8 | 77.0 | 1.0 | 10.2 | | | |
| Nursery | 29 | 194.0 | 9.3 | 31.3 | | | |
| Puddling | 11 | 308.0 | 18.2 | 66.8 | 5 % of | | |
| After transpl. | 73 | 1874.0 | 256.3 | 452.6 | TWA | | |
| Before harvest | 3 | 0.0 | 0.0 | 16.0 | | | |
| | | 2453.0 | - | 577.0 | - 123 | - 100 | = 1653 = 67.4 % of TWA |

where:

Dur. = Duration

TWA = Total water applied including rain

ET = Evapotranspiration

Seep.= Seepage loss

ΔSM = Change of soil moisture storage

Perc.= Percolation loss

In the Irven Plot the values of pan class A evaporation deviated markedly from the figures obtained for the other sites. This was found to be due to the unreliability of the local man taking the measurements. Hence, the experiment was discontinued and the doubtful results disregarded.

The Water Balance Method has limitations due to inaccurracies involved in discharge measurements and the lack of precision in the estimation of evapotranspiration and seepage losses. However, because the normal irrigation practices of the farmers remain unaltered, a realistic valve of the actual losses can be obtained.

### 3.3.4.2 Results of Drum Culture Studies

The results given in Table 3.3 are average values calculated for the 1986 monsoon season. The daily percolation ranged from 4.7 mm in subplot 006 to 13.6 mm in subplot 019. In all plots, apart from plot 006, it was observed that the entire irrigation supplied to the drums infiltrated in a few hours. Therefore, it can be concluded that the hydraulic conductivity in these plots is higher than the percolation rates given in Table 3.3. For this case the percolation appears to be a function of the water supplied (submergence depth) and the evapotranspiration. On rainy days the submergence depth is increased by rain. Consequently more water is available for percolation and actual percolation will be closer to the hydraulic conductivity or will even equal it. The "greater than" sign ( › ) in Table 3.3 indicates that percolation would be higher when the level to which the drum is refilled every morning is raised. In plot 006 raising of the initial submergence depth would not cause an increased percolation, since the hydraulic conductivity is limiting.

Table 3.3: Results of Drum Culture Studies

| Subplot | Soils | Tot. water applied incl. rain [mm/d] | Evapo-trans-piration [mm/d] | Percolation [mm/d] | Remarks |
|---|---|---|---|---|---|
| 001 | Loamy Sand | 20.8 | 8.0 | › 12.5 | Lysimeter |
| 006 | Loamy Sand | | | 4.7 | Drum cult. |
| 008 | Loamy Sand | | | › 5.7 | Drum cult. |
| 019 | Loamy Sand | | | › 13.6 | Drum cult. |
| 020 | Loamy Sand | | | › 12.5 | Drum cult. |

(Depth to ground water table › 5 m)

The values obtained with the Water Balance Method are greater than those determined with the Drum Culture Method because of the higher average submergence depth in the water balance studies.

### 3.3.4.3 Results of Ponding Tests

The average percolation plus seepage losses for the three paddy plots monitored varied between 1.9 and 34.3 mm/h. The variation over time was much lower. The data did not show a correlation between the rate of seepage plus percolation and the depth of water in the field, probably because of the only slight differences in depth (0.0 to 4.2 cm). The details are given in Appendix K.

### 3.3.4.4 Results of Infiltrometer Tests

In an infiltration test carried out in the catchment area of the Gopal Reddy Plot the initial infiltration rate of 1240 mm/h decreased to about 270 mm/h after 2 h and remained at this level for the last 1.5 h of the test period (Appendix J). Thus infiltration into this particular red sandy soil appears to be too high to expect any runoff from this area, unless extremely high rainfall intensities occur. During the infiltration test executed in the uncultivated subplot 019, infiltration started at 168 mm/h rapidly decreasing to a level of 36 mm/h (Appendix J). High rainfall intensities could generate infiltration excess on the loamy-sandy soil of this subplot, but when taking into account the considerable surface storage in a paddy field runoff does not seem to be very likely.

A comparison of the results of ponding and infiltration tests can provide an indication of the order of magnitude of the lateral percolation. During infiltration tests only the vertical percolation is recorded. In ponding tests the drop in the water table is measured which is caused by visible seepage losses through the outer field bunds, lateral percolation losses through the inner bunds, evapotranspiration and of course vertical percolation. Figures 3.2 and 3.4 explain the different loss parameters. Evapotranspiration losses during the test period were estimated from lysimeter data. Visible seepage losses were excluded because the ponding test was executed in the centre of a wetland area.

In subplot 1 the ponding test yielded an average value of 5.40 mm/h and the infiltration test 5.25 mm/h. In subplot 8 the figures were 34.3 mm/h and approximately 17 mm/h for the ponding and infiltration tests, respectively. In both cases there were differences, which could be attributed to lateral percolation and also to heterogenities of the soil within the subplots. It is not possible to obtain statistically significant estimates of the order of lateral percolation from the data collected.

Similar experiments were conducted by Walker and Rushton [258]. They found that lateral percolation losses occurred from tank irrigated paddy fields in West Sumatra especially when the water depth in the paddy field was higher than 28 mm. In their test plots, Walker and Rushton found a linear relationship between inital depth of water and lateral percolation. The lateral percolation started at about a depth of 28 mm and reached a value of 28 mm/d at 150 mm. Total losses were found to be approximately 10 mm/d higher than the lateral losses. At depths of over 60 mm the lateral losses become the prinipal loss factor (see Figure 3.6).

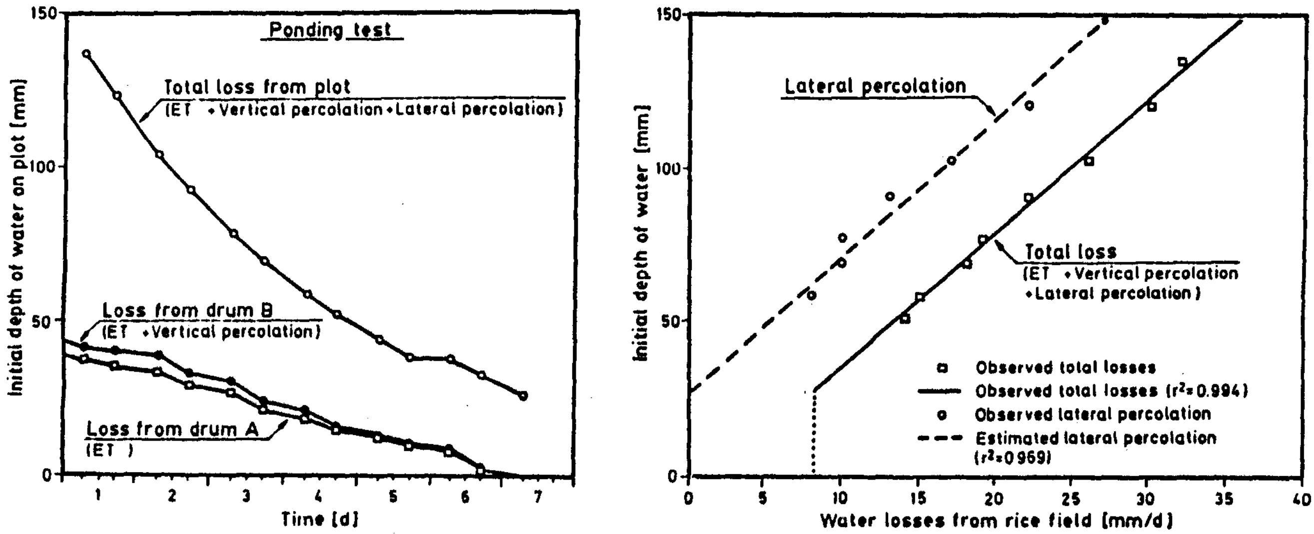



Figure 3.6: Results of Water Balance Studies of Paddy Fields at Sungai Dareh, West Sumatra [258]

The author assumes that the lateral percolation also varies for different ratios of bund length to terrace area. The higher the ratio the higher the loss. Under Aurepalle conditions the submergence depth was normally not much higher than 50 mm. The vertical percolation proved to be higher than in the study quoted above. Therefore under normal irrigation practices lateral percolation will be relatively unimportant. However, during rainstorms when water is harvested in the paddy fields, the water depth can rise to over 80 to 90 mm and larger quantities could be lost by lateral percolation. The questionnaire on rainwater harvesting practices showed that about 90 mm of water harvested in paddy fields infiltrated within 1.2 to 1.6 days. Taking into account evapotranspiration losses this amounts to an infiltration rate of 50 to 70 mm/day. These figures are watershed averages including lowland paddy on relatively impermeable black soils. The ponding tests which were carried out on coarser soils suggest values between 45 and some hundred mm/d.

#### 3.3.4.5 Results of Soil Sampling

Analytical results are given in Table 3.4 and Table 3.5. The soils were found to be very coarse in texture. High volumetric percentages of gravel and sand were encountered. Based on these percentages the soils were classified as sandy to loamy-sandy soils. Consequently the water retention of the soil proved to be very poor but was found to be higher in the second layer. The dryland soil in subplot 100 showed by far the poorest water retention with 11.6 mm of available water for a soil column of 30 cm. The coarse texture of the soils provides a logical explanation for the high infiltration rates and percolation losses of the plots under investigation.

The gravimetric analysis of the moisture content of the same soils at the end of the dry season showed a lower moisture content than determined with a pressure chamber at 15 bar. This inconsistency could be explained by soil evaporation which extracts moisture to a lower level than the wilting point. It could also be possible that the standard procedure to determine the field capacity is not appropriate for red soils in the SAT. Therefore, available water could be higher than presented in table 3.4.

Table 3.4: Results of Physical Analysis of Aurepalle Soil Samples

| Plot | Depth [cm] | Texture | Gravel [%] | Sand [%] | Silt [%] | Clay [%] | Bulk Dens. [g/cm³] | Water Retention 15 Bar [g/100 g] | Water Retention 0.33 Bar [g/100 g] | Avail. Water [mm] |
|---|---|---|---|---|---|---|---|---|---|---|
| 001 | 00 - 22 | Sand | 25.5 | 63.3 | 6.0 | 5.2 | 1.44 | 5.39 | 8.75 | 10.7 |
| | 22 - 37 | L. Sand | 33.5 | 48.5 | 6.0 | 12.0 | 1.68 | 10.30 | 16.01 | 14.4 |
| 002 | 00 - 22 | L. Sand | 26.3 | 57.5 | 11.8 | 4.4 | 1.49 | 4.67 | 7.86 | 10.5 |
| | 22 - 37 | L. Sand | 29.7 | 56.3 | 4.9 | 9.1 | 1.63 | 7.49 | 12.61 | 12.5 |
| 020 | 00 - 28 | L. Sand | 21.4 | 66.0 | 4.7 | 7.9 | 1.24 | 6.72 | 10.11 | 11.8 |
| | 28 - 43 | L. Sand | 19.3 | 54.0 | 8.9 | 17.8 | 1.20 | 12.79 | 20.25 | 13.5 |
| 019 | 00 - 24 | L. Sand | 25.7 | 60.9 | 5.2 | 8.2 | 1.23 | 7.12 | 11.38 | 12.6 |
| | 24 - 39 | L. Sand | 20.2 | 61.4 | 16.0 | 2.4 | 1.35 | 8.89 | 15.27 | 12.8 |
| 008 | 00 - 16 | L. Sand | 30.2 | 56.5 | 4.9 | 8.4 | 1.40 | 8.10 | 13.11 | 11.2 |
| | 16 - 31 | L. Sand | 46.9 | 39.8 | 4.8 | 8.5 | 1.37 | 11.52 | 16.98 | 7.5 |
| 006 | 00 - 16 | Sand | 23.6 | 64.9 | 5.4 | 6.1 | 1.33 | 5.74 | 11.18 | 11.5 |
| | 16 - 31 | L. Sand | 32.6 | 49.2 | 6.7 | 11.5 | 1.54 | 10.02 | 16.48 | 15.0 |
| 100 | 00 - 15 | Sand | 19.9 | 76.1 | 2.4 | 1.6 | 1.27 | 1.82 | 3.33 | 2.9 |
| | 15 - 30 | L. Sand | 34.9 | 50.8 | 3.9 | 10.4 | 1.37 | 8.20 | 12.47 | 8.7 |

L. Sand ≙ Loamy Sand

Table 3.5: Results of Chemical Analysis of Aurepalle Soil Samples

| Plot | Depth [cm] | pH | EC [mmhos/cm] | Na [available | Ca | K | Mg ppm] | $CaCo_3$ [%] | OC [%] | CEC [me./100 g] |
|---|---|---|---|---|---|---|---|---|---|---|
| 001 | 00 - 22<br>22 - 37 | 8.40<br>8.12 | 0.12<br>0.11 | 50<br>66 | 1425<br>1550 | 40<br>103 | 187<br>360 | 1.02<br>0.73 | 0.51<br>0.29 | 9.06<br>18.60 |
| 001 | 00 - 22<br>22 - 37 | 8.39<br>8.14 | 0.11<br>0.15 | 30<br>33 | 1550<br>1150 | 36<br>78 | 175<br>210 | 0.94<br>0.68 | 0.44<br>0.24 | 8.69<br>12.46 |
| 020 | 00 - 28<br>28 - 43 | 8.40<br>8.50 | 0.15<br>0.14 | 42<br>34 | 1825<br>3250 | 58<br>119 | 275<br>525 | 0.86<br>3.28 | 0.35<br>0.24 | 13.04<br>21.37 |
| 019 | 00 - 24<br>24 - 39 | 8.58<br>8.62 | 0.14<br>0.12 | 41<br>50 | 2000<br>2325 | 89<br>125 | 325<br>385 | 2.12<br>1.91 | 0.41<br>0.21 | 14.63<br>16.81 |
| 008 | 00 - 16<br>16 - 31 | 8.40<br>8.48 | 0.14<br>0.11 | 63<br>53 | 1600<br>2325 | 178<br>326 | 250<br>375 | 0.94<br>0.90 | 0.39<br>0.30 | 13.62<br>19.56 |
| 006 | 00 - 16<br>16 - 31 | 8.27<br>8.38 | 0.15<br>0.10 | 72<br>53 | 1280<br>1550 | 89<br>369 | 177<br>350 | 0.58<br>0.88 | 0.31<br>0.32 | 9.42<br>19.92 |
| 100 | 00 - 15<br>15 - 30 | 7.85<br>7.50 | 0.04<br>0.04 | 31<br>38 | 250<br>1200 | 33<br>181 | 28<br>150 | 0.23<br>0.48 | 0.08<br>0.24 | 1.45<br>11.60 |

## 3.4 Investigations in other Areas

Karanth and Prasad [115] reported that the average infiltration rate for paddy fields is generally higher than that for traditional irrigation tanks in south India. For tanks they observed an average infiltration rate of 9 mm/d and for paddy ratios of 55 % to 88 % of the total water applied corresponding to 12 to 19 mm/d. They concluded that infiltration from paddy fields constitutes a substantial part of groundwater recharge in Andhra Pradesh. Subrahmanyam, who also studied paddy infiltration on red silty to loamy sands, presented infiltration rates of around 10.9 mm/d [239].

Helweg and Sharma [82] studied the permeability of the bed and the bund of tanks. They found much lower permeabilities for heavily silted tank beds (less than 1 mm/d) than for tank bunds (up to several thousands of mm/d). These figures indicate that considerable quantities of water seep through the tank bund. Thus the infiltration occurs in a similar manner to the lateral percolation in paddy fields, but on a larger scale.

Hantke [76] compared different structures for artificial ground water recharge such as infiltration wells, infiltration pipes, percolation tanks, percolation slots and infiltration polders. An explanation for the high infiltration in paddy fields can be derived from his research:

Infiltration polders are small basins normally covered with plants or trees and are submerged to depths of about one meter. After all the water has infiltrated the polder will not be submerged for a short period in order to allow regeneration. The same process is repeated again. Good infiltration efficiency is ensured over long periods of time because regeneration prevents flora and soil fauna, such as worms and larvae, from dying. Roots of plants, worms and larvae loosen the soil thus maintaining the hydraulic conductivity at a higher level than in the case where a basin is continously submerged and no vegetation can proliferate. Infiltration polders are very similar to rice terraces, although the average depth of submergence is much lower.

The effect of vegetation on infiltration rates was studied in detail by Bouwer et al [28]. They found that infiltration varies for different types of vegetative cover. For cultivated plots they observed generally higher infiltration rates than for uncultivated ones.

## 3.5 Summary and Conclusions

Important observations are summarized below:

- Harvesting of rainfall and runoff in paddy fields is a common practice in the study area. About 90 mm of water can be stored for subsequent use by the crop.

- In the monsoon the cumulative infiltration from rainfall alone adds up to 300 to 600 mm depending on the distribution of rainfall.

- When additional overland flow and runoff is retained much higher infiltration can be expected, unless the hydraulic conductivity of the soil is limiting.

- Recharge from paddy fields proves to be a major and dependable portion of the total ground water recharge.

- In fields with loamy- sandy soils around two-thirds of the applied water is lost through vertical and lateral percolation. Under normal irrigation practices in the pre-monsoon and monsoon season, rice recieves irrigation and rainfall of 28 mm/d. Of this 7 mm/d are lost through evapotranspiration and 19 mm/d through vertical and lateral percolation. Other losses such as seepage amount to 2 mm/d.

- The mean potential percolation rate or hydraulic conductivity of an average soil lies between 50 to 70 mm/d. On coarse soils the values range between 50 mm and several hundreds of millimeters.

- In the monsoon of 1986 with maximum rainfall intensities of less than 60 mm/d no runoff from paddy fields was observed.

- Under high submergence infiltration is increased through lateral percolation.

- The high infiltration in rice terraces can be attibuted to intermittant irrigation, the positive effect of soil flora and fauna, and the coarse texture of the soils in the test plot.

- The high infiltration in paddy fields suggests that paddy fields fields could be used as ground water recharge basins.

# 4 PADDY IRRIGATION AS PART OF A WATERSHED MANAGEMENT CONCEPT

## 4.1 General

Management of water at the watershed level aims at an optimum allocation and distribution of the available water resources between the different water users. It is often difficult, especially in semi-arid and arid regions, to ensure that the water demand is met by the water supply. Ground water plays an exceptional role in water management, because it is the only source of water which is available throughout the year. In some areas with arid climates the ground water resources are depleted over a succession of dry years before the aquifer is recharged again in a wet year [20].

In principle the following measures can be employed to meet increasing water demand:

- increase the water retention of surface water in a watershed ("water harvesting").

- or augment the ground water resources.

In order to increase agricultural production in India it is necessary to store water for use in dry periods of the monsoon and, if feasible, for use in the post-monsoon season. As mentioned earlier it is already a common practice in India to collect surface water in tanks. However the water stored in such tanks is subject to evaporation and seepage losses. If water is transferred underground these losses do not occur. Augmentation of the ground water resources can therefore be a measure to further increase available resources.

Augmentation of ground water resources can be accomplished by:

- planned lowering of the ground water table in order to increase the natural ground water recharge.

- planned lowering of the ground water table in order to reduce evaporation losses from the surface ground water which is very important in semi-arid and arid areas [229].

- prevention of subsurface outflow through construction of subsurface dams.

- artificial ground water recharge for a more efficient utilization of the ground water storage.

In many areas in India the ground water table is already maintained at levels at which only negligible evaporation losses occur. Hence emphasis has to be placed on the development of methods to efficiently recharge the ground water. In the introduction the need for improved ground water recharge structures was already pointed out and this was one of the objectives given in chapter 1. With knowledge of the hydrological and socio-economical characteristics of the study area provided in the previous chapters one is now able to evaluate different methods of water management adapted to the existing environment.

In the following chapter the general methods applied to artificially recharge the ground water are discussed. The experience gained concerning the traditional designs in south India is then described.

An alternative to the existing methods of artificial ground water recharge is the use of paddy terraces as ground water recharge basins. The design and advantages of such structures are discussed below.

## 4.2 Artificial Ground Water Recharge

### 4.2.1 Definition and Principles

Artificial ground water recharge is defined as the augmentation of ground water by technical means. The following principles can be applied [25]:

- Extension of the natural infiltration area through "spreading of surface water".
- Enhancement of the infiltration capacity through surface treatment and construction of infiltration areas (infiltration basins, infiltration pits, percolation ditches and furrows).
- Increase of the duration of submergence for example through construction of low dams or other retaining structures in a stream bed (check dams).
- Increase of the depth of submergence.
- Infiltration of water below impermeable layers (injection wells, recharge pits and shafts)
- Increase of the storage capacity of the subsoil (sand dams)

There are six general designs of ground water recharge structures (Figure 4.1)[158]:

- Recharge basins, percolation ponds and tanks
- Flooding
- Ditches and furrows
- Natural stream channels
- Pits and shafts

and

- Injection wells

Each of these designs have advantages and disadvantages and are therefore useful under specific conditions.

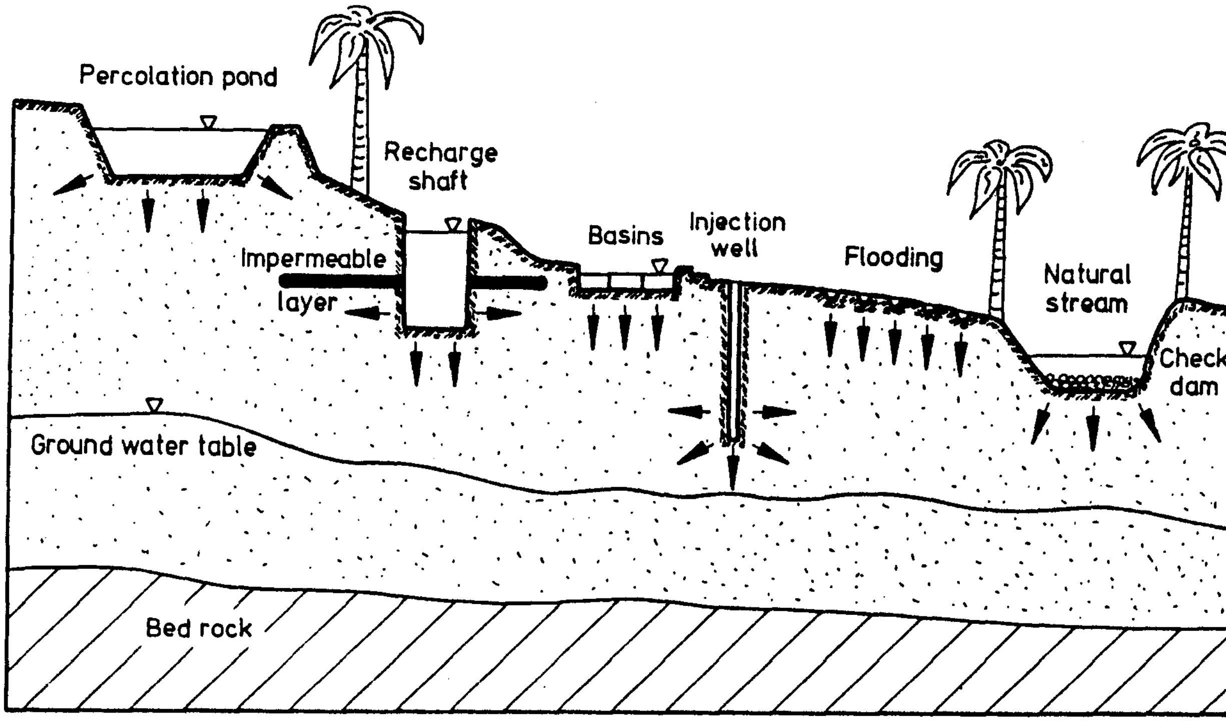



Figure 4.1: General Designs of Ground Water Recharge Structures

Basins and percolation ponds are common designs adopted for ground water recharge, both are similar in construction and operation. Basins are square or rectangular in shape and are generally constructed in series. They are excavated in the land surface and the excavated soil is used for forming an embankment around the basin. Recharge basins can be used for recharging by stream flow or any excess irrigation canal water. They can also handle uneven flows. Both percolation ponds and percolation tanks are useful for collecting the excess runoff from small catchments for recharge purposes. Whereas ponds are generally dug out, percolation tanks are constructed by building an earth dam across a small stream. They need to be constructed, depending upon the topographical conditions, to give a large storage capacity with a minimal bund length. One of the problems in operating recharge basins and percolation ponds is progressive sedimentation leading to reduction of infiltration rates over a period of time. However, when recharge basins are operated in series, sediment settles in the first few basins and in the others normal infiltration rates are maintained.

Flooding is the simplest method of recharge and costs less in terms of land preparation. The water is conveyed to the site selected where small embankments have been constructed to contain the water. The land should be relatively flat to facilitate the control of the water. The original infiltration rates can be maintained so long as the native vegetation and soil cover are not disturbed and the water does not contain sediments. The main disadvantage is the large land requirement. Compared to other methods the evaporation losses are higher, because of the large exposed water surface.

In the "ditch" or "furrow" method water is distributed to a series of shallow ditches or furrows which are flat-bottomed. Feeder ditches should be designed with gradients sufficent to carry suspended material through the system. A collecting ditch is required at the bottom end of each area to convey excess water back into the main stream [245]. A ditch and furrow system can be a useful design in undulating areas. With this system less water is lost through evaporation than in a flooding system. It is often the case that ditches and furrows are combined with flooding systems [158].

In stream channels the ground water is recharged naturally during flow. By constructing low dams or retaining structures such as check dams the stream flow can be retained for a longer time in the stream bed and spread over a larger area. Check dams are built of reinforced concrete or of rock and wire. Generally, stream beds are porous and therefore good sites for artificial recharge. Additional recharge from streams can be induced by lowering the water table in the aquifer adjoining the stream through extensive pumping. This approach is useful, when the stream flow is prolonged and the ground water can be utilised for irrigation of agricultural lands situated near the stream.

Pits and shafts are similar to recharge basins with the exception that they are deeper and of different shape. Recharge shafts are large diameter wells. Water is led into these wells and allowed to stand. Recharge shafts and pits use less land than basins, flooding, and ditch and furrow systems, but are costlier and recharge smaller volumes of water. However, where less permeable surface soils are encountered, pits and shafts can penetrate to more permeable substrata and allow the water to infiltrate at higher rates in lower layers. Abandoned gravel pits have been used occasionally for this purpose. Sediment loaded water can cause problems and therefore it may be necessary to construct a holding pond for settlement of the sediments [158], [245].

The construction and operation of injection wells is a comparatively expensive method to artificially recharge the ground water. The design is not justified in places where low returns are obtained from a unit of water, as is the case in developing countries.

Land management works such as contour and graded bunding help to retain water on the land surface for a longer time, thereby increasing infiltration and ground water recharge. In areas taken up for bunding on a large scale significant impovement in the water levels of wells was observed [247].

### 4.2.2 Factors Influencing Recharge Rates

Generally infiltration rates are directly proportional to the head of water in the recharge structure [204]. A high ground water table reduces the downward flow of recharged water. For efficient operation of a spreading system the depth to the ground water table should be at least 3 to 6 m [245].

Recharge rates also decrease as the mean partical size of the soil decreases. Surface compaction by heavy equipment in preparing the recharge site may adversely affect infiltration. Where less pervious strata lie below the surface stratum, the recharge rate depends on the rate of subsurface lateral flow.

Spreading of surface water in narrow, widely spaced strips recharges nearly as much water as spreading water over the entire area [205], [206].

Water containing silt or clay is known to clog soil pores resulting in declining recharge rates. Rapid sand filtration to eliminate fine material may be economically justifiable where municipal water supplies are involved.

Wave action in large, shallow ponds may stir bottom sediments and seal pores which would otherwise remain open.

Typical plots of recharge rates over time show an initial decrease which is attributed to dispersion and swelling of soil particles after wetting. A subsequent rise of recharge rates accompanies elimination of entrapped air which is dissolved in the percolating water. The final gradual decline is due to microbial growth clogging the soil pores (Figure 4.2) [152]. Laboratory tests with sterile soil and water give nearly constant maximum recharge rates, thereby substantiating the effect of microbial growth.

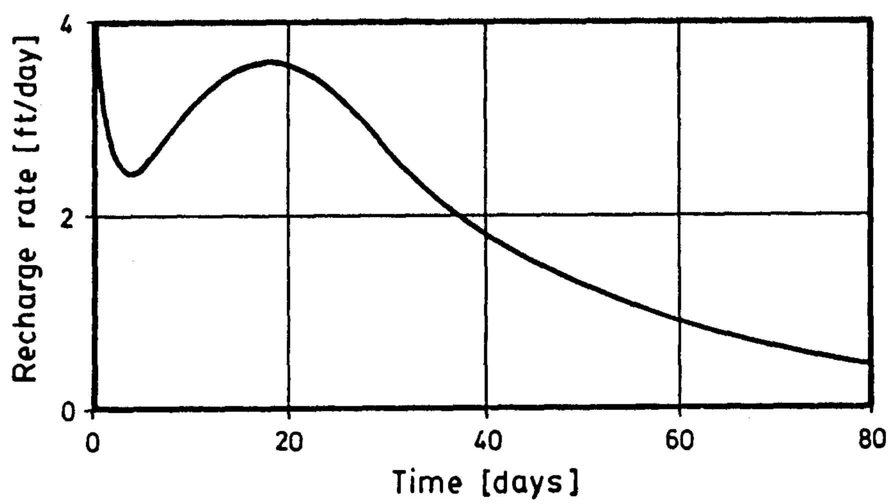



Figure 4.2: Typical Recharge Rate Variation with Time for Water Spreading on Undisturbed Soil [152]

Alternating wet and dry periods in a basin generally lead to a higher total recharge than continous spreading, despite a much lower duration of submergence. Drying out destroys the microbial growth which combined with scarification of the soil surface, reopens the soil pores.

Addition of organic matter and chemicals to the soil as well as growing vegetation on the submerged area can help to maintain soil pores free for the passage of water. Bermuda grass was found to be the best at surviving prolonged submergence and at improving intake rates.

The effect of sunlight on bacterial action in soil, algal growth in water and on temperature has not been fully evaluated as a recharge factor. A high water temperature with accompanying high viscosity should increase infiltration, but this effect may be more than compensated for by the stimulation of bacterial activity [245].

Water quality can be an important factor, for example, recharging water of high sodium content tends to deflocclulate colloidal soil particles and thereby hinder water passage.

### 4.2.3 Percolation Tanks in Maharashtra

Structures currently designed for artificial recharge do not efficiently transfer the water underground. For example the following problems are encountered with percolation tanks as constructed in Maharashtra:

- Due to siltation initially high percolation rates decrease to values below 10 mm/d.

- Siltation reduces the storage capacity of a tank.

- The tanks in Maharashtra cover large areas, hence evaporation losses are high.

- The submerged area is not available for agricultural production.

- Counteracting parameters have to be optimized. A percolation tank should cover large areas to obtain high percolation, but conversely have a small surface area in order to maintain evaporation at a low level.

- Percolation tanks are normally placed in narrow valleys with steep slopes where tank bunds can be kept short in order to obtain a favourable ratio of tank bund length to storage capacity. In the depressions ground water levels normally rise early in the monsoon close to the surface thus reducing the percolation rates of such tanks and the available storage in the soil.

### 4.2.4 Agronomically Productive Percolation Systems (APPS)

Reviewing the advantages and drawbacks of the different recharge structures described above a properly designed system should have the following features provided a suitable site can be found:

- Low costs of construction and land preparation.
- High depth of submergence.
- High depth to ground water table.
- Large water contact area.
- Low evaporation losses.
- Cultivation of the water spread area.
- Intermittent water supply.

Apart from these features there are other factors which influence the success of the recharge structures. If recharge structures could be integrated in small irrigation systems under the control of farmers it would ensure that they were maintained and run efficiently. Therefore the design of these systems should not be over sophisticated and they should be adapted to the local situation.

There is no such design incorporating all features mentioned above but there are two general options to approach the problem in a semi-arid environment.

The first approach is to develop structures where percolation rates are maximized in order to reduce the ponding period and consequently the evaporation losses. Such structures include percolation ditches, dug out tanks or tanks with infiltration dykes. The limitation here is that these structures are expensive and not always easy to maintain.

The second approach requires a different way of thinking, the principle being to accept lower infiltration rates, but to minimize evaporation losses during the infiltration process. This can be achieved by cultivating the submerged area with a suitable crop, thus converting evaporation losses into productive evapotranspiration. These structures could be called "Agronomically Productive Percolation Systems" (APPS).

#### 4.2.4.1 Design Alternatives

"Agronomically Productive Percolation Systems" can be realized as shallow submergence tanks, overspilled bunds and percolation terraces. Figures 4.3, 4.4 and 4.5 give a general idea of the design of APPS and how they could be positioned in a watershed.

Percolation terraces (Figure 4.3) are similar to ground water recharge basins with the exception that a crop is grown in the basin and the depth of submergence is less. Water is diverted from a check dam in a small channel to the terraces. The field bunds can be raised up to about 50 cm in order to increase the storage capacity of the basins and to increase lateral seepage through the field bunds. It is desireable to keep the basins fairly small to increase the total length of the field bunds and the water contact area. Rice can be considered a suitable crop since submergence of 10 to 50 cm over short periods does not affect yields significantly, provided an appropriate variety is selected [72]. The height of the bunds should be selected depending on the rainfall regime and the percolation rates in such a way that the submergence is not detrimental to the crop and the basin falls dry frequently.

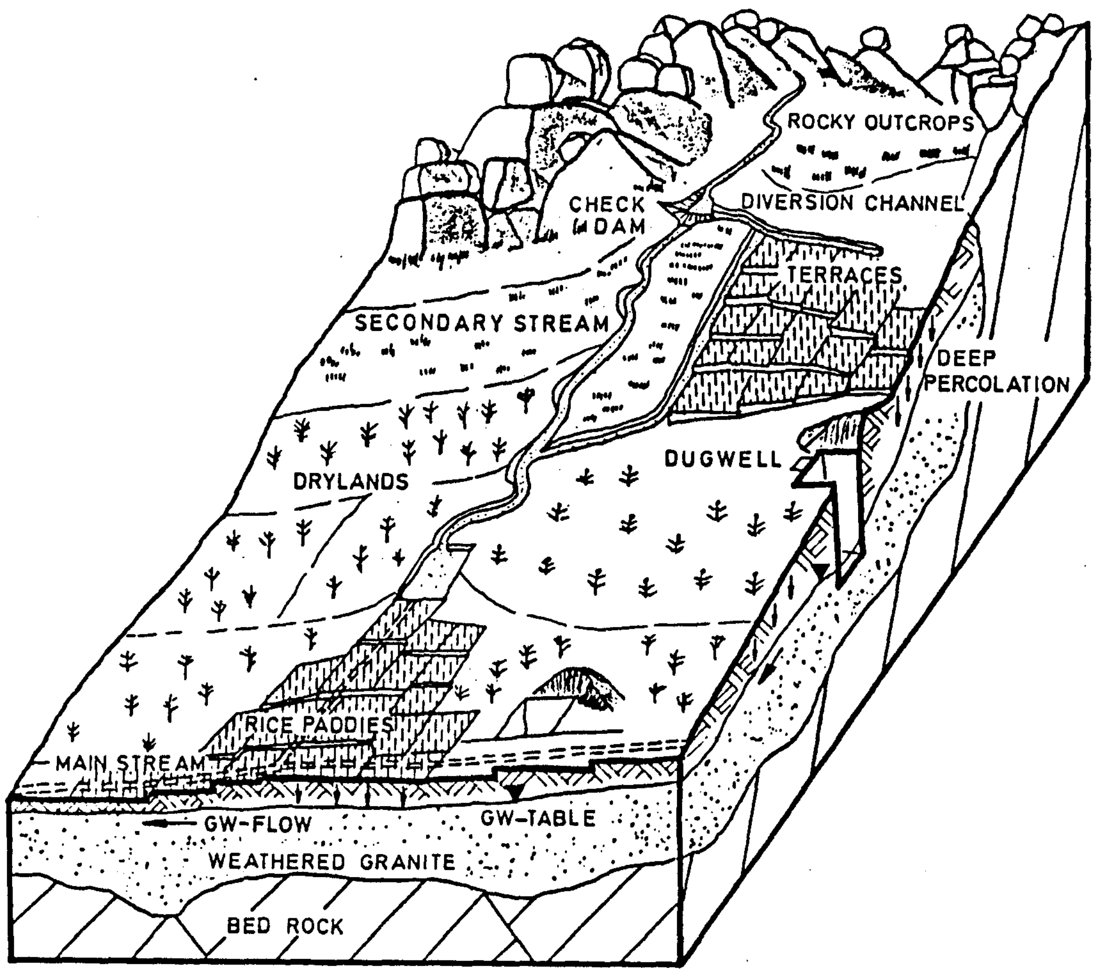



Figure 4.3: Agronomically Productive Percolation Terraces (APPT)

Shallow submergence tanks (Figure 4.4) are similar to traditional tanks but should not be deeper than about 1 m. They are also cultivated with rice or another suitable crop. At the centre where the depth is greatest a rice variety has to be grown, which can sustain submergence for a few days. Here again evaporation losses are transferred into productive evapotranspiration. Due to the low depth the tank falls dry depending on inflow and the percolation rate, microbial growth is then discontinued and the soil pores are opened.

Overspilling bunds (Figure 4.5) consist of a low dam of about 0.5 m height with a flat cross section. They are protected against erosion during overflow by a grass cover. In this case the low depth also ensures the necessary intermission of the irrigation and the survival of the crops.

Wells are an essential part of all types of agronomically productive percolation systems as they provide the crops with water during dry periods. The monitoring of the water balance of rice terraces described in chapter 3 gave a ratio of the consumptive use to the total water applied of about 1:3. On the prevailing soils such a high water use is required to achieve high yields. This, however, leads to high costs for lifting of the ground water. Since electricity is highly subsidised in India farmers can still afford pump intensive cultivation of rice on the highly permeable red soils, but from a government standpoint the pump costs can not be disregarded. In the monsoon season a major part of the irrigation requirement is already covered by the rainfall and diverted runoff to be recharged. In contrast in the dry season only negligible rainfall can be expected and, therefore, cultivation of groundnut or other irrigated dryland crops on the terraces might be more economical.

Compared to percolation terraces the two other designs have a higher storage capacity but are normally constructed in the valley bottom, where the depth to the ground water table and the storage capacity in the aquifer are lower.

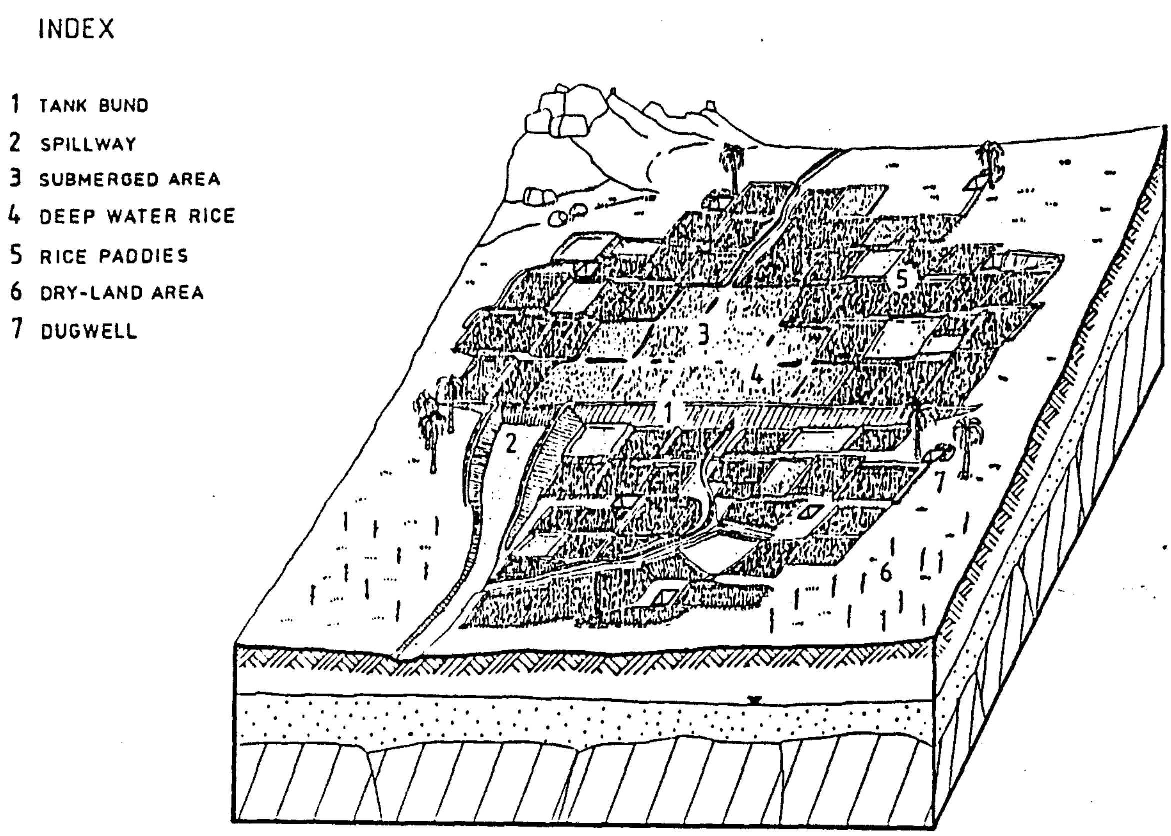



Figure 4.4: Shallow Submergence Tank

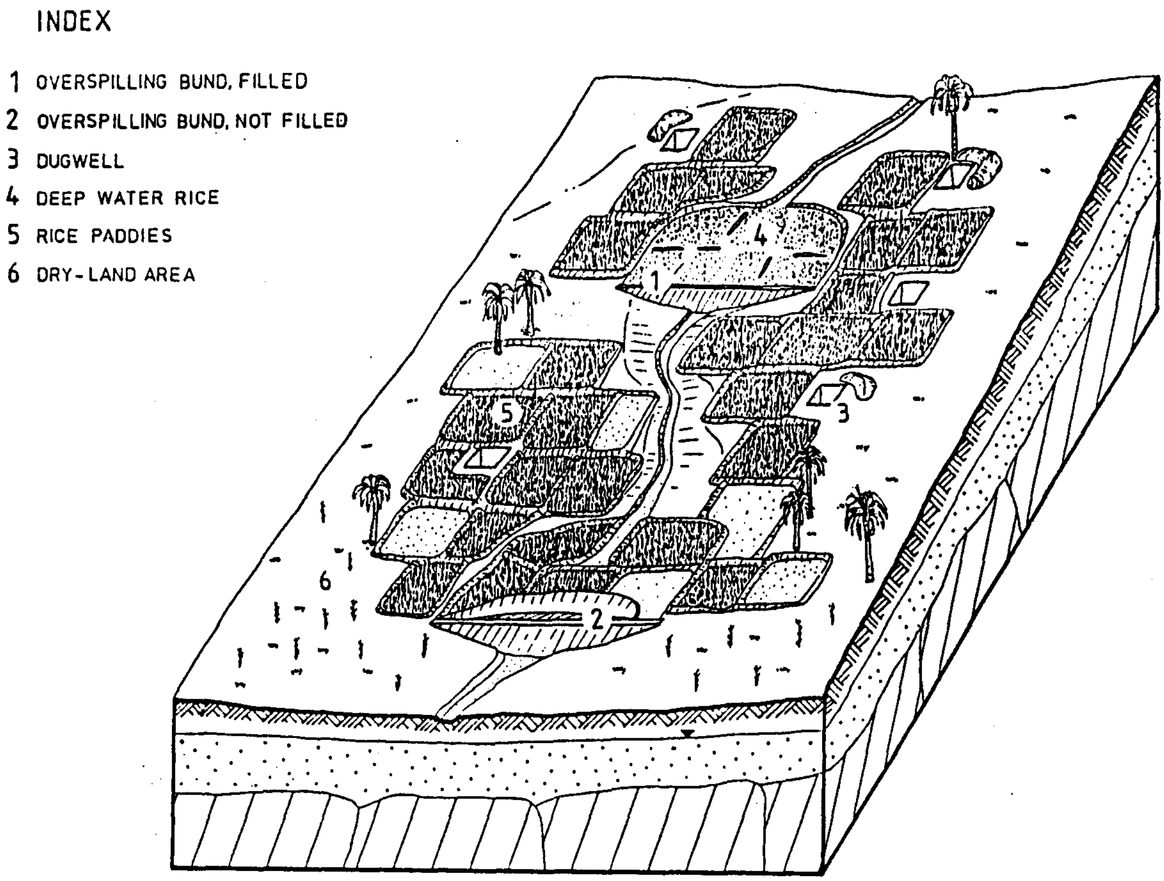



Figure 4.5: Overspilling Bunds

4.2.4.2 Advantages of APPS

The main advantages of APPS are:

- Due to the presence of a cultivated crop the evaporation loss that would occur from the free water surface is transferred into productive evapotranspiration.

- The percolation is higher than in traditional tanks due to lateral seepage through field bunds and the positive effect of flora and fauna on infiltration (loosening of the soil) [76].

- Structures are small and simply built and therefore easy to maintain by the farmers.

- No new technology has to be introduced to the farmers. They are familiar with terraces, tanks and diversion structures.

- Siltation is not considered a problem. The farmers even appreciate the beneficial nutrient value of the siltation.

- If a suitable crop like rice is grown on a percolation terrace, the water standing in the field does not cause significant reductions in yields [72].

- Paddy cultivation is preferred by the farmers because of its stable yield, therefore low risk, and its relative disease resistance compared to other crops grown in this region. In addition to the value of the grain, rice has a considerable fodder value [57]. Furthermore, it is a status symbol to be a wetland farmer [251].

- Percolation terraces can be located in areas where the depth of the ground water table is high and the aquifer has unused storage capacity.

- When groundwater is recharged in upland areas, the recharge wave reaches the lowland areas when the water level there is already declining. Thus water levels are maintained at a level where evaporation losses from the groundwater table are still low.

- Recharge from paddy fields also occurs when annual rainfall is low, while recharge in tanks can be zero due to the absence of inflow. In the dry year of 1986 this was the case at Aurepalle where no inflow was recorded in the tank. Recharge from paddy fields proves to be much more dependable.

- Another advantage of infiltration polders or percolation terraces are the low costs incurred. Artificial recharge in percolation terraces is most economical, where stream water can be harvested at low costs [76].

- Cleaning of the water to be infiltrated is not necessary, unless the concentration of suspended material is higher than 2 to 3 mg/l [76].

- The high land requirement cannot be considered a drawback, since the submerged area is also used for agricultural production.

- There are no additional costs for land preparation as the distribution system and the terraces already exist in rice irrigation systems.

- Through the recharge the ground water table is raised and consequently power costs for irrigation in dry spells are reduced [245].

# 5 VALIDATION OF THE APPS CONCEPT USING MODELLING TECHNIQUES

## 5.1 General

In this chapter an attempt is made to test the concept of APPS using modelling techniques. Firstly the general idea of the model and the testing strategies are presented, followed by a definition of the system. Thereafter the assumptions made and the input data requirements are outlined. The structure and the different components of the model are explained in detail. Finally the process of calibration of the model, the sensitivity analysis and results of model runs are presented.

## 5.2. Principle Model Considerations

The main objective of the model is to provide further information on APPS in order to assess the impact that such systems would have on the water balance of small semi-arid watersheds and to evaluate their technical and economical feasibility. Before such a model can be developed one requires a thorough knowledge of the climatic, agricultural, and hydrogeological conditions of the region. This information has been provided in the previous chapters. In addition one needs to:

- define the system to be modelled.
- simplify the system in such a way that the main processes, such as the water flow and agricultural production, are considered in the model and the outputs of the model and the system only differ to a tolerable extent.
- choose a suitable model type and structure for efficient input of data, output, and presentation of results as well as easy identification and elimination of faults.
- develop a theory for each main process or choose a suitable existing model from the literature.
- test and calibrate the model thoroughly in order to ensure a high degree of accurracy of prediction.
- run the model with different sets of input data, each representing a certain physical framework, in order to systematically examine the model under various environments.
- examine the effect of different management alternatives on the agricultural production, the ground water discharge, and surface outflow from the system.
- analyse the results of the various model runs and suggest design criteria for APPS on the basis of these findings.

After calibration the model can then be used to define and recommend appropriate locations for pilot projects.

In chapter 4 three possible designs for APPS were presented; percolation terraces, shallow submergence tanks and the so called spillway bunds. In order to reduce the amount of modelling work to a managable volume only the percolation terraces were studied. The most positive effect on the water balance of a watershed can be expected from this design, since unused storage capacity in the aquifer of the upper parts or side slopes of a watershed can be utilised for recharge. In contrast the depth to the ground water table at the valley bottom where shallow submergence tanks and spillway bunds are usually constructed is often shallow.

The water balance and the annual benefits of the system must be simulated continously for a minimum period of 10 years preferably for 30 years. A time step of one day was selected in order to reduce the computing time and because only daily rainfall and daily climatic data were available for such long data series. Since the system to be modelled was very complex it was mandatory to work with relatively simple models of sub-processes.An attempt was made to work as far as possible with parameters having physical significance.

### 5.2.1. Physical Definition of the System to be Modelled

The terrace percolation system to be studied is physically defined as follows: it comprises a catchment or runoff area with rainfed agriculture and the terrace or "run on area" where rice is grown. By means of a check dam and a small channel, surface water running off the catchment can be diverted to the terraces for irrigation and recharge. Surface flow in excess of the storage capacity of the paddy fields leaves the system. During dry spells ground water can be lifted from a dug well and supplied to the rice terraces. The part of the precipitation not running off infiltrates und fills the soil moisture storage, evaporates partially and recharges the aquifer. In the terraces a portion of the stored rainfall, runoff or ground water is lost through evapotranspiration another portion reaches the aquifer after percolating through the terrace soil moisture storage. The aquifer is replenished by the deep percolation from the catchment and "run on area" and depleted through ground water abstraction through the well and the ground water discharge.

A farm pond can be operated as an optional element of the system. It increases the surface water retention in the system, provides irrigation in prolonged dry spells but also looses water by evaporation from its water spread area and by lateral and vertical percolation to the ground water storage (Figure 5.1).

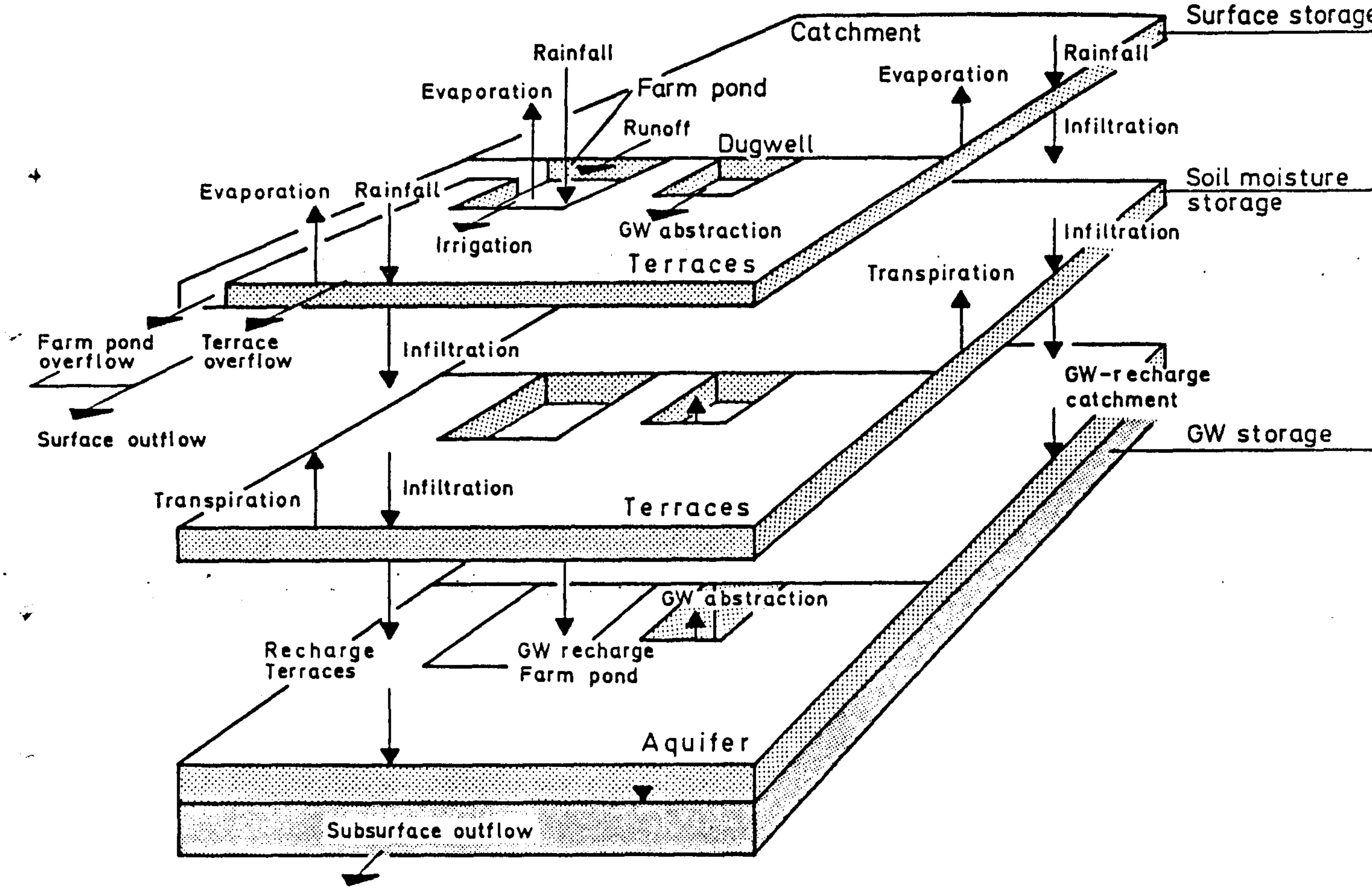



Figure 5.1: Physical Definition of Agronomically Productive Percolation Terraces (APPT).

### 5.2.2. Simulation of the Water Flow

The simulation of the different processes of water movement in the system involves the separate simulation of runoff, infiltration and soil water balance of the catchment and the terraces. It also includes the simulation of the processes in the aquifer such as the fluctuation and movement of the ground water table, the ground water discharge, and the ground water abstraction. When a farm pond is included the water balance must also be calculated. Figure 5.2 illustrates the water flow in the system in an idealised manner.

The movement of water in the system is influenced by inputs from precipitation and climate, and the physical framework such as the geographical characteristics, the type of vegetation and the properties of the soils and aquifer. The water movement also depends on the operation and management of the system.

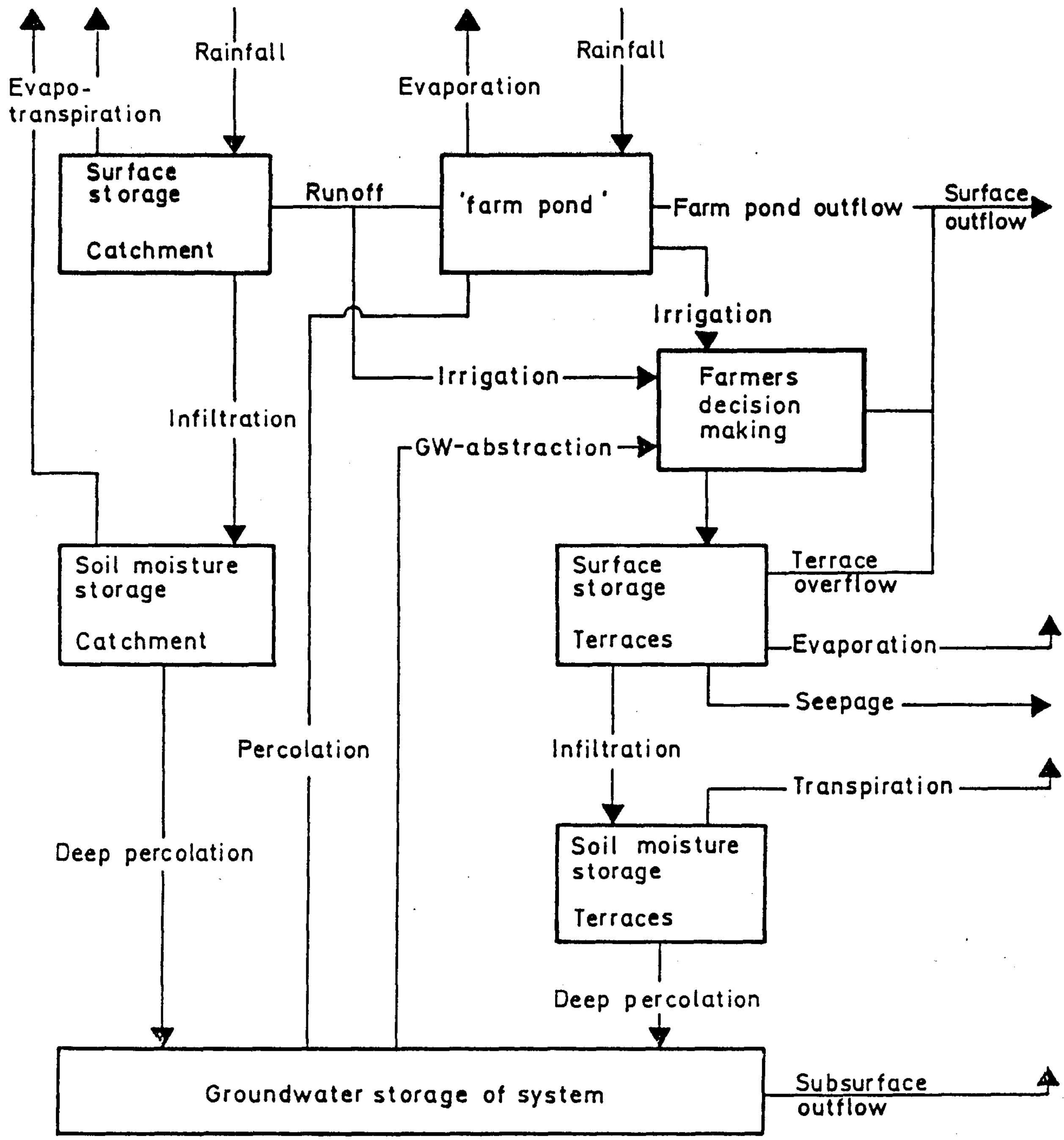



Figure 5.2: Simplified Model of the Water Flow in APPT

Apart from precipitation, climate and vegetation the other above mentioned factors are time invariant. Hence they can be implemented in the model by using input data files.

The climate is represented in the model by daily pan evaporation derived from long term means of monthly pan class A data. The varying date of the onset of the monsoon and excessive precipitation with long dry spells interrupted by torrential rain, caused a tremendous variation in the climate between years. In a climate submodel this variation is taken into account by employing the correlation between antecedent rainfall and pan evaporation. The mean monthly pan evaporation data is adjusted to an actual daily value depending on the preceding rainfall history.

In the semi-arid tropics the vegetation changes enormously during the course of a year. The degree of ground cover has a marked effect on the interception of rainfall, the runoff and the evapotranspiration. For this reason a time dependence of the vegetation has to be taken into account.

### 5.2.3. Simulation of the Management of the System

The operation and management of the system can be modelled by developing a submodel controlling the use of ground- and pond water for irrigation. This controlling submodel must be able to decide on a reasonable area to be irrigated during the different seasons, taking into consideration the currently available and expected (during the growing season) water resources. In other words the decision making of the farmer operating the system also has to be simulated (Figure 5.2).

### 5.2.4. Model Runs

In order to systematically examine under which rainfall regime, climate and physical framework an APPT is technically and economically feasible, quite a number of model runs have to be executed. The differences in rainfall, climate and physical framework can be described by a set of input files. For the region under study, i.e., the stations Anantapur, Aurepalle, Hyderabad and Warangal there are long term rainfall records available. They represent rainfall-regimes with mean annual rainfalls between 500 and 1000 mm/a. The physical frameworks in this region are relatively uniform and are characterised by the flat topography, prevailing red soils and a granitic hard rock aquifer. With only a few parameters such as runoff coefficients or curve numbers (Chapter 5.4.2.2), various levels of soil water available to plants, the aquifer transmissivity and specific yield, and the rainfall files different "environments" can be defined which form as a whole a representative cross section of the study region.

For each of these environments the best manner of operation and management of the APPT system must be determined. In total four alternatives of operation are considered.

A: Only dryland agriculture in the entire system.
B: Dryland agriculture in the catchment plus terraces with 10 cm surface storage.
C: Dryland agriculture in the catchment plus terraces with 30 cm surface storage.
D: Alternative B plus a farm pond with a capacity to store 20 mm of runoff from the effective catchment area (0.85 · System area).

Alternative A represents the traditional situation before the introduction of APPT, while cases B to D represent the different stages of development of APPT.

MODEL RUNS

MODEL RUNS: RAINFALL-REGIME WARANGAL 1000 mm/a

MODEL RUNS: RAINFALL-REGIME HYDERABAD 750 mm/a

MODEL RUNS: RAINFALL-REGIME ANANTAPUR 500 mm/a

MODEL RUNS: RAINFALL-REGIME AUREPALLE 625 mm/a

| Run | Physical Parameters | | | | | | Management Alternatives | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Runoff | | Soil | | Aquifer | | | | | | |
| | A | B | A | B | A | B | A | B | C | D | E |
| 1 | X | | X | | X | | X | | | | |
| 2 | X | | X | | X | | | X | | | |
| 3 | X | | X | | X | | | | X | | |
| 4 | X | | X | | X | | | | | X | |
| . | | | | | | | | | | | |
| . | | | | | | | | | | | |
| . | | | | | | | | | | | |
| 37 | | X | | X | | X | | X | | | |
| 38 | | X | | X | | X | | | X | | |
| 39 | | X | | X | | X | | | | X | |
| 40 | | X | | X | | X | | | | | X |

EXPLANATIONS

Physical parameters

Runoff: "Curve number" after US Soil Cons. Service
Soil: Plant available water
Aquifer: Transmissivity, specific yield

Management Alternatives

A: Only dryland agriculture in the entire system
B: A plus terraces with 10 cm surface storage
C: A plus terraces with 30 cm surface storage
D: B plus "farm pond"

Figure 5.3: Schedule of Model Runs (scheme)

Figure 5.3 provides an indication of the necessary model runs. For the test-rainfall-regime Aurepalle more runs were executed to become familiar with the mechanisms and behaviour of the model.

5.2.5. Evaluation of Management Alternatives

The model generates an output file for each combination of environment and management alternative. The most important outputs are the surface outflow and the ground water discharge from the system, the evapotranspiration, and the areas of irrigated and rainfed crops. These parameters provide the inputs for a cost benefit analysis which forms the basis for evaluation of the various management alternatives of each environment. For the cost benefit analysis the parameters surface outflow, ground water discharge and evapotranspiration are converted into monetary parameters by employing water-yield functions.

5.2.6. Type of Model

The model can be characterised as a discrete, physical, semi-distributed, continous simulation model. "Discrete" refers to the time step of one day and "physical" to the parameters which have mostly physical significance and can be measured in the field. The model is called semi-distributed, because it does not possess the complexity of a finite element model but is distributed in different land use units and therefore not a lumped model. The attribute "continous" was assigned since the model simulates the water balance not only for a single rainfall-runoff event but continously for several years. Below the model is referred to as "APPSMOD" (Agronomically Productive Percolation System Model). A flow chart of APPSMOD is presented in Appendix X.

5.3. Input Data

The entire data input set is read from three files. One file provides general input information including information on the system and its components as well as all hydrological, soil, crop and agro-economical data. A second input file supplies the input data for the ground water model and the third one provides the daily rainfall which is read in a daily loop.

For the components of APPSMOD the data requirements are as follows:

First of all the dimensions of the system, i.e., length and width, have to be specified.

The water input to the model is daily rainfall and the climatic input is represented by average weekly pan class A data. The pan data is interpolated from monthly long term means. This input data combination was chosen because daily rainfall and pan evaporation data are generally available in semi-arid India.

For the potential evapotranspiration submodel the above mentioned values of pan class A evaporation and a monthly changing pan coefficient $k_{pan}$ are required.

The dryland model requires data on the extent of the dryland zone. The infiltration and runoff characteristics as represented by the SCS curve number, the maximum soil moisture holding capacity of two soil layers, average monthly light interception factors of the crops grown, as well as monthly figures of the fraction of water which is available to the growing roots of plants.

The elevation of the terraces above the reference plane, the area, the hydraulic conductivity of the terrace soil as well as the maximum surface storage and the curve number have to be supplied to the wetland model.

For the tank or farm pond model the elevation of the pond, its capacity and depth, the slopes of the bunds as well as the average percolation plus seepage rate are needed. Furthermore, monthly coefficients which relate the pan class A evaporation to lake evaporation have to be provided.

For the ground water model the number of nodes, their distances in the X- and the Y-direction and the definition of the nodes as dryland, wetland, farm pond or well nodes have to be specified. In addition the matrix of initial and maximum ground water levels is to be established. Further inputs are the internal time step, the values of specific yield and transmissivity and the boundary conditions.

The data needed in the Agro-economical component comprises data for the crop models, the farmers decision model and the cost benefit analysis. For the crop models the plant available water for all crops, the soil moisture at saturation for the rice models, the planting or puddling dates, the length of the growing seasons and the end dates and yield response factors of all growth stages of all crops have to be specified. The inputs to the farmers decision model are as follows:

- a list of crops suitable for the study region,
- a schedule of possible planting dates,
- the mean rainfall in the growing seasons of the respective crops,
- their seasonal consumptive and total water use,
- the attitude of the farmer to risk expressed in a risk factor,

and

- a factor which determines the extent of use of the ground water resources in the dry season.

For the cost benefit analysis, the interest rate, the value of the agricultural inputs for all crops, the maximum yields, the farm gate prices and the value of the by-products are required. Furthermore the investment, maintenance, operation and capital costs need to be specified. Additional inputs are the specific benefits of surface and ground water leaving the system.

Apart from all the above described external inputs, most of the submodels need further inputs which are determined by the model internally. These inputs are treated in the following chapters, where all model components and their interactions are described in detail.

A complete list of all inputs required by the model is presented in Appendix U.

## 5.4. Description of Model Components

Apart from subroutines which handle the input of data and output of results, the APPSMOD consists of 6 components:

- the weather component
- the dryland component
- the wetland component
- the ground water component
- the farm pond component, and
- the agro-economical component

In the weather component the rainfall and monthly pan class A evaporation is read from a file and the latter is converted into daily potential evapotranspiration.

In the dryland component the soil water balance in the catchment is simulated. The computations include generation of runoff, the infiltration process, the movement of water in the soil and the determination of actual evapotranspiration and deep percolation.

In the wetland component, in principle, the same processes as in the dryland component are modelled. The differences lie in the modelling of the surface storage, the terrace overflow, the evaporation from the waterspread area and the infiltration depending on the hydraulic conductivity of the soil and the depth of submergence.

The ground water component simulates the water table fluctuations and the ground water discharge from the system. These factors are in turn influenced by the ground water recharge from wetlands, drylands and the farm pond, the ground water abstraction through the well and of course the aquifer properties and boundary conditions.

In the farm pond component the change of water level and storage, the inflow, overflow and irrigation outflow as well as the percolation and evaporation losses are modelled.

The agro-economical component simulates the area to be cultivated in each season and the growth and yields of crops. It also computes costs and benefits of the system for the calculation period.

A more detailed description of the different model components is presented below.

### 5.4.1. Weather Component

Naturally the performance of an APPS heavily depends on the weather conditions in the area where it is constructed. For example high rainfall to a certain extent increases the ground water recharge from the terraces. Less water has to be pumped from the aquifer and thus more ground water is discharged from the system for further use in lower lying areas. Higher yields from the system can be expected as long as the rainfall does not fall to a level where crop production is adversely affected. Variation of the other climatological parameters such as temperature, humidity, solar radiation and wind speed also significantly influences the water balance and agricultural production from an APPS.

The objective of the weather component is to generate values of potential evapotranspiration, which can be used in the dryland and wetland components to determine actual evapotranspiration. It is also employed in the farm pond component to determine actual evaporation. Several approaches are possible and their selection mainly depends on the available input data. To facilitate the application of the model it would be advantageous to use only easily obtainable input data. In many hydrological and agro-economical models it has been considered sufficient to use rainfall and evapotranspiration as the main climatological inputs. Such a simple approach certainly must have an effect on the significance of the simulated result especially when as mentioned above, only long term monthly means of pan class A evaporation are used.

In the semi-arid tropics large differences in important environmental factors can be observed. The monsoon and therefore the distribution of rainfall is the dominant factor. It influences to varying degrees solar radiation, air and soil temperatures, and the saturation vapor pressure deficit of the atmosphere [230]. Hence, it is apparent that the high variability of monsoon rainfall has a strong impact on the evapotranspiration and of course on pan class A evaporation.

Whereas the fluctuations in yearly totals of pan evaporation are very small with a coefficient of variation $C_V$= 3.2 % , seasonal fluctuations for the period from June to August present a coefficient of variation of about 11 % . The standard deviation amounts to 68.5 mm (ICRISAT Meteorological Station). The high variability of monthly pan class A evaporation is illustrated in Figure 5.4.

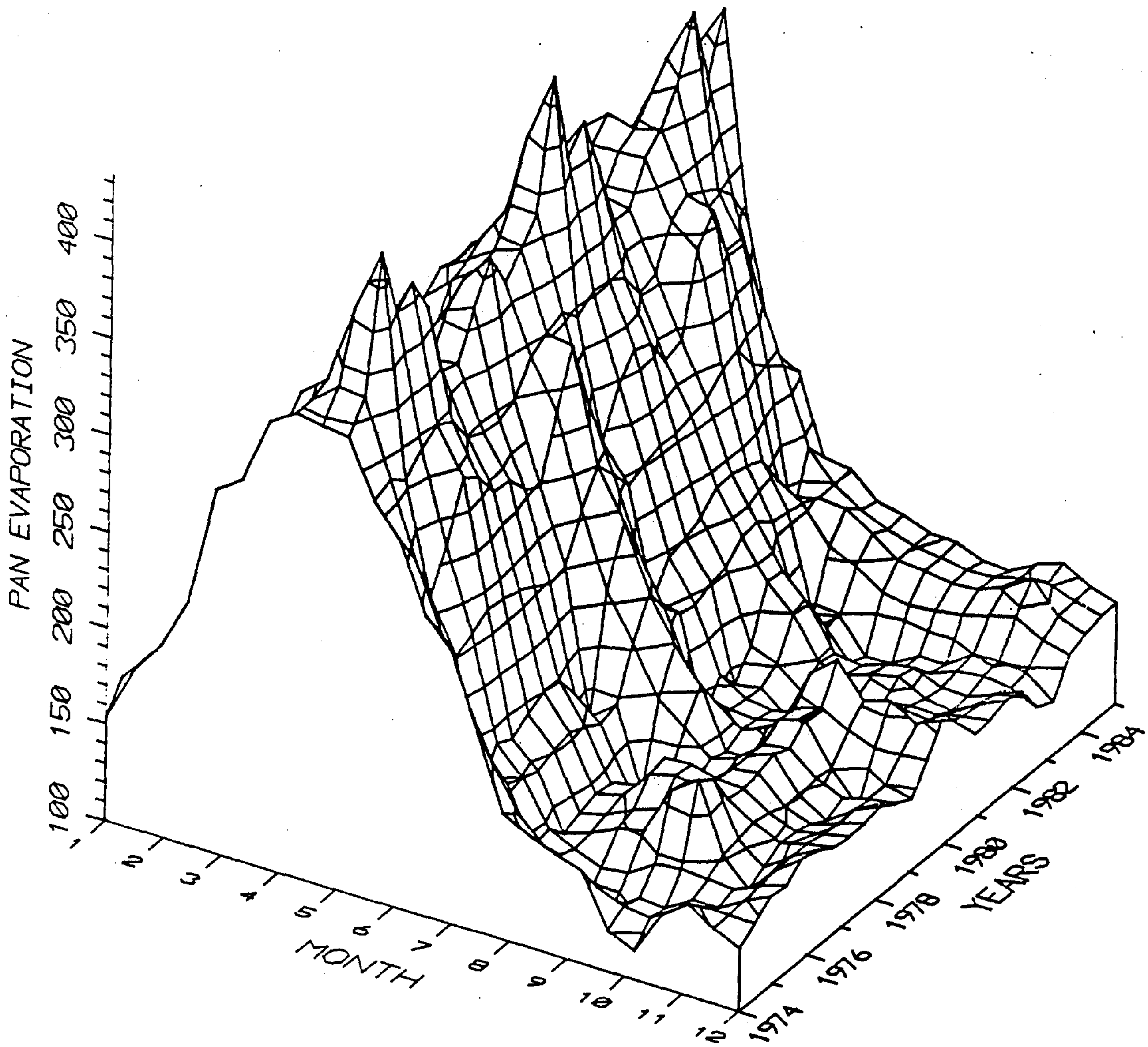



Figure 5.4: Distribution of Monthly Average Pan Class A Evaporation over the Year and between Years (mm/month).

In July the range of the monthly total of pan class A evaporation (PCAE) was found to vary between years from 240.7 mm/month down to 139.7 mm/month, the long term mean being 187.8 mm/month, the standard deviation 32.1 mm/month and the coefficient of variation being 17.1 % . If the monthly long term mean is used in the model then large errors can occur in the simulation of the soil water balance and especially in the simulation of the ground water recharge, which is in the order of the standard deviation of the mean monthly pan class A value. This value is in turn fairly close to the potential evapotranspiration in paddy fields [216]. Therefore it is necessary to improve the simulation of pan class A evaporation.

As a first measure the constant monthly values are converted into weekly constant values by fitting several straight lines to the yearly distribution (Figure 5.5). This results in a much more realistic simulation of the pan class A evaporation over the year.

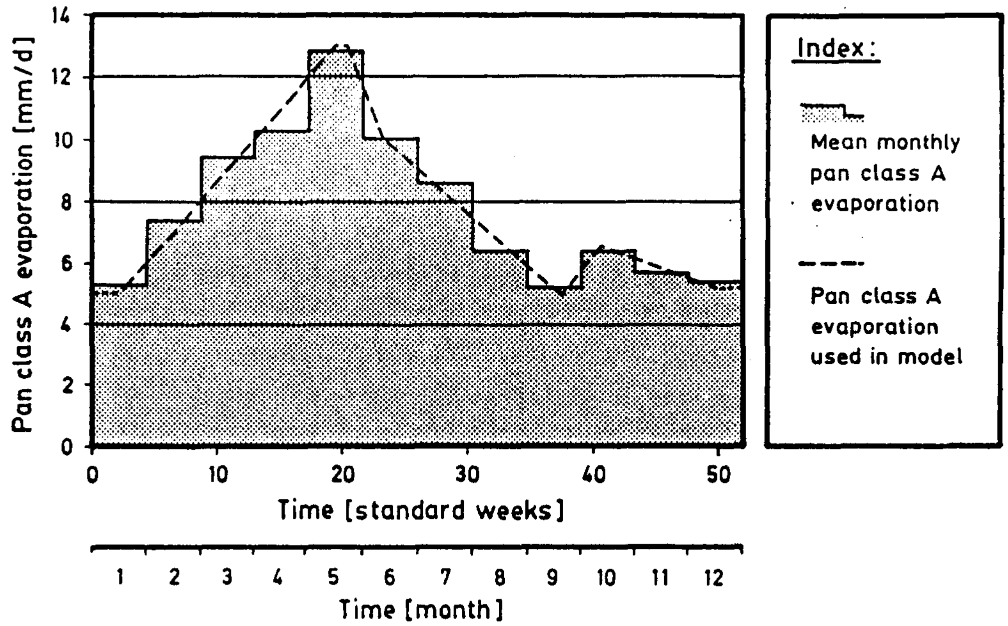



Figure 5.5: Mean Monthly Pan Class A Evaporation and Derived Mean Weekly Pan Class A Evaporation used in the Model for Aurepalle.

Other ways to improve the simulation of pan class A evaporation ($E_{pan}$) are:

- reduction of $E_{pan}$ on rainy days
- reduction of $E_{pan}$ depending on rainfall history
- correlation between rainfall history and the ratio of actual $E_{pan}$ and mean weekly $E_{pan}$.

Reduction of $E_{pan}$ on rainy days:

If in a model a monthly long term mean of $E_{pan}$ is used, it is obvious that on a day with heavy rainfall the $E_{pan}$ is overestimated. If there are more rainy days than the statistically average number in this month, then the actual $E_{pan}$ during this whole month is overestimated. Therefore one may consider to derive a $E_{pan}$ reduction factor for rainy days. To be consistent with the monthly long term mean, the overall reduction due to reduction on rainy days must be compensated by an increase of the long term mean value.

The necessary increase depends on the average number of rainy days in the particular month. When such a correction procedure is applied, the increased long term monthly $E_{pan}$ will be reduced in a month with less than average rainy days to an actual value which is still above the statistically correct long term mean. In months with more than the average number of rainy days the actual monthly value will be lower than the long term mean. In such a way the simulation of $E_{pan}$ could be improved and hence brought closer to the actual value, when only long term means of $E_{pan}$ are available. However, the above considerations are only valid provided that a close relationship between rainfall and $E_{pan}$ exists.

The choice of a reduction factor could be based on theoretical or empirical investigations. A comparison of rainfall and $E_{pan}$ data of the Aurepalle and ICRISAT weather records revealed that selection of a reduction factor was problematic, since the ratio of actual to average $E_{pan}$ varied on rainy days between 0.1 and 0.9. The reduction factor appeared to be influenced by the amount, time and daily distribution of rainfall, and the time of the year. For example the reduction of $E_{pan}$ would have to be lower in the monsoon because of higher humidity, higher cloud cover and fewer hours of sunshine. Furthermore on days after a rainfall event lower $E_{pan}$ rates were observed. A thunderstorm occurring in the late evening often had little effect on the $E_{pan}$ of the same day but a significant effect on the $E_{pan}$ of the following day.

Reduction of $E_{pan}$ depending on rainfall history:
A more reasonable reduction factor can be chosen when the amount of rainfall and the time of occurrence of the precipitation in relation to the day for which the $E_{pan}$ is to be determined are taken into account. From an analysis of Aurepalle and ICRISAT pan evaporation and rainfall data the following algorithm (Version 1) was derived:

$f_{red}(n) = 1.0$
If $P(n) > 60.0$ then $f_{red}(n) = 0.20$ else
If $P(n-1) > 40.0$ then $f_{red}(n) = 0.36$ else
If $P(n) > 40.0$ then $f_{red}(n) = 0.50$ else
If $P(n-1) > 20.0$ then $f_{red}(n) = 0.56$ else
If $P(n-2) > 40.0$ then $f_{red}(n) = 0.80$ else
If $P(n) > 20.0$ then $f_{red}(n) = 0.80$ else
If $P(n-1) > 2.5$ then $f_{red}(n) = 0.90$ else
If $P(n) > 2.5$ then $f_{red}(n) = 0.90$

(beginning from the top the algorithm is left as soon as one condition is satisfied)

where:

| | | |
|---|---|---|
| $P(n)$ | = Precipitation on day n | [mm] |
| $P(n-1)$ | = Precipitation on previous day | [mm] |
| $P(n-2)$ | = Precipitation on day before previous day | [mm] |
| $f_{red}(n)$ | = Pan evaporation reduction factor on day n | [-] |

Correlation between rainfall history and the ratio of actual $E_{pan}$ and mean weekly $E_{pan}$:

Another possibility to simulate actual $E_{pan}$ is to determine the correlation between the rainfall history expressed through the antecedent rainfall index and the normalized $E_{pan}$ which is defined as follows:

$$E_{pan,norm} = \frac{E_{pan,act}}{E_{pan,ltm}} \tag{5.0}$$

where:

$E_{pan,norm}$ = Normalized pan class A evaporation [mm/mm]
$E_{pan,act}$ = Actual $E_{pan}$ [mm/d]
$E_{pan,ltm}$ = Daily value of long term mean $E_{pan}$ for a certain period [mm/d]

The correlation equation is of the form:

$$\frac{E_{pan,act}}{E_{pan,ltm}} = a + b \cdot P_{ind} \qquad (5.1)$$

with:

$$P_{ind} = \sum_{n=0}^{n=n_{max}} P(n) \cdot f_{ind}^{(n-1)} \qquad (5.2)$$

where:

$P_{ind}$ = Rainfall index [mm]
$P(n)$ = Precipitation on day n [mm]
$n$ = Day [d]
$n_{max}$ = Period of days prior to day n for which rainfall index is computed [d]
$f_{ind}$ = Precipitation Reduction factor [-]

A correlation of a similar type is used in the Penman equation where solar radiation and the ratio of actual to maximum sunshine hours are correlated.

For the correlation a separate programme was developed which calculates the rainfall index and the normalized pan class A evaporation, based on the daily rainfall and $E_{pan}$ data of the Aurepalle weather record established during the data collection period from May 1985 to December 1986. In this programme the coefficients a,b and the correlation coefficient R were computed according to standard procedures [123]. The correlation proved to be between R= 0.4 and R= 0.7. The index periods $n_{max}$ and the reduction factors $f_{ind}$ were varied between 30 and 3 and 0.95 and 0.5, respectively, in order to improve the correlation. The best results were obtained with $n_{max}$ around 15 and a reduction factor of around 0.75. In order to take into account the dependency on the time of the year, correlations were determined for short periods of time. Due to the small sample of rainfall events within some of these periods the corresponding coefficients a and b appeared to be out of range. Therefore, such values were corrected to be consistent with the values of neighbouring periods. The final algorithm (Version 2) is given below:

if $P_{ind} > 70$ then $P_{ind} = 70$

$f_{red}:=1;$

if ( (week >= 1 ) and (week < 17) )
then $f_{red} = 1.01 - 0.020 \cdot P_{ind}$

or else if week $< 22$ then $f_{red} = 1.09 - 0.038 \cdot P_{ind}$
or else if week $< 25$ then $f_{red} = 1.18 - 0.033 \cdot P_{ind}$
or else if week $< 28$ then $f_{red} = 1.32 - 0.033 \cdot P_{ind}$
or else if week $< 31$ then $f_{red} = 1.38 - 0.033 \cdot P_{ind}$
or else if week $< 36$ then $f_{red} = 1.32 - 0.025 \cdot P_{ind}$
or else if week $< 40$ then $f_{red} = 1.27 - 0.008 \cdot P_{ind}$
or else if week $< 44$ then $f_{red} = 1.12 - 0.009 \cdot P_{ind}$
or else if week $< 48$ then $f_{red} = 1.06 - 0.028 \cdot P_{ind}$
or else if week $<=52$ then $f_{red} = 1.12 - 0.019 \cdot P_{ind}$

For verification pan class A evaporation was simulated for the measuring period from May 1985 to December 1986 by employing both algorithms. The area of deviation between the actual values and simulated values of $E_{pan}$ were calculated using both methods. The same was performed for the long term monthly $E_{pan}$ values. However, an initial visual assessment already showed that $E_{pan}$ simulated with the correlation method (Version 2) seemed to follow the cycle of the actual pan class A evaporation more closely than the $E_{pan}$ simulated with the first method (Version 1), which in turn did not prove to be better than the long term averages (Figure 5.6). Thus, the rainfall index method was adopted in the model.

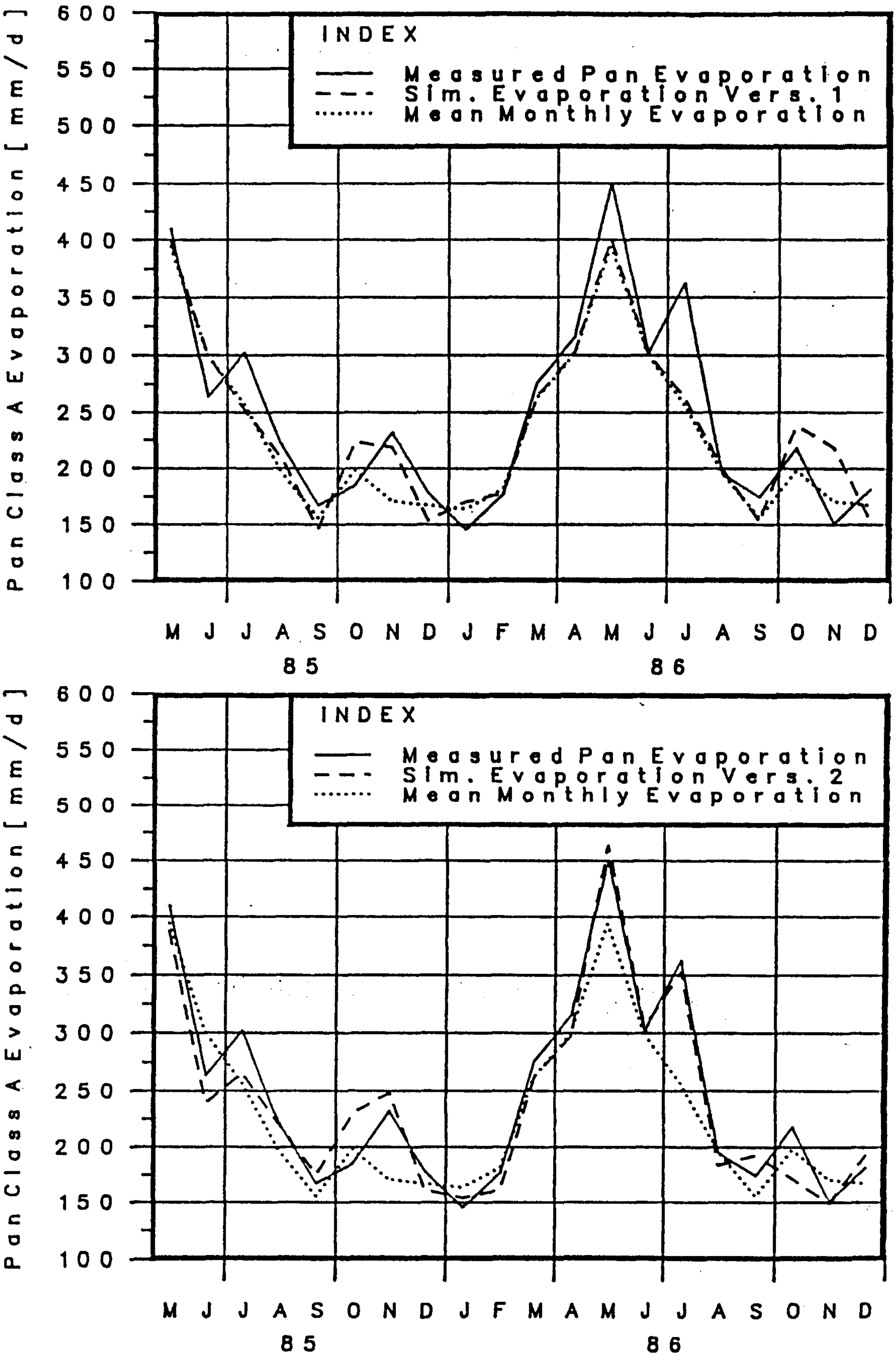



Figure 5.6: Comparison between Simulated Monthly, Monthly Long Term Means of $E_{pan}$ and Measured $E_{pan}$

The selected approach is considered to be a good compromise between easy applicability of the model due to the limited input requirements and the accuracy of prediction. The main advantage of the algorithm is that on using the model for an area with higher or lower rainfall the $E_{pan}$ is automatically adjusted to the new conditions depending on the rainfall history, without the need to supply a new corresponding weather data set. However, the automatic adaptation of the $E_{pan}$ only yields proper results as long as the amount and pattern of rainfall does not deviate too much from the Aurepalle rainfall distribution.

When detailed long term weather data is available it is certainly preferable to use such data rather than the selected simulation method. Only little modifications to the model are necessary to calculate potential ET on a daily or weekly basis by using an appropriate ET-equation such as the Penman formula [62], Priestly-Taylor equation [180] etc.

In the model the simulation of $E_{pan}$ and potential evapotranspiration follows the following sequence:

1. reading daily rainfall
2. calulation of rainfall index
3. calculation of daily value of weekly $E_{pan}$
4. selecting correlation and computation of $E_{pan,norm}$
5. multiplication of $E_{pan,norm}$ with $E_{pan,ltm}$ to obtain $E_{pan,act}$
6. computation of potential evapotranspiration using Equation 5.3.

$$ET_{pot} = k_{pan} \cdot E_{pan} \tag{5.3}$$

where:

| | | | |
|---|---|---|---|
| $ET_{pot}$ | = | potential evapotranspiration | [mm] |
| $E_{pan}$ | = | pan class A evaporation | [mm] |
| $k_{pan}$ | = | pan coefficient | [-] |

The parameter still unknown in this equation is the pan coefficient:

Long term weekly pan class A data were calculated from the 1.5 years Aurepalle weather station data, and were corrected for the long term trend by comparing the Aurepalle and ICRISAT records. Monthly long term potential evapotranspiration was computed by adopting the Penman equation. The ratio of Penman evapotranspiration and pan class A evaporation yielded the monthly pan coefficients. From these values weekly pan cofficents have been derived.

Since pan coefficients are influenced, among several other factors, by the relative humidity pan coefficients were increased on rainy days by 0.1 . The value of 0.1 was estimated by considering daily values of relative humidity and pan evaporation measured at Aurepalle and calculated values of potential ET (Penman). A table for the selection of pan coefficients published in [109] was also used (See Appendix Z). For compensation of this increase of the coefficient the base value of monthly pan coefficients was reduced depending on the average number of rainy days in the respective month (Figure 5.7).

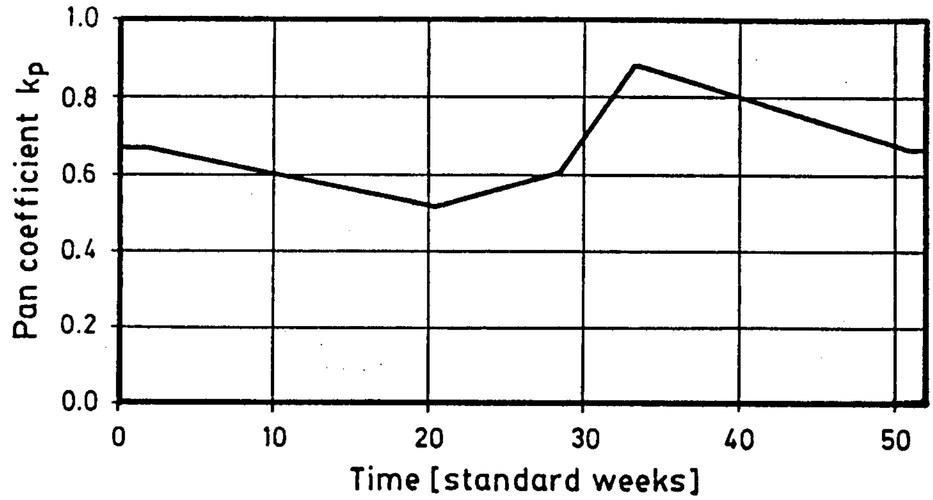



Figure 5.7: Base Value of Pan Coefficient over Time as used in APPSMOD

### 5.4.2. Dryland Component

#### 5.4.2.1. Interception

A considerable proportion of natural precipitation is intercepted by the vegetation foliage. Most of the intercepted water does not enter the soil or vegetation but is evaporated directly; evaporation of this intercepted water is controlled by meteorological factors. Overall interception losses are also dependent on the rainfall intensity, distribution and canopy storage. In forests the annual interception may be 10 to 40 % of the annual precipitation and is therefore certainly of hydrological significance. The argument that there is not much difference between the evaporation that occurs from foliage or from the soil is certainly not valid for forests. Several studies show that the rate of evaporation of intercepted water may be several times higher than that from a dry canopy even when the supply of soil water does not limit transpiration [215]. Experimental data confirm that the ratio of evaporation from a wet canopy and unstressed evapotranspiration ranges between 5 to 2 for forests and is at unity for short grasses as well as other short agricultural crops. Irrigated rice can certainly be grouped in the latter category because evapotranspiration is in most of the cases unstressed and rice grows in standing water. In the semi-arid environment in which the dryland crops sorghum, millet and castor are grown plant densities, plant height and leaf area indexes are often small. For these reasons and the fact that the number of rainy days is very low in the study region, storage of water on the foliage is limited. Therefore in this model interception is neglected.

#### 5.4.2.2. Runoff

The runoff computation is based on the US Soil Conservation Service (SCS) curve number method [248]. It is probably the most commonly used technique to predict runoff volumes using daily totals of rainfall [175]. The curve number method was developed based on measured rainfall-runoff-events in a large number of small watersheds in the USA. Therefore it can be used with some confidence for determination of runoff in ungauged watersheds. A modified version of the curve number method has been proposed in [53]. It has been adapted for semi-arid conditions in India by Pathak et al [175]. Runoff is calculated by employing Equation 5.4:

$$Q = ((P - 0.2 \cdot S)^2) / (P + 0.8 \cdot S) \qquad (5.4)$$

where:

| | | | |
|---|---|---|---|
| Q | = | Runoff | [mm] |
| P | = | Rainfall | [mm] |
| S | = | Retention parameter | [mm] |

and:

$$S = 25.4 \cdot ((1000 / CN) - 10)$$

with:

CN = Curve number
CN = f (Soil, land use, antecedent soil moisture)

Equation 5.4 is derived by starting with the equation:

$$(P - Q) / S = Q / P \qquad (5.5)$$

Where (P-Q)/S is visualized as the ratio of actual to potential difference between P and Q, and Q/P is visualized as the ratio of actual to potential runoff. Solving for Q leads to:

$$Q = P^2 / (P + S) \qquad (5.6)$$

Equation 5.6 is useful under conditions where there is a possibility of runoff whenever there is rainfall. However in most of the cases runoff occurs only after a certain threshold value is exceeded, for example due to high initial infiltration and filling of a depression storage. Therefore, an initial abstraction $I_a$ should be considered. By incorporating $I_a$ Equation 5.6 then becomes:

$$Q = ((P - I_a)^2) / (P - I_a + S) \qquad (5.7)$$

Since S includes $I_a$, an empirical relation derived from watersheds in the USA can simplify Equation 5.7:

This relation being: $$I_a = 0.2 \cdot S \qquad (5.8)$$

Substituting $0.2 \cdot S$ for $I_a$ in Equation 5.7 yields Equation 5.4.

The curve number CN is normally taken from tables. The value has to be chosen depending on the antecedent soil moisture condition (Appendix Y, Table Y.3) and the hydrological soil cover complex which includes the land use, the land treatment, the hydrological infiltration condition and the hydrological soil group (Appendix Y, Tables Y.1 and Y.2). The dependency of the runoff on the curve number and precipitation according to Equation 5.4 is illustrated in Figure 5.8.

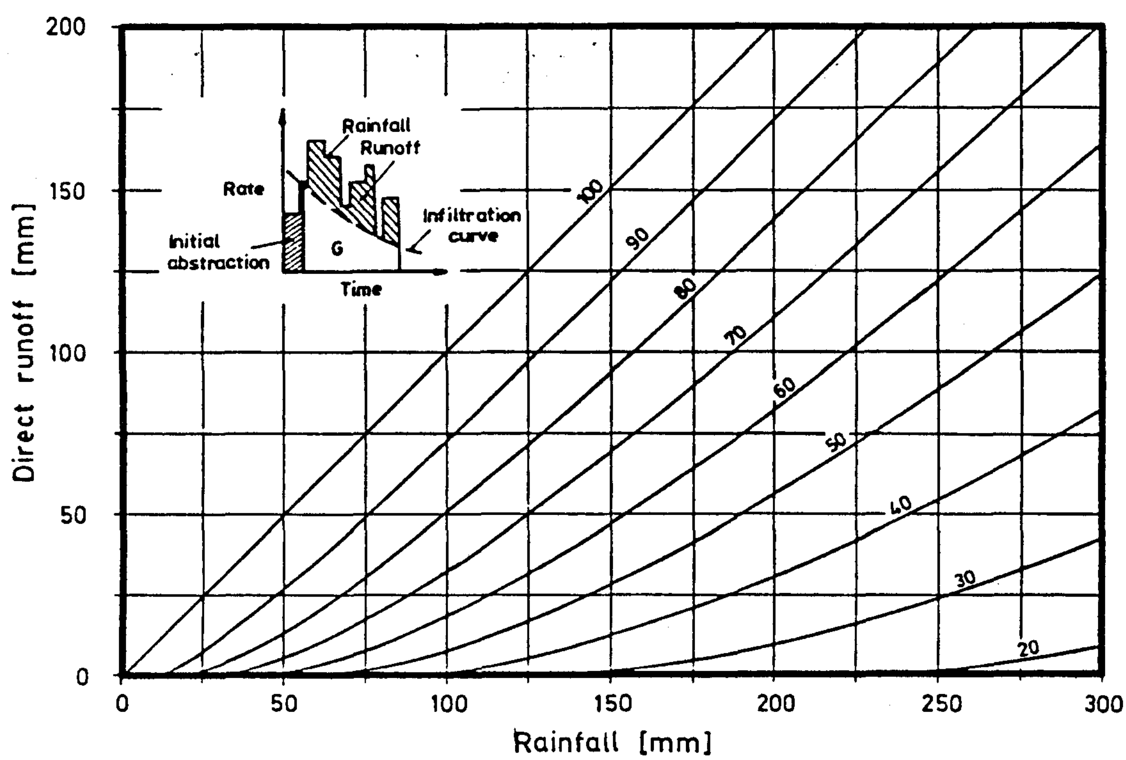



Figure 5.8: US Soil Conservation Curve Number Method [248].

In the original procedure a curve number is chosen for a medium soil moisture condition. In case of wet or dry antecedent soil moisture conditions the "dry" or "wet" value corresponding to the normal value is then selected from Table Y.3, Appendix Y. The range of the curve numbers between the two extremes is also indicated in this table. The difference is maximum around curve numbers of about 50 and zero for the curve numbers 0 and 100. This shows that the influence of the soil moisture status is greatest for average soil and land use conditions but negligible for extreme conditions, which is quite plausible because the runoff from a wet or dry gravel or a wet or dry metal road should be nearly the same.

In order to computerize the procedure it was necessary to alter the model slightly. Following the idea of Pathak et al [175] the antecedent soil moisture condition is simulated in APPSMOD as the soil moisture in the upper layer of the catchment soil. The procedure adopted in APPSMOD is as follows:

First a curve number matching the characteristics of the environment to be studied is selected from Table Y.1, Appendix Y for a medium soil moisture condition. In the model the curve number is then adjusted according to the degree of filling of the storage of the uppermost soil layer taking into account the varying sensitivity of the curve number to the antecedent soil moisture at different curve number levels. For this purpose the range in curve numbers between condition I and III was plotted against the curve numbers of soil moisture condition II and third order parabolas were fitted (Figure 5.9).

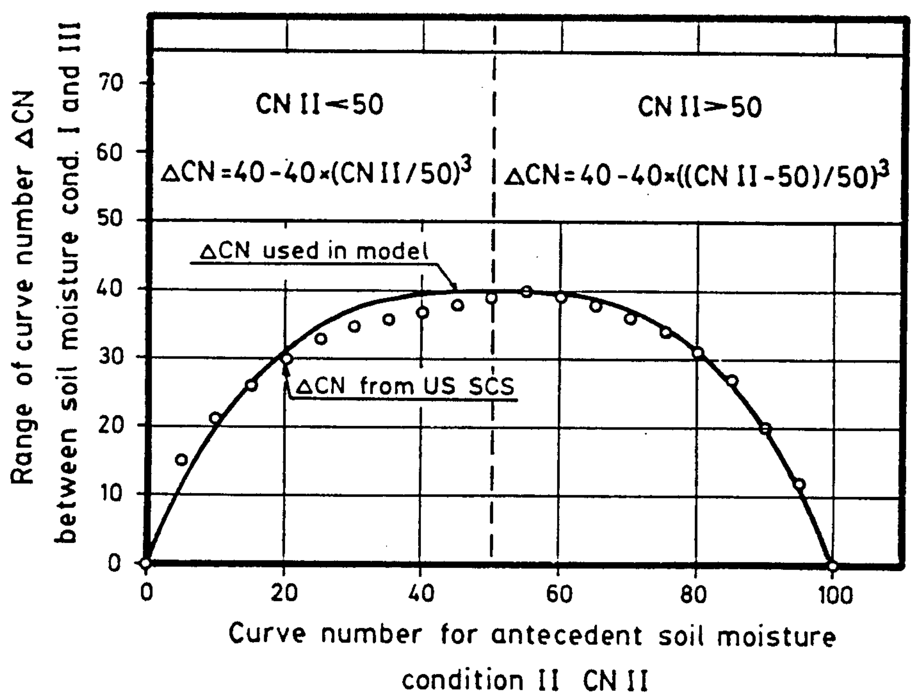



Figure 5.9: Soil Moisture Dependent Range of Curve Number

Depending on the curve number of condition II the potential range of curve numbers can be calculated. Then from the potential range the actual curve number adjustment is computed by multiplication of the potential range with the ratio of actual to maximum soil moisture (Equation 5.9).

$$CN(SM_{act}) = CN(SMCII) - 0.5 \cdot \Delta CN + \frac{\Delta CN \cdot SM_{act}}{SM_{max}} \qquad (5.9)$$

Within the scope of this thesis it is not intended to develop a new infiltration model, but to select a suitable model from the literature and adapt it to the semi-arid conditions of peninsular India. Since APPSMOD operates with a daily time step, an infiltration model based on the input of daily rainfall had to be selected. Also, since determination of infiltration and runoff are closely linked, an infiltration model had to be chosen that was compatible with the runoff model.

The SCS runoff model considers an initial infiltration loss and infiltration rate depending on the cumulative infiltration, in a similar manner to the Green-Ampt model. Therefore, it is a simple and physically justifiable approach to simulate the infiltration as the difference between the daily precipitation and the daily runoff.

#### 5.4.2.4. Soil Moisture Movement

The vast number of existing models simulating the movement of water in the soil differ greatly in their structure and objectives. Apart from the data requirements, the main criteria for classification is the complexity of the mathematical interpretation of the physical processes. Simulation models are also classified into short-term and long term models, depending on the period of simulation. Models are considered long-term models when the hydrological processes are simulated continously for longer periods, in contrast to short-term models, where only single rainfall-runoff-infiltration events are reconstructed.

Depending on the approach to which the movement of water in the unsaturated soil zone is described, models are commonly grouped into physical or hydrological models:

Physical models use the general flow equation for the unsaturated soil zone [135], [35]:

$$\frac{\delta\theta}{\delta t} = \left( k(\theta) \left( \frac{\delta\psi}{\delta z} - 1 \right) \right) \qquad (5.10)$$

in periods with withdrawl of water by plants an additional volumetric sink term QS (z,t) has to be added to equation 5.10:

$$\frac{\delta\theta}{\delta t} = \left( k(\theta) \left( \frac{\delta\psi}{\delta z} - 1 \right) \right) - QS\,(z,t) \qquad (5.11)$$

where:

| | | | |
|---|---|---|---|
| $CN(SM_{act})$ | = | Curve number for the actual soil moisture condition | [-] |
| CN(SMCII) | = | Curve number for soil moisture condition II | [-] |
| Δ CN | = | Range of curve number as per Figure 5.9 | [-] |
| $SM_{act}$ | = | Actual soil moisture in first soil layer of catchment soil | [mm] |
| $SM_{max}$ | = | Soil moisture holding capacity of first soil layer | [mm] |

### 5.4.2.3. Infiltration

Infiltration is defined as the entry of water from the surface into the soil profile. An understanding of the infiltration process and the factors affecting it is important in the determination of surface runoff as well as the subsurface water movement. The factors which influence infiltration are the soil properties the most important of which is the hydraulic conductivity of the soil, surface sealing and crusting, movement and entrapment of air within the soil [65], the initial soil water content and finally the rate of water application. Different soil strata, large channels formed by roots, cracking due to shrinkage and worm holes also have a great effect on infiltration as they provide pathways both for ponded water and an escape route for entrapped air [74].

A lot of research has been carried out in the past on infiltration models and a number of recognized models exist of varying complexity and different input requirements. A review of the models is presented in [74]. They can be divided into:

- Methods to solve the governing differential equations describing the infiltration process such as the Richards equation [195], and

- Approximate methods such as the Kostiakov, Horton, Philip, Holtan, Green-Ampt and Mein-Larson models [74]. In these models an attempt is made to characterize infiltration using simplified concepts which permit the infiltration rate or cumulative infiltration volume to be expressed algebraically in terms of time and certain soil parameters. Although attributed to different physical phenomena, the rapidly decreasing infiltration rate (in case of ponding) during the early part of an infiltration event is the main characteristic reflected in all the above equations [74].

Although the first categorie provides a physically consistent means to quantify infiltration and is extremely valuable in analysing certain effects of various factors on the infiltration process, it has so far been of limited value for production scale applications in modelling watershed hydrology. This is due to the difficulties in obtaining the necessary soil property data and the immense computation times.

where:

| | |
|---|---|
| $\theta$ | = Volumetric soil moisture content |
| t | = Time |
| z | = Depth below surface |
| $\psi$ | = Capillary Potential |
| $k(\theta)$ | = Unsaturated hydraulic conductivity |
| QS | = Sink term to account for ET loss |

Equations 5.10 and 5.11 are second order, non-linear, partial differential equations, which are often referred to as Richards-Equation [135]. Analytical solutions of the above equations do not exist due to the non-linearity of the unsaturated hydraulic conductivity and the capillary potential which are both a function of the soil moisture content (Figure 5.10).

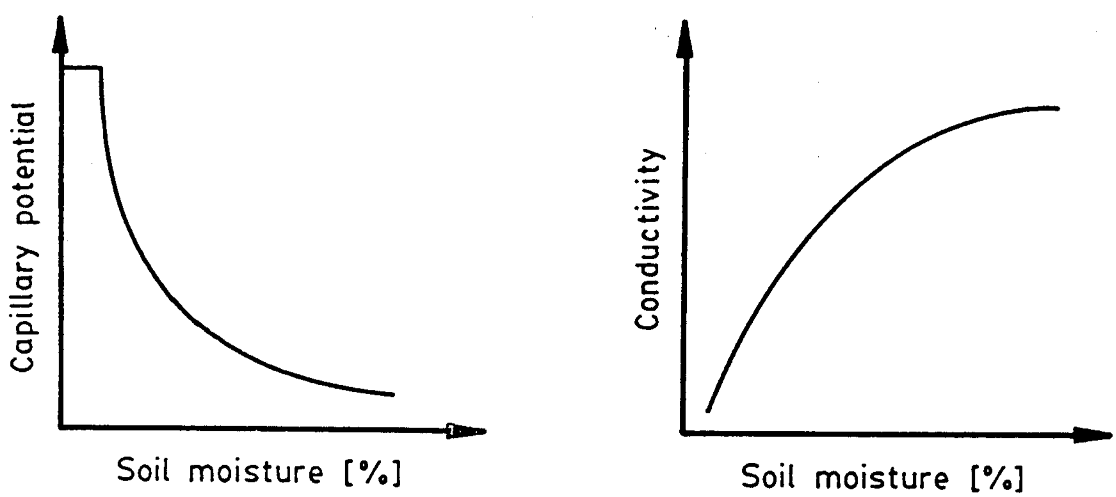



Figure 5.10: Schematic Diagrams of the Relationship between Conductivity, Capillary Potential and Soil Moisture [74].

For physically simplified flow and boundary conditons quasianalytical solutions are possible. However continous hydrological processes under natural conditions with changing meteorological conditions can only be solved by employing numerical solution techniques, such as the Finite Element or Finite Differential methods. Such methods are applicable for a wide range of conditions. Soil layers with different conductivity-soil moisture and capillary potential-soil moisture relationships can be taken into account by dividing the soil profile into separate soil compartments. The choice of the compartment depth and the time step determine, along with the value of the hydraulic conductivity, the convergence and the stability of the solution algorithm. The deviations from the exact solution decrease with decreasing compartment depth and time step. However, for a required number of often more than 100 time steps per day and a compartment depth of around 20 cm, the resulting immense computation time can not be justified within a complex continous watershed model.

Models belonging to this group are described in [262], [195], [135], [58].

The category of models computing the vertical soil water movement (upwards and downwards) by using the one dimensional Darcy equation for unsaturated flow can also be regarded as physical models. The models developed by [202], [192], [107] fall in this group. With time steps between 1 and 4 hours the redistribution of soil moisture between soil layers is computed according to Equation 5.12.

$$q_z = - k\ (\theta) \cdot \frac{\delta H}{\delta z} \tag{5.12}$$

where:

| | | |
|---|---|---|
| $q_z$ | = Flux , or volume of water in z-direction | [m/s] |
| $k(\theta)$ | = Unsaturated hydraulic conductivity | [m/s] |
| H | = Total potential head | [m] |
| H | = h - z | |
| h | = Pressure head | [m] |
| z | = Distance measured positively downwards from surface | [m] |

Hydrological models simulate the water balance of a soil-water-plant continuum with the water balance equation. They need much less input data and computation time. The unsaturated soil zone is divided into layers. Vertical movement of water from layer to layer is assumed only when a layer is filled to field capacity. Then any surplus water is passed into the layer below. Any water which passes beyond the bottom layer is assumed to be lost to deep percolation. The soil layers or storages can be depleted by evapotranspiration as long as the water content in the respective soil layer is above the permanent wilting point. The models described in [36], [3], [197] belong to this categorie.

To select a model from the first categorie would certainly be desirable but is not a viable solution due to time and data constraints within the framework of a three-dimensional watershed model.

For a model of the second group a time step of around 1 hour and consequently hourly rainfall data would be necessary. This would increase the execution time by a factor of 24 compared to the envisaged daily time step and would limit applicability of the model to a few stations where such data is available. In addition for each soil layer the conductivity-soil moisture and capillary potential-soil moisture relationships would be required which are very time consuming to obtain.

Due to the above reasons a hydrological model appears to be the only sensible alternative. The selected soil moisture model consists of two storages which represent the soil moisture holding capacity of two soil layers. The upper soil moisture storage is filled by infiltration. When the infiltration is higher than the available storage in the upper layer the excess flows into the lower layer. If there is not enough capacity in the lower layer, then the surplus is considered as deep percolation or ground water recharge. Upward movement of water is neglected. This can not be considered an unreasonable assumption since upward movement of water in the sandy alfisols encountered in the study area is limited. Whereas the upper soil moisture storage is depleted by evaporation from the soil and transpiration from plants, the lower soil moisture storage is only reduced through transpiration (Figure 5.11).

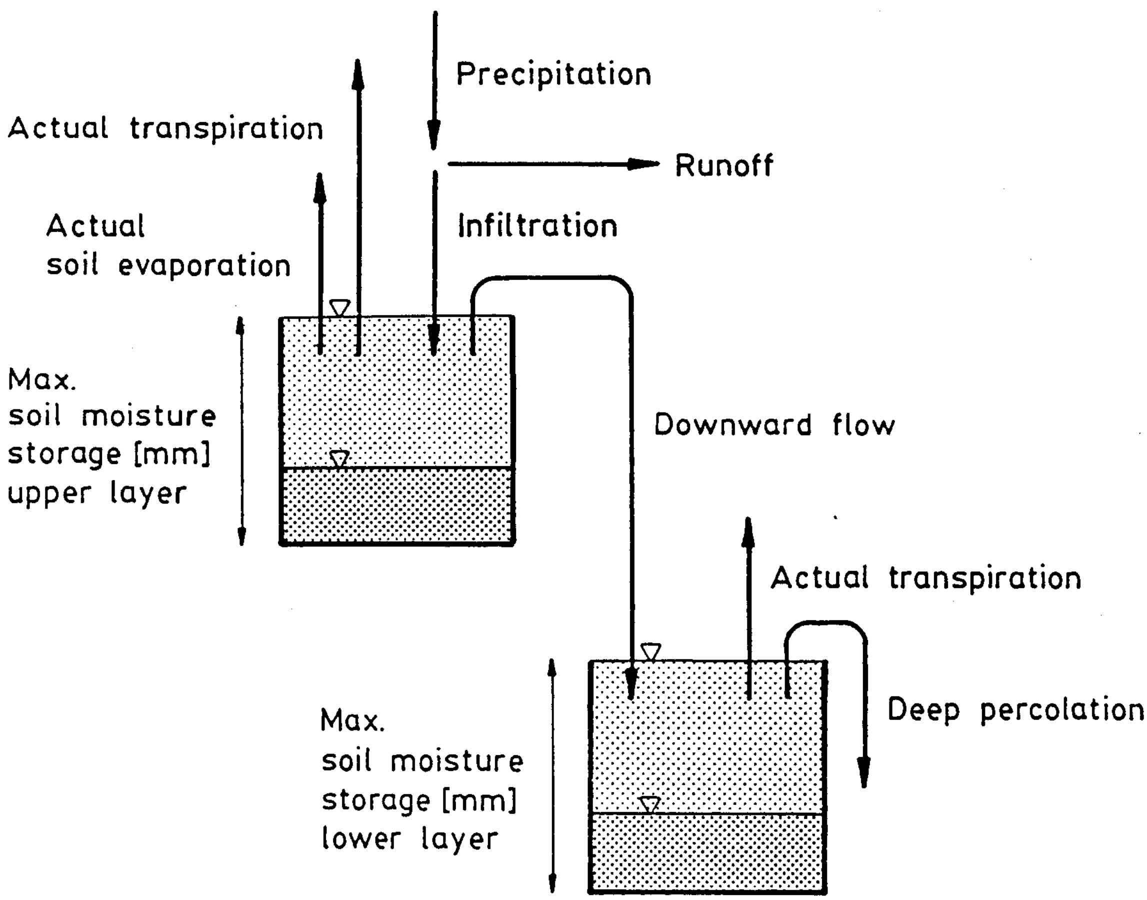



Figure 5.11: Parameters of Dryland Water Balance Model

Despite its simplicity the hydrological approach chosen still has physical significance since the main parameter (the soil moisture holding capacity) can be derived from measurements of field capacity and permanent wilting point for a given soil depth.

### 5.4.2.5. Actual Evapotranspiration

The procedure used to simulate actual evapotranspiration is a simplified version of the ET-model presented in [202] (Figure 5.12).

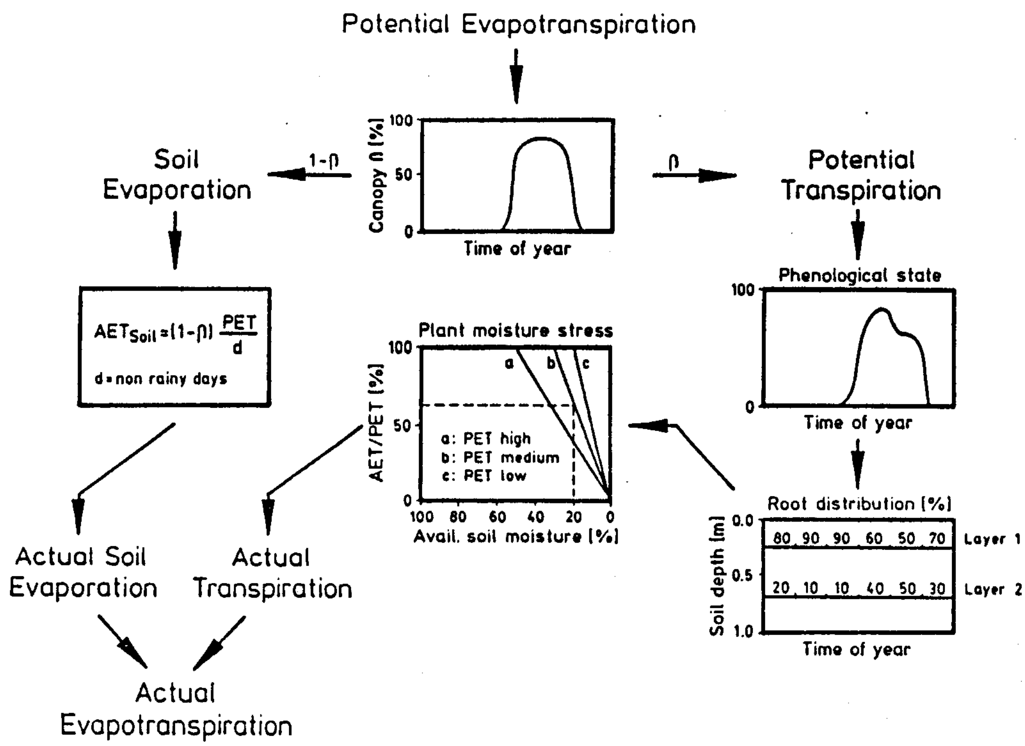



Figure 5.12: Procedure to Compute Actual ET as Used in the Model.

The calculation of actual ET begins with the partitioning of potential evapotranspiration into potential soil evaporation and potential transpiration. Potential transpiration is assumed to be the fractional interception of radiation by the crop canopy ($\beta$) multiplied by potential evapotranspiration:

$$T_{pot} = \beta \cdot ET_{pot} \quad (5.13)$$

Potential soil evaporation is assumed to be the remainder of ET:

$$E_{pot} = ET_{pot} - T_{pot} \quad (5.14)$$

or

$$E_{pot} = (1 - \beta) \cdot ET_{pot} \quad (5.15)$$

The fractional interception is provided as input to the dryland ET model. The distribution of fractional interception or the percentage of crop cover over the year was derived from ICRISAT data [96] for a typical dryland crop in the growing season and an estimate of crop cover in the off-growing season.

Another input to be supplied to the model is the distribution of plant roots over the soil profile during the growing period. This information is required, since the root distribution determines the partitioning of potential transpiration between the soil layers:

$$T_{pot1} = k_{root1} \cdot T_{pot} \quad (5.16)$$

and

$$T_{pot2} = T_{pot} - T_{pot1} \quad (5.17)$$

or

$$T_{pot2} = k_{root2} \cdot T_{pot} \quad (5.18)$$

where:

| | | |
|---|---|---|
| $T_{pot}$ | = Potential transpiration | [mm/d] |
| $T_{pot1}$ | = Potential transpiration in soil layer 1 | [mm/d] |
| $T_{pot2}$ | = Potential transpiration in soil layer 2 | [mm/d] |
| $k_{root1}$ | = Root partitioning factor for soil layer 1 | [-] |
| $k_{root2}$ | = Root partitioning factor for soil layer 2 | [-] |
| ($k_{root2}$ | = 1 - $k_{root1}$) | |

In order to account for withdrawl of water from the soil profile by bushes, trees etc., the root partitioning factor for soil layer 2 was assumed to decline rapidly after the growing season but not to fall below a value of 10 % .

Values of actual evapotranspiration are generally lower and mostly only a fraction of the potential rates. However, in a well watered field with a fully developed crop canopy the actual evapotranspiration can approximate the potential rates. As the level of available soil moisture decreases, actual evapotranspiration will decline [96].

In many models [3], [202], [110] potential (evapo)transpiration is converted into actual (evapo)transpiration by employing the above relationship between the ratio of actual/potential (evapo)transpiration and soil moisture content. Albert [3] reviewed such relationships developed for humid climates. A relationship developed and adapted for semi-arid conditions is given by Shaw in [96]. According to Shaw the value of actual (evapo)transpiration not only depends on the level of available moisture, but also on the atmospheric demand.

A simplified version of Shaws method is used in APPSMOD (Figure 5.12). High, medium and low atmospheric demands are defined as follows:

| | |
|---|---|
| High atmospheric demand: | $ET_{pot} > 10$ mm/d |
| Medium atmospheric demand: | 10 mm/d $> ET_{pot} >$ 5 mm/d |
| Low atmospheric demand: | $ET_{pot} <$ 5 mm/d |

With the help of this diagram actual transpiration is computed in the model for each soil layer.

The conversion of potential soil evaporation into actual soil evaporation is based on a procedure suggested in [223] which was confirmed in experiments carried out at ICRISAT for Alfisols [96]:

$$E_{act} = E_{pot} / t \qquad (5.19)$$

where:

t = time after cessation of rainfall [d]

This empirical approach approximates soil evaporation over three stages. After rainfall part of the water retained in the soil profile will be lost through direct evaporation at the surface at a level that initially approaches the evaporation from a free water surface. After further drying of the soil, evaporation will be controlled by capillary transport which is a much slower process. The third stage would be the extremely slow process of vapor transport through nearly dry soil.

### 5.4.3. Wetland Component

The wetland component of APPSMOD deals with the simulation of the soil water balance of the terraces (run-on area), where three rice crops are grown during pre-monsoon, monsoon and post-monsoon and one irrigated dryland crop in the dry season. Further details on crops, cropping patterns etc., are presented in the section on the agro-economical component of APPSMOD.

The water balance is simulated separately for the three rice crops and the irrigated dryland crop. The routines used for the rice crops are identical. The differences in the routines between the terrace model and that for the irrigated dryland crop are described in chapter 5.4.3.6.

Of particular interest in the different wetland water balance models are the actual evapotranspiration from the crops, the irrigation demand, the overflow or runoff from the terraces and the ground water recharge. The parameters of the wetland water balance component have already been exlained and illustrated in chapter 3.

As far as possible routines similar to the ones used in the dryland component were also adopted in the wetland component of APPSMOD.

For the paddy wetland water balance model a hydrological approach was again selected. The model consists of a surface water storage and a soil water storage. The surface water storage, which can be as high as 100 mm (as found by the author in the investigations on water harvesting in paddy fields), is provided as input to the model. Since the roots of irrigated rice only extend to a shallow depth, one soil storage was assumed to be sufficient. The water holding capacity of this storage represents another input to be supplied to the model.

Some of the water related processes in rice terraces such as evapotranspiration, infiltration and overflow take place simultaneously. Exact solutions of the differential equations describing such simultaneous processes would require a lot of detailed input data and unjustifiable programming. Due to the limitations in computation time and the selected time step of one day it was necessary to employ a simpler approach and simulate the water balance in a sequential manner. Depending on the sequence in which the different parameters of the water balance equation are computed, large differences in results can be obtained. For example if daily ET and daily infiltration are substracted from the surface storage in a paddy field prior to the calculation of overflow, then the overflow will be smaller than if determined before substraction of ET and infiltration. The smaller the selected time step the closer the result will be to the exact solution. As a compromise, an internal time step of 6 hours was chosen. The sequence of processes is simulated in an attempt to follow the sequence of events occurring in nature:

1. Supply of irrigation to the surface water storage (in the morning).
2. Withdrawl of water by evapotranspiration from the soil water storage (during the day).
3. Infiltration of half of the daily value from the surface storage into the soil storage (during the day).
4. If the soil moisture holding capacity of the soil moisture storage is execeeded by infiltration and storage, then the excess water is considered as deep percolation.
5. Inflow to the terraces (runoff from the catchment area) and rain on the terraces, if any, as well as simultaneous infiltration of a quarter of the daily value from the surface storage into the soil storage (evening).
6. Overflow from rice terraces if the surface storage is exceeded.
7. If infiltration and soil moisture storage exceed the soil moisture holding capacity of the soil moisture storage then deep percolation occurs.
8. Infiltration of a quarter of the daily value from the surface storage into the soil storage (night).
9. Deep percolation from the soil moisture storage when infiltration plus actual soil moisture storage exceed the soil moisture holding capacity of the soil profile.

Further details referring to the several subprocesses are presented below.

5.4.3.1. Irrigation Demand and Supply

One of the parameters to be simulated in the wetland submodel is the actual amount of water supplied to the different crops. On one hand this depends on the water requirement of the crops and on the other hand on the water availability. Whereas the water requirement is influenced by the maximum evapotranspiration, the required submergence depth and the water stored in the surface storage and the soil storage of the terrace, the water availability depends on the actual storage of water in the tank and the maximum yield of the dugwell.

In the morning the soil storage is normally at field capacity due to infiltration of the water provided by irrigation the day before. Since the amount of rainfall and inflow generally to be expected in the late afternoon is not known by a farmer at the time when the irrigation is given, the water will be provided in a quantity that ensures the proper growth of the crop. Therefore, the irrigation has to include enough water to cover the maximum evapotranspiration and an additional amount to create the humid environment, which rice requires for good yields. The following set of equations describes the above considerations in quantitive terms:

$$ID_{act} = SD + ET_{max} - h_{surf} \quad (5.20)$$

where:

| | | |
|---|---|---|
| $ID_{act}$ | = Actual irrigation demand | [mm] |
| $SD$ | = Submergence depth | [mm] |
| $ET_{max}$ | = Maximum evapotranspiration (see following chapter) | [mm] |
| $h_{surf}$ | = Surface storage in paddy field | [mm] |

The volume of irrigation then amounts to:

$$IV_{act} = ID_{act} * A_{pad} \cdot 1000 \quad (5.21)$$

where:

| | | |
|---|---|---|
| $IV_{act}$ | = Volume of irrigation demand | [$m^3$] |
| $A_{pad}$ | = Cultivated area of terrace (paddy) | [$m^2$] |

The total water requirement is the sum of the volumes of the irrigation demands for all crops grown.

After determination of the total water requirement the model checks to see whether the actual irrigation demand can be met by tne available water resources. If there is enough water in the farm pond, then the water requirement is met entirely from the farm pond storage. If the model is run without a farm pond or the actual volume of water stored in the farm pond is not sufficient, then the deficit will be covered by well water. Another check is carried out to determine whether the remaining water requirement can be withdrawn from the ground water aquifer. Details on this aspect are given in the section on the ground water component of the model.

The total water requirement or the available fraction of it is distributed between the different crops (actual irrigation supply $IS_{act}$). The algorithm which controls the distribution of water, in case the total water requirement can not be met, is described in the section on the agro-economical component of APPSMOD.

5.4.3.2. Actual Evapotranspiration

Computation of actual evapotranspiration within the wetland component includes the following steps:

1. Determination of maximum evapotranspiration of the crop:

$$ET_{max} = ET_{pot} \cdot k_c(GS) \qquad (5.22)$$

where:

| | | | |
|---|---|---|---|
| $ET_{pot}$ | = | Potential evapotranspiration | [mm] |
| $k_c(GS)$ | = | Crop coefficient as a function of the growth stage | [-] |

The function of the crop coefficient of the growth stage was obtained by comparing Penman evapotranspiration and the lysimeter data collected on the "Gopal Reddy Plot" (chapter 3). To incorporate this function into the model a series of straight lines were fitted to the data and a set of corresponding equations derived, which allow calculation of the crop coefficient for any day of the crop growing season.

2. Actual evapotranspiration is computed by adopting the relationship between the ratio of actual/potential ET and the percentage of plant available water described in chapter 5.4.2.5.

Actual evapotranspiration is assumed to deplete the soil moisture storage only during the two internal time steps during daytime.

5.4.3.3. Infiltration and Deep Percolation

Infiltration and deep percolation take place during all internal time steps (day and night).

Apart from the maximum surface storage and the maximum soil moisture storage the hydraulic conductivity of the terrace soil is the main input to the paddy field infiltration model. As mentioned in chapter 3 the hydraulic conductivity determined in infiltration tests varied between 2 mm/d and several hundred mm/d for the soils encountered in the study area.

Although not explicitly measured in the paddy fields at Aurepalle a dependency of the infiltration rate on the depth of submergence and the depth to the ground water table can be imagined. It is a reasonable assumption that the equations developed for infiltration basins also apply for paddy fields when the submergence depth is significantly higher than the normal 20 to 50 mm. This is the case when water is harvested in paddy fields for recharging the ground water aquifer. Thus the infiltration rate can be derived from Equation 5.23 [30]:

$$k_{pot} = k_{aw} \frac{z_{gw} \cdot h_{surf}}{z_{gw}} \qquad (5.23)$$

where:

| | | | |
|---|---|---|---|
| $k_{pot}$ | = | Potential rate of infiltration | [m/d] |
| $k_{aw}$ | = | Conductivity in air water filled soil (measured in paddy fields with high depth to ground water table) | [m/d] |
| $z_{gw}$ | = | Depth to ground water table | [m] |
| $h_{surf}$ | = | Depth of water in paddy field | [m] |

From the potential daily infiltration rate the infiltration during the internal time step is determined. The depth of water in the paddy field is reduced by the infiltration. When the infiltration is higher than the former depth of water standing in the field, then the actual infiltration is set equal to the former water depth and the water depth is set to zero.

The actual infiltration augments the soil water storage. If the updated soil water storage is higher than the maximum soil water storage then the exceeding portion becomes deep percolation and the soil water storage is set to the maximum level (compare Figure 5.13).

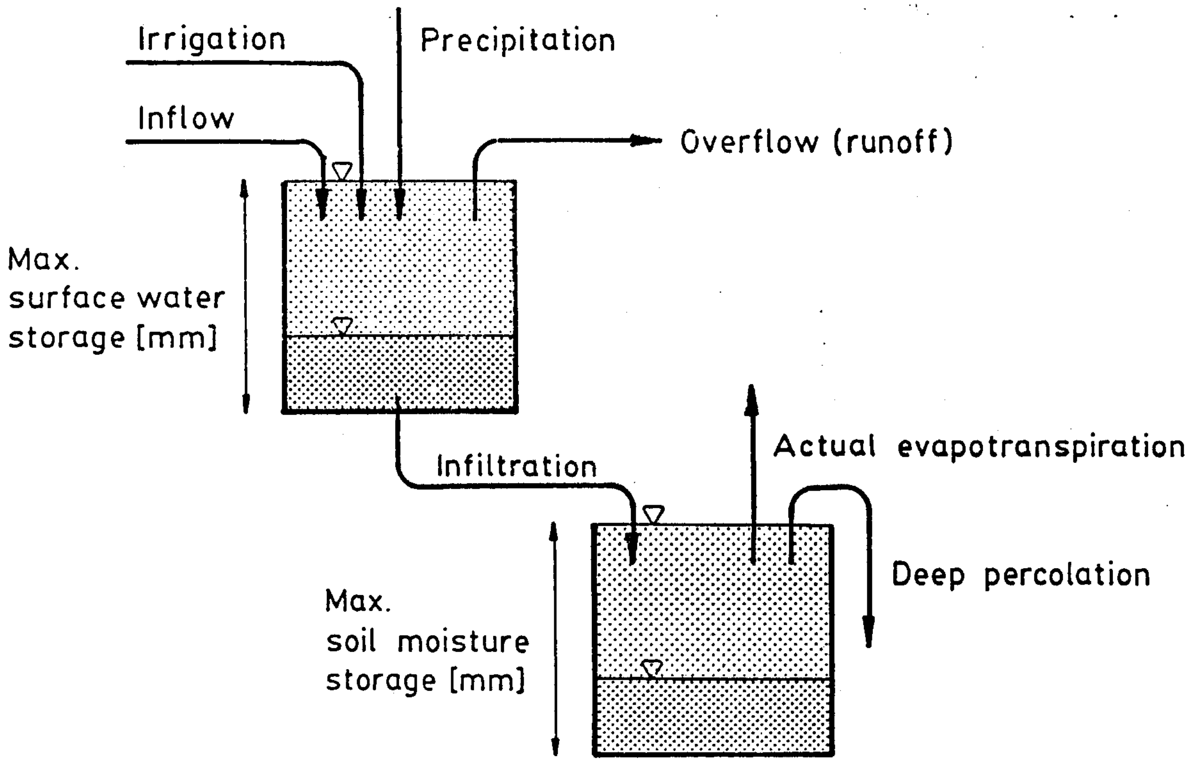



Figure 5.13: Parameters of Paddy Water Balance Model

The above described procedure is executed in each of the internal time steps.

5.4.3.4 Inflow to and Rainfall on Terraces

On rainy days rainfall and runoff from the catchment area are retained in the terraces. For the reasons already laid down in the corresponding section on dryland interception, interception of rainfall on the rice canopy is not considered in the wetland component of APPSMOD. If the model is run with a farm pond then the runoff is collected in the farm pond and only when the storage capacity of the farm pond is exceeded does the surplus flow onto the paddy fields. The water reaching the terraces is distributed between the different rice crops, depending on the proportion of the total paddy area under cultivation.

5.4.3.5. Runoff (Terrace overflow)

Rainfall on the terraces, overflow from the tank or direct runoff from the catchment area cause an increase of the water level in the terraces. If the surface storage exceeds the maximum value of the surface storage which is supplied as an input to this model component then overflow (runoff) from paddy fields occurs. In order to account for the infiltration during filling of the terraces, the infiltration during the internal time step of 6 hours is substracted from the overflow.

5.4.3.6. Terrace Model for an Irrigated Dryland Crop

As explained in the section describing the agro-economical component of the model, irrigated dryland crops are only grown in the dry season. The rainfall during this period is almost negligible and the irrigation is applied in a water saving way so that no runoff or deep percolation losses occur. During this period the only hydrologically significant impact on the system is the withdrawl of ground water from the aquifer for irrigation. Therefore, a very simple approach can be applied to model the water balance of the dryland crops with sufficient accuracy.

Interception of rainfall in the dry season can be neglected. Runoff is computed with the US SCS curve number method. Infiltration is modelled as the difference between rainfall and runoff. Again the hydrological model is selected for computation of the soil water balance but in this case only one soil moisture storage is considered. Vertical downward flow (deep percolation) only occurs when the water holding capacity of the single soil moisture compartment is exceeded. Upward movement of water is not taken into account because of the prevailing sandy soils and the great depth to the ground water table in the dry season. Apart from considering a different distribution of the crop factor over time, the actual evapotranspiration loss from the soil profile is simulated employing the same procedure used in the rice water balance model. Irrigation is provided when the plant available water in the soil has dropped below a value of 30 % of field capacity:

$$IV_{act} = 1.1 \cdot (PAW_{max} - PAW_{act}) \cdot 1000 \cdot A_{idc} \qquad (5.24)$$

where:

| | | |
|---|---|---|
| $IV_{act}$ | = Volume of irrigation demand | $[m^3]$ |
| $PAW_{max}$ | = Maximum plant available water | [mm] |
| $PAW_{act}$ | = Actual plant available water | [mm] |
| $A_{idc}$ | = Area of irrigated dryland crop | $[m^2]$ |

The farmer can only estimate the actual soil moisture status and the irrigation requirement. The factor 1.1 in the above equation accounts for this. However, the actual amount of water applied to the fields is computed in the model based on the check of the availability of water in the farm pond and the aquifer.

### 5.4.4. Ground Water Component

As mentioned earlier, a well to withdraw ground water from the aquifer for irrigation of the rice crop during dry periods represents an important element of an APPT. The model must be able to simulate the amount of water that can be pumped from the well at any time during any season. The yields and returns from the system can only be reasonably estimated when the amount of water applied to the terraces is known. It is also important to be able to simulate the effect of the APPT on the ground water regime.

The ground water conditions in the study area were already described in detail in chapter 2.

In the real system the ground water discharge, water level fluctuations and their spatial distribution are a function of the hydraulic conductivity and the specific yield of the aquifer. They are also a function of the initial and boundary conditions and of course a function of the inputs and losses from the system. As already illustrated in Figure 5.1 the main inputs and losses are deep percolation from the catchment and the terraces, percolation from the farm pond, as well as the ground water draft and subsurface outflow.

It is the aim of the ground water component of the model to simulate the ground water flow conditions with such accuracy that the hydrological and economic feasibilty of an APPT can be reasonably appraised.

#### 5.4.4.1 Ground Water Movement

It was initially considered to assume that the ground water level within the system was horizontal and that the ground water fluctuations could be computed with a hydrological model using the aquifer dimensions and the specific yield as the main parameters. Using this approach it was intended to compute the subsurface outflow by employing Darcy's law [245]. In this equation a constant gradient equal to the surface slope was to be considered. However, in reality a cone of depression would form near the well due to ground water draft during dry periods and a ground water mound would develop below terraces and below the farm pond in periods with high rainfall. At the top of the system the ground water table would be horizontal but with increasing distance from the top the gradient would become steeper until an equilibrium is reached. Therefore, the presumption that the ground water level is horizontal would lead to marked errors in the simulation of ground water discharge, ground water draft and the ground water surface which in turn influences infiltration.
For the above reasons a more complex approach was chosen based on the following physical principles and assumptions:
The general flow equation of ground water movement can be derived from Darcy's law and the equation of continuity. For two dimensional non-steady flow a frequently applied form is [245], [43], [32]:

$$\frac{\delta}{\delta x}\left(T\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(T\frac{\delta h}{\delta y}\right) = S\frac{\delta h}{\delta t} - n \qquad (5.25)$$

where:

| | | | |
|---|---|---|---|
| h | = | Hydraulic head | [m] |
| n | = | Vertical GW-recharge or GW-draft | [m/s] |
| S | = | Storage coefficient (for unconfined aquifer specific yield Sy) | [-] |
| T | = | Transmissivity | [$m^2$/2] |
| t | = | Time | [s] |

with:

$$h = f(x,y,t);\; q = f(x,y,t)$$

Equation 5.25 is valid on assuming that there is:

- irrotational flow
- cinetic energy is neglected
- incompressible fluid and constant fluid density
- homogeneous and isotropic aquifer
- Horizontal impermeable underlying strata

Strictly speaking equation 5.25 is only linear for confined flow. When there is unconfined flow the transmissivity is a function of the saturated thickness (hydraulic head) which is expressed in equation 5.26:

$$T = k_{aq} \cdot h \qquad (5.26)$$

where:

$k_{aq}$ = hydraulic conductivity of aquifer [m/s]

With the additional assumption that the water table fluctuations are small compared to the saturated thickness of the aquifer, the transmissivity of the aquifer could be assumed to be constant. In the study area the water table fluctuations unfortunately proved to be of almost the same order of magnitude as the saturated thickness (Chapter 2).

In APPSMOD the non-linear ground water flow equation is solved by employing the finite difference method. The phreatic single story ground water aquifer formed be the zone of weathered granite over impermeable bedrock is replaced by a grid of 9 rows and 5 columns, where the intersections or nodes represent the area around them (cells) (Figure 5.14). These cells represent the aquifer in a discretized form. For each cell the water balance is computed and the corresponding set of implicit equations is solved simultaneously by adopting the Gauss-Seidel algorithm [33]. Further details of the method are outlined in Appendix SS.

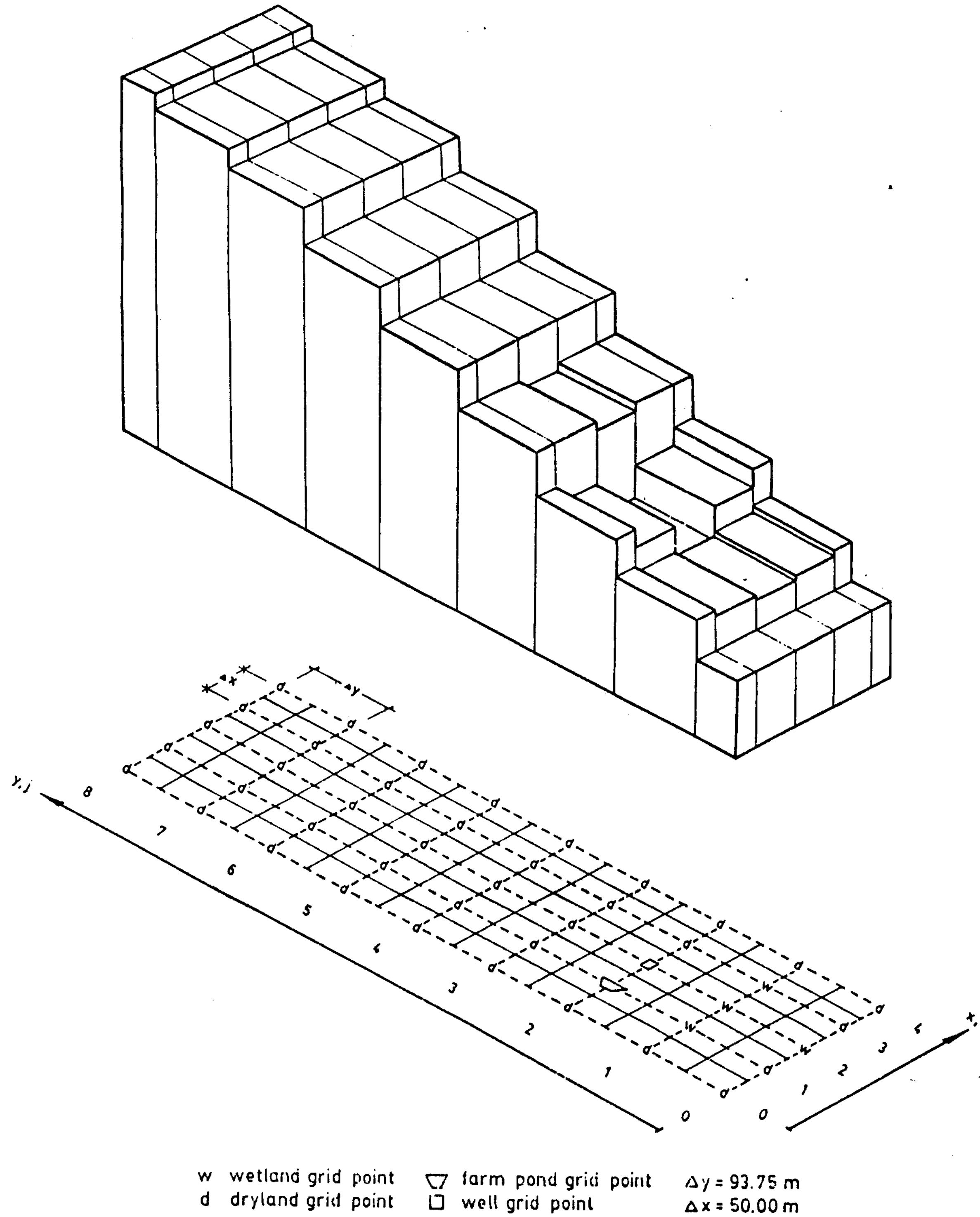



Figure 5.14: Discretized Form of Aquifer as used in APPSMOD

The higher the number of nodes or cells the more accurately the actual ground water surface is approximated by the model. However, the run time of the model extends drastically with increasing number of nodes. A high number of nodal points is certainly desirable in parts of the system where high gradients can be expected, i.e., near the well. However, the programme developed can only cope with equal distances between nodes in the x and y direction and thus a dense net of nodes over the entire area would be needed. As a reasonable compromise the number of nodes was limited to 45.

The run time also depends largely on the values of specific yield and hydraulic conductivity. The smaller the specific yield and the higher the hydraulic conductivity, then the quicker and larger are the water level fluctuations, consequently a larger number of iterations need to be executed and the run time will be longer.

The algorithm generally required 7 to 20 iterations to reach the given maximum water balance error of 1 mm. The number of iterations is influenced by the amount of infiltration, ground water draft and ground water discharge which generate distortions and high gradients of the ground water table.

To take into account the different infiltration below dryland, wetland and the farm pond and the "negative infiltration" near the well, the nodal points were defined either as wetland, dryland, farm pond or well node with the objective to model the distribution of infiltration as close as possible to reality (Figure 5.14). The infiltration rate to each cell and the ground water draft are supplied to the ground water model by the respective model components.

Since the model is designed for a relatively small area, the hydraulic conductivity and the storage coefficient of the aquifer are considered constant in all flow directions for all nodes. These parameters are external inputs to the ground water model. Further external inputs supplied by the input file are the number of intervals between nodes and the distances between nodes in both directions (x and y), the maximum saturated thickness, the surface slope, the time step and the initial ground water levels. For details refer to Appendix U.

The following initial and boundary conditions were defined:

- the distribution of initial water levels supplied to the model in the standard input file (Appendix U), represents a typical ground water table at the end of April after a year with approximately average annual rainfall.
- the top end of the system is assumed to be formed by impermeable rocky outcrops. No ground water flow occurs through this boundary (zero flow boundary condition).
- based on the supposition that identical well terrace irrigation systems are found on both sides of the system and that the water level is always horizontal at the lateral boundaries, the right and left boundary were also defined as zero flow boundaries.
- the ground water discharge leaving the system is calculated in the model for a given gradient at its bottom boundary.

In exceptionally wet years the ground water table could rise to the surface level below the terraces and farm pond. This effect has been taken into account in the model by assuming that all the water rising beyond a certain level would appear as baseflow in a stream and leave the system as surface runoff.

With the above assumptions and conditions the algorithm is able to simulate the ground water outflow from the system and the ground water level in each cell.

#### 5.4.4.2 Well Model

The amount of water that can be withdrawn from the well to meet the irrigation requirements cannot be computed in the ground water movement model because the grid is too coarse to simulate the radial flow in the vicinity of the well. Therefore, the maximum well yield is estimated in a separate model component.

The maximum well yield is approximated as the discharge from the well for steady radial flow. This is not an unrealistic assumption because in general ground water is supplied to the fields in constant quantities on a daily basis and becomes limiting in long dry spells after several days of pumping.

For unconfined conditions the steady well discharge can be estimated with Equation 5.27 [245] (compare Figure 5.15):

$$Q_{abs,gw} = \pi \cdot k_{aq} \frac{H^2 - ho}{\ln (R/r_o)} \tag{5.27}$$

where:

| | | | |
|---|---|---|---|
| $Q_{abs,gw}$ | = | Ground water discharge from well | [$m^3/s$] |
| $k_{aq}$ | = | Hydraulic conductivity | [m/s] |
| $H$ | = | Original saturated thickness | [m] |
| $h_o$ | = | Saturated thickness in well | [m] |
| $R$ | = | Radius of cone of influence | [m] |
| $r_o$ | = | Diameter of well | [m] |

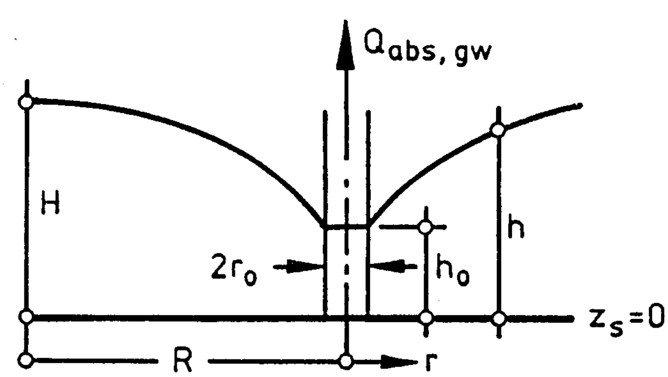



Figure 5.15: Ground Water Table near a Well (Steady Radial Flow)

The above formula needs to be adapted to the situation in an APPS because:

1. During pumping water is recharged from the terraces and farm pond.
2. The original water table is not horizontal.
3. The dug wells commonly used in the study area provide a considerable storage volume. This fact is not taken into account in equation 5.27.

The second point is not so critical, since for most relatively flat natural slopes the above equation can be applied without appreciable error (Todd 1967). However, results have to be evaluated with caution for steeper slopes.

The third point can also be neglected, for the well storage will be depleted when the well yield becomes limiting in dry spells.
A uniform recharge is taken into account in Equation 5.28 [245], [194]:

$$Q_{abs,gw} = \pi \cdot k_{aq} \frac{H^2 - ho^2}{\ln (R/r_o)} - \frac{Q_{perc}}{2 \ln (R/r_o)} \qquad (5.28)$$

where:

$i_s$ = Uniform recharge [m/s]
$Q_{perc} = i_s \cdot R^2 \cdot \pi$ [$m^3/s$]

In the model $Q_{perc}$ is determined by adding the deep percolation from the terraces and the percolation from the farm pond simulated for the previous time step.

For use of the above equation in the model the radius of the cone of influence is still to be defined. It is assumed to be half the width of the system (See Figure 5.14). The minimum permissible water depth $h_o$ in the well fulfilling the above criterion is determined by the model by solving the Sichardt Equation (5.28) for $h_o$ [121], [84]:

$$R = 3000 \cdot (H - h_o) \cdot \sqrt{k_{aq}} \qquad (5.28)$$

Using the described procedure the model can check to see whether the irrigation requirement can be met by water drawn from the well. If the water requirement is higher than the well yield, the well yield is considered as ground water draft and only the available water is supplied to the fields.

5.4.5. Tank/Farmpond Component

5.4.5.1 General Considerations

In the design of tanks in south India it has been a rule to determine the maximum storage capacity as follows [162]:

Assuming that the tank is filled twice during the monsoon season the tank capacity should be equal to half of the runoff generated in at least 50% of the years.

For an area like Aurepalle where the runoff in the majority of the years seems to be less than the mean value (5.16) this is not a recommendable approach, since only 16% of the surface water resources would be utilized. Due to the scarcity of water in the area, higher investments and a higher degree of water retention appear to be justified [162]. By employing the criterion to retain the runoff, which is exceeded in only 33% of the years, approximately 40% of the resources could be utilized. For Aurepalle this would amounts to 40 mm. When considering that the tank should be filled twice, the tank or farm pond should be designed with a capacity to collect about 20 mm of runoff from the catchment area.

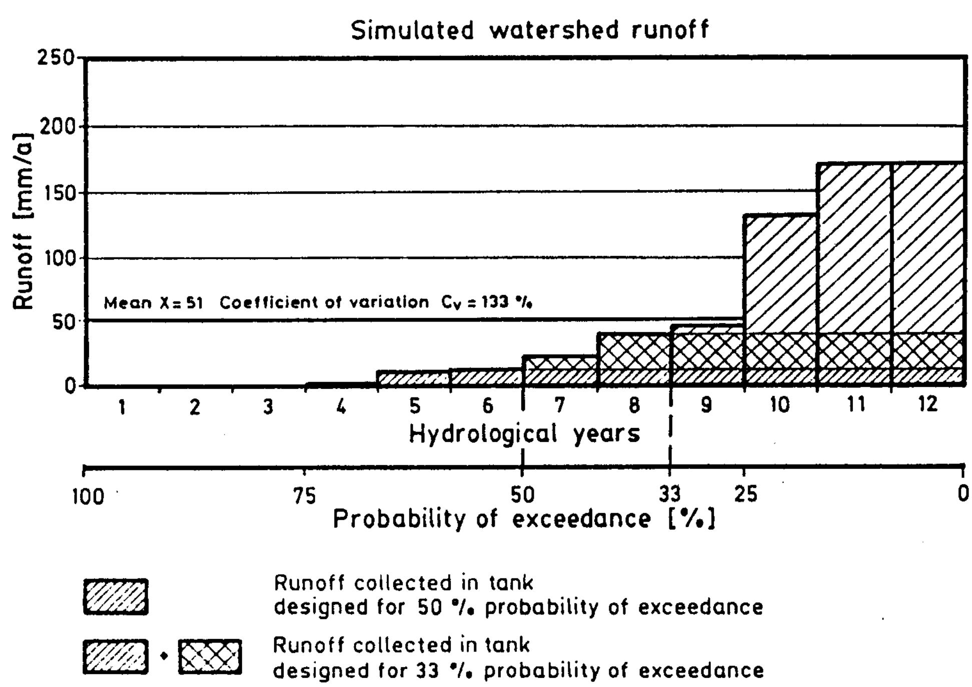



Figure 5.16: Frequency Distribution of Annual Runoff in the Aurepalle Watershed.

In an APPS runoff can be diverted from gullies for recharge during rainy spells. However, the storage in the terraces is limited. For a maximum storage depth of 10 cm and a terrace area of 1 ha (6.66% of the system area) the storage capacity works out to be 1000 $m^3$. This is just enough to retain the rain falling on the terraces during a rainfall-runoff event where 20 mm of runoff are generated. For these 20 mm of runoff additional storage needs to be provided. Assuming the effective catchment is 85% of the system area, the necessary additional storage is equivalent to a volume of 2550 $m^3$. Thus a total storage of ca. 3500 $m^3$ is required to retain the rainfall on the terraces and the runoff from the catchment.

Within the pre-existing agricultural structure there are two options available to create this storage capacity. Firstly, the storage in the terraces can be increased by raising the field bunds or secondly, additional storage can be provided through a farm pond.

For the first option a storage depth of 35 cm (Storage volume = 3500 $m^3$ on 1 ha) is considered a critical limit because above this limit the longer and deeper submergence could have a detrimental effect on crop yields. The field bunds become very large and the effective cultivated area is reduced. Furthermore, breaching of the field bunds which is not an uncommon event would cause much greater damage to crops and the terraces below.

The second option is the construction of a farm pond. A volume of approximately 2500 $m^3$ would be enough to retain the runoff from the catchment under the conditions outlined above. The question of which option to choose is an economical problem. The lower costs of the terraces could be outweighed by the reductions in yields due to prolonged submergence. Therefore both management options are compared by executing separate model runs (Figure 5.3).

In areas with higher runoff potential only a farm pond can provide the necessary surface storage.

### 5.4.5.2 The Farm Pond Model

The optimal design of a small reservoir with reduced percolation losses was found to be a reservoir with the shape of a truncated cone [219]. In an APPS the percolation loss from a farm pond does not present a problem because surface and subsurface water are used conjunctively. In this study the more commonly used design of a truncated quadratic pyramid with a slope of 1:2 is considered (Figure 5.17).

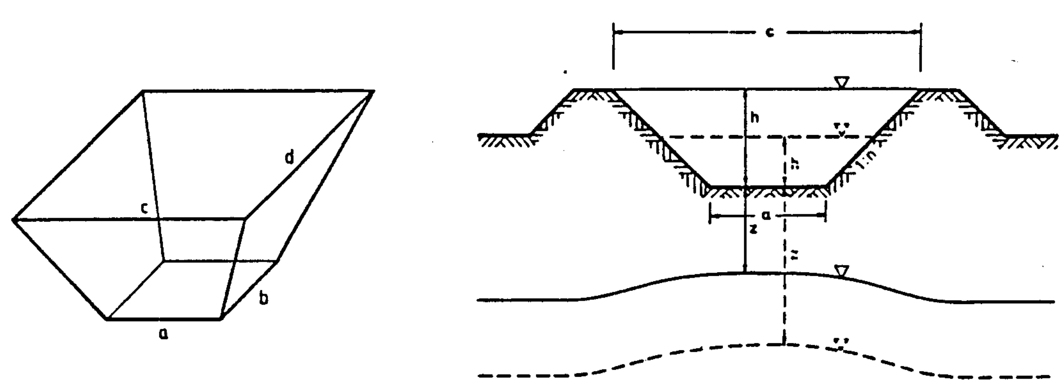



Figure 5.17: Type of Farm Pond as Considered in the Model.

For a quadratic pond:

$$a = b,\ c = d$$

and the relationship between base and top width:

$$c = a + 4 \cdot h$$

the volume of the farm pond is only a function of the depth of the pond and the base width (Equation 5.29) [33]:

$$V_{ta} = \frac{h}{3} ((a + 4 \cdot h)^2 + a \cdot (a + 4 \cdot h) + a^2) \tag{5.29}$$

With the inputs maximum volume and maximum water depth the base width of the pond is determined by solving Equation 5.29 for a:

$$a_{1/2} = - 2\ h \pm \sqrt{(2h)^2 - (\frac{16}{3} h^2 - \frac{V_{ta}}{h})} \tag{5.30}$$

Given the base width a, the actual water depth for any volume can be computed according to Equation 5.31:

$$\frac{16}{3} h^3 + 4ah^2 + ha^2 - V_{ta} = 0 \tag{5.31}$$

This third degree polynom is solved employing the Newton-Horner algorithm and the deflation technique (Borland, Mathematical Tool Box, Turbo Pascal). A plausibility check is carried out to determine the plausible solution. Equations 5.29 and 5.31 allow the model to switch between calculation of the water balance in water levels and volume. This is necessary because some parameters of the water balance are given as length per day and others as volume per day.

The parameters of the water balance of a tank or farm pond have already been described in chapter 2.3.4. The change of storage in the farm pond over time can be described as a function of several processes (Equation 5.32):

$$\frac{\delta V_{ta}}{\delta t} = f\,(P_{ta}, Q_{in}, Q_{in,gw}, E_{ta}, Q_{over}, Q_{irr}, Q_{perc}, Q_{seep}, Q_{vis}) \qquad (5.32)$$

where:

$P_{ta}$ = Precipitation on tank
$Q_{in}$ = Inflow to tank
$Q_{in,gw}$ = Ground water inflow to tank
$E_{ta}$ = Evaporation from tank
$Q_{over}$ = Overflow over spillway
$Q_{irr}$ = Irrigation outflow
$Q_{perc}$ = Percolation through tank bed
$Q_{seep}$ = Seepage through tank bund
$Q_{vis}$ = At surface visible seepage
$V_{ta}$ = Tank volume
$t$ = Time

By neglecting $Q_{vis}$ and $Q_{in,gw}$ and by combining $Q_{perc}$ and $Q_{seep}$ to $Q_{perc}$, Equation 5.32 can be simplified to:

$$\frac{\delta V_{ta}}{\delta t} = f\,(P_{ta}, Q_{in}, E_{ta}, Q_{over}, Q_{irr}, Q_{perc}) \qquad (5.33)$$

The above parameters are taken into account in the model. The rainfall is read from the rainfall file. The percolation rate is supplied to the farm pond component of the model from the standard input file and is multiplied with the factor $(z + h)/z$ to take into consideration the dependency of the percolation rate on the water depth in the pond and the depth to the ground water table (compare chapter 5.4.3.3). The inflow is taken as the runoff computed in the dryland component. The shallow lake evaporation is determined by multiplication of the pan class A evaporation with a monthly changing coefficient kta. The coefficients were derived from data published in [250]. While the irrigation requirement is computed in the wetland model component, the tank model checks to see whether the requirement can be met from the tank storage.

Most of the processes leading to a change of storage occur simultaneously. Therefore, as explained in chapter 5.4.3, errors in the computation of the storage change can occur, when a daily time step is used. In order to reduce such errors a half daily internal time step was employed.

In an attempt to simulate all processes in the order of their occurrence in nature, the model executes the following tasks:

1. Calculation of the shallow lake evaporation, subtraction of 50 % of the daily evaporation rate from the actual farm pond water level and updating of the farm pond storage.

2. Subtraction of the irrigation requirement (volume) from the farm pond storage and updating of the farm pond water level.
3. Subtraction of 50 % of the daily percolation rate from the farm pond water level.
4. Subtraction of 50 % of the daily evaporation rate from the farm pond water level.
5. Increase of the water level by 50 % of the daily rainfall and updating of the farm pond storage. If the maximum storage is exceeded the surplus is considered as overflow.
6. Addition of inflow (volume) to the farm pond storage and calculation of overflow if maximum storage is exceeded. Updating of the farm pond water level.
7. Addition of 50 % of the rainfall to the water level and calculation of overflow.
8. Subtraction of 50 % of the daily percolation rate from the farm pond storage.

### 5.4.6. Agro-economical Component

#### 5.4.6.1. Farmers Decision Making

In reality an agronomically productive percolation system would be operated by a farmer. In order to simulate the operation of such a system, a subprogramme has been developed which controls the system by simulating the farmers decision making process.

During the course of an agricultural season the farmer has to make the following main decisions:

- which crops to grow
- when to plant
- how many acres to cultivate
- from which sources irrigation should be supplied
- when irrigation should be given
- how to distribute the water to the fields during water shortage
- how much fertilizer or other inputs should be supplied.

Decision on type of crops to grow:
The APPS only functions properly when a crop is planted that can withstand prolonged submergence without a reduction in yield. In the study area rice is the crop that meets this requirement. Therefore a rice based cropping pattern was chosen for the model. The water conserving effect of the terraces is highest in the monsoon. During the dry season rice must be considered less water efficient than irrigated dryland crops. For these reasons it is best to grow rice crops during monsoon and a suitable ID-crop such as groundnut which promises good returns in the dry season. Sorghum is grown under rainfed conditions in the catchment area.

More details on the crops and cropping pattern adopted in the model are provided in Section 5.4.6.2.

Decision on planting dates:
As a simplification fixed planting dates were used for the irrigated crops. For the sorghum crop the sowing date was set by the model. In the study

area the rainfed crops are planted after the first good monsoon rains. Although good pre-monsoon showers can occur in May, crops are not normally planted before the end of May because the rainfall is not dependable during this period. The model sets the planting date when the soil moisture in the upper layer of the dryland soil storage is greater or equal to 20 mm, but never before the 22nd standard week (personal communication with ICRISAT Agroclimatologist).

Decision on area to be cultivated:
The decision for the rainfed crop is straight forward because in general the entire arable area, excluding the terraces and grazing areas, is cultivated. The sorghum area was assumed to be 80 % of the system area.

As far as the irrigated crops are concerned the decision of how many acres to cultivate is normally based on an assessment of the available resources. In this study it was assumed that sufficient labour and funds were available. Therefore, the assessment of resources concentrates on the water resources.

Decisions have to be made for several crops grown in different seasons, hence the distribution of the available water resources over the year must be taken into account.

To represent the actual conditions in the study area the following sequence of crops is simulated in the model:

In the monsoon season the resources are assessed six times. Three rice crops with overlapping cropping seasons are grown. An estimation of available water resources and the decision are made twice for each crop. The first assessment is made at the beginning of nursery stage in order to choose a suitable nursery area which is assumed to be 20 % of the transplanted paddy area. The second one is made just before transplanting to determine the final cultivated area. Depending on the rainfall during the nursery stage, the farmer can adjust the size of the area under cultivation at this date. In the monsoon the resource assessment will include an estimation of the available ground water and surface water resources plus an assessment of their renewal or depletion.

In the dry season the decision is only required at a fixed date before sowing of the irrigated dryland crop. Here no renewal of resources is considered since the rainfall in this period is negligible.

The water resources that the farmer has to take into account can be grouped into dependable, non-dependable and bound water resources. Dependable resources are the resources which are readily available for irrigation (Equation 5.34):

$$V_{dep} = V_{gw} + V_{ta} + V_{te} \tag{5.34}$$

where:

| | | |
|---|---|---|
| Vdep | = Dependable resources | [$m^3$] |
| Vgw | = The ground water storage | [$m^3$] |
| Vta | = The volume of stored water in the tank | [$m^3$] |
| Vte | = The volume of water stored in the surface storage of the terraces | [$m^3$] |

In addition, losses from the dependable resources by evaporation and ground water outflow have to be taken into consideration (Equation 5.35):

$$V_{dep} = V_{gw} - V_{gw,red} + 0.8 \cdot V_{ta} + 0.8 \cdot V_{te} \qquad (5.35)$$

where:

| | | | |
|---|---|---|---|
| $V_{gw,red}$ | = | Ground water outflow during season | [$m^3$] |
| 0.8 | = | Factor to account for evaporation losses during growing season | [-] |

Non-dependable resources are defined as the resources which can become available during the crop growing season but are not assured, i.e., rainfall etc. (Equation 5.36):

$$V_{ndep} = k_{risk} \cdot (V_{p,exp} + V_{in,exp} + V_{rc,exp}) \qquad (5.36)$$

where:

| | | | |
|---|---|---|---|
| $V_{ndep}$ | = | Non-dependable resources | [$m^3$] |
| $V_{p,exp}$ | = | Effective expected rainfall on terraces | [$m^3$] |
| $V_{in,exp}$ | = | Effective expected inflow from the catchment area | [$m^3$] |
| $V_{rc,exp}$ | = | The expected GW-recharge from the dryland area | [$m^3$] |
| $k_{risk}$ | = | Risk factor | [$m^3$] |

In the model these resources are multiplied with a risk factor since the farmer can not depend on the occurrence of the above resources. The risk factor represents the probability of occurrence of such resources as well as the attitude of the farmer on making risky decisions. The optimum factor for a certain area can be determined by a sensitivity analysis.

Depending on his attitude to risk the farmer estimates the expected resource renewal through rainfall, runoff and recharge above or below an average value. Several risk attitudes can be tested to find an attitude that leads to stable yields at a high level. In the study area farmers were found to be risk averse [57], [23]. According to a few interviews conducted by the author, farmers indicated that they use the n-1 rule, which means that they estimate the water resources and determine the number of acres to be cultivated, but actually plant one acre less. This indicates that for a normal number of acres they use only 60 to 80 % of the available water resources.

It can be the case that under certain circumstances, at the time when the decision is due to be made little dependable but large undependable resources are included in the assessment. In such a case it would be a too greater risk for the farmer to rely, in such a case, on only non- dependable resources for irrigation of the area to be cultivated. The farmer does not know if and when these resources will become available during the growing period. The dependable resources should therefore cover the volumetric water requirement for about half of the season. For this reason the non-dependable resources are only taken into account with a maximum value that does not exceed the dependable resources.

The third group of resources (bound resources) are those which the farmer can not take into account because they have already been accounted for in irrigation of an earlier planted crop (Equation 5.37):

$$V_{prom} = \sum_{k=0}^{k=n} (k_{rem(n)} \cdot CU_{pad(n)} \cdot A_{pad(n)}) \qquad (5.37)$$

where:

| | | | |
|---|---|---|---|
| $V_{prom}$ | = | Bound or promised resources | [$m^3$] |
| $CU_{pad(n)}$ | = | Consumptive seasonal water use (paddy) | [m] |
| $A_{pad(n)}$ | = | Cultivated terrace area (paddy) | [m] |
| $k_{rem(n)}$ | = | Percentage of remaining growing season of earlier planted crop | [-] |
| n | = | Number of earlier planted crops | (1,2 ..) |

It became apparent during several interviews with local farmers that they estimate available ground water resources based on the water level in their wells. The water level is an indicator of the magnitude of the ground water resources and the well yield. From experience the farmer knows what area he can cultivate for a given water level.

Preliminary model runs for the Aurepalle rainfall regime indicated that not the volume of available resources but the well yield is the limiting factor in meeting the water requirement during the entire season. Apart from exceptionally wet years the ground water is the most reliable resource in this area and provides the only source that can ensure that the crops survive dry periods without severe yield reductions. The estimation of the area to be cultivated, therefore, is to be based on an assessment of the well yield during the most critical part of the growing season. During this time the daily well yield should still match the daily water requirement. In order to determine this expected critical well yield, Equation 5.38 was applied (compare Equation 5.28):

$$Q_{abs,exp} = \pi \cdot k_{aq} \frac{H_{exp}^2 - h_o^2}{\ln (R/r_o)} - \frac{Q_{perc}}{2 \ln (R/r_o)} \qquad (5.38)$$

where:

| | | | |
|---|---|---|---|
| $Q_{abs,exp}$ | = | Expected GW-discharge from well | [$m^3$] |
| $k_{aq}$ | = | Hydraulic conductivity | [m/d] |
| $H_{exp}$ | = | Expected original saturated thickness | [m] |
| $h_o$ | = | Saturated thickness in well | [m] |
| R | = | Radius of cone of influence | [m] |
| $r_o$ | = | Diameter of well | [m] |
| $Q_{perc}$ | = | $i_s \cdot R \cdot \pi$ | [$m^3$/d] |
| $i_s$ | = | Uniform recharge | [m/d] |

The main unknown factor in this equation is the saturated thickness. All other parameters are either external inputs from the standard input file or internal inputs from other subroutines (chapter 5.4.4.2). The saturated thickness can be approximated by using Equation 5.39:

$$H_{exp} = V_{gw,exp} / (A_{sys} \cdot S_y) \tag{5.39}$$

where:

| | | |
|---|---|---|
| $H_{exp}$ | = Expected ground water level | [m] |
| $V_{gw,exp}$ | = Expected ground water storage | [m$^3$] |
| $S_y$ | = Specific yield of aquifer | [Vol/Vol] |
| $A_{sys}$ | = System area | [m] |

The expected critical ground water storage at the most critical time is calculated from equation 5.40:

$$V_{gw,exp} = k_t \ (V_{dep} + V_{ndep} - V_{prom} - k_t \cdot IR_{crop}) \tag{5.40}$$

where:

| | | |
|---|---|---|
| $V_{dep}$ | = Dependable resources | [m$^3$] |
| $V_{ndep}$ | = Non-dependable resources | [m$^3$] |
| $V_{prom}$ | = Promised resources | [m$^3$] |
| $V_{gw,red}$ | = Ground water outflow during season | [m$^3$] |
| $IR_{crop}$ | = Irrigation requirement for season | [m$^3$] |
| $k_t$ | = Factor to consider the critical time | [-] |

In the model a factor $k_t$ of 0.9 is employed which means that the critical time is assumed to be 90 % of the growing season. A shortage of water in the remaining 10 % of the growing season would not cause considerable yield reductions.

In Equation 5.40 not only ground water resources but also the surface water resources are taken into account, since utilization of the surface water resources leads to a slower depletion of the ground water storage.

During the monsoon season it is sensible to cultivate the maximum possible area of paddy to benefit as much as possible from the water harvesting and recharging effect of the rice terraces. However, in the dry season it would be advantageous not to utilize the entire available resource for irrigating the dryland crop so that there is still ground water for the first paddy crop starting in May. Therefore, in the farmers decision subroutine for the irrigated dryland crop the expected ground water storage is multiplied with a factor $k_{gn}$. The standard value chosen was 0.6.

The critical daily well yield has to match the daily water requirement of the crop (Equation 5.41).

$$ID_{act} = TWA \cdot A_{pad} / d_{crop} \tag{5.41}$$

where:

| | | |
|---|---|---|
| $ID_{act}$ | = Daily crop water requirement (demand) | $[m^3/d]$ |
| TWA | = Total water applied to crop over the season | [m] |
| $A_{pad}$ | = Cultivated area of crop | [m] |
| $d_{crop}$ | = Length of crop growing season in days | [d] |

The non-dependable resources and the daily crop water requirement are a function of the area to be cultivated. Therefore an iterative procedure has been employed. In the algorithm adopted in the model the estimated terrace area is increased stepwise according to Equation 5.42:

$$A_{pad} = A_{pad} + 250 \tag{5.42}$$

where:

| | | |
|---|---|---|
| $A_{pad}$ | = Estimated cultivated terrace area (paddy) | $[m^2]$ |
| 250 | = Average size of a terrace | $[m^2]$ |

In each step the critical expected well yield and the daily crop water requirement are computed. The area for which the water requirement just does not exceed the well yield is taken as the area to be cultivated.

The above described procedure is executed for each rice crop prior to the fixed nursery puddling and final puddling dates, and for the irrigated dryland crop before the fixed sowing date.

To enable the model to carry out the assessment of the different types of resources as mentioned in Equation 5.40, rules of thumb were used to estimate:

| | |
|---|---|
| $V_{p,exp}$ | = Effective expected rainfall on terraces |
| $V_{in,exp}$ | = Effective expected inflow from the catchment area |
| $V_{rc,exp}$ | = The expected GW-recharge from the dryland area |
| $V_{gw,red}$ | = Ground water outflow during season |

Based on the results of the data collected in the Aurepalle watershed and the watershed model described earlier, simple equations were developed taking into account mean seasonal, mean annual rainfall, and the SCS curve number to consider soil parameters. In the rule of thumb for the seasonal ground water outflow the additional parameters actual ground water storage, specific yield, hydraulic conductivity and seasonal consumptive water use were included. If the model is fed with data other than the standard input data, for example with a different SCS curve number and with a different rainfall file, then the equations respond to the changed conditions.

Decision on the time when irrigation should be given:
For the rice crops planted on the relatively coarse and permeable soils in the study area, a daily irrigation interval is employed in the model. Irrigation is provided to the irrigated dryland crop when the water content in the soil is below the level where the ratio of actual to potential evaporation is smaller than unity (Figure 5.12 ET Model).

Decision on source of water supply:
The farmer has to decide from which source, i.e., farm pond or well the irrigation requirement should be met. The model selects the source of water supply based on the following decision process:

1. If there is still sufficient water (rain or harvested runoff) standing in the paddy fields to meet the irrigation requirement for the day, no additional irrigation is given.
2. If the irrigation requirement can only be met partially or not at all from the surface terrace storage, the required water is taken from the farm pond.
3. If there is not enough water in the tank, then the remaining water deficit is met from the ground water storage. As mentioned earlier the model also checks to see whether the well is able to yield this amount of water.

The order of priority of water sources given above appears to be justified. Use of water from the surface terrace storage obviously has priority. The use of farm pond water should come second, because the costs of water distribution are lower, evaporation and percolation deplete the storage if not used for irrigation, and because additional storage capacity to collect runoff is created when the storage is being rapidly reduced through irrigation.

Decision on distribution of water in case of drought:
During an unusually long dry spell the farm pond can fall dry and the ground water can drop to a level where the water requirement can not longer be met entirely by the well. The farmer is then faced with the decision to allocate the available water between the different crops. This should be done in a way that the reduction in returns due to the water deficit is minimized. Since it is not known at this point when the next rain will fall, and therefore the water resources available in the future are not known, it will be difficult to make this decision. According to the cropping pattern only rice crops are grown at the same time, thus making the problem a little simpler. There are several strategies which could be adopted by the farmer, i.e.,:

- to allocate the water depending on the yield response factor of the crops, which varies over the season (see chapter on crop models (5.4.6.2).
- to allocate the water depending on the proportion of the volumetric water requirement of each crop.
- to supply water with preference to the earlier planted crop.
- to reduce the paddy area, when the water shortage leads to drastic yield reduction.
- a combination of the above strategies.

If the assessment of water resources and the choice of the area to be cultivated has not been completely unreasonable (not a risk adverse attitude) then generally no severe water shortages will occur. For the chosen cropping pattern the water has to be only allocated between two crops for most of the time. It was therefore considered acceptable to allocate the water depending on the proportion of the volumetric water requirement of each crop as long as the daily available water is greater than the daily evapotranspiration of both crops. If the available water is lower than this value then water is supplied with preference to the first crop.

Decision on level of inputs:
The decision on the level of inputs such as fertilizer, pesticides, etc., has to be made depending on available capital, the response of the crop to fertilizer and, as far as pesticides are concerned, on occurrence of pests. In the model a standard level of inputs reperesentative for the study area has been considered.

The procedure for trying to model the farmers decision making described above has the advantage that the actual situation in the farmers field is taken into account. In contrast a linear programming model calculates the optimum area for given constraints. However the constraint "available water resources" is never given exactly in the actual field situation. In addition, when testing the economical feasibility of APPT's, it would be unrealistic to assume that the farmer operating the system would always make optimum decisions. Therefore, the selected approach can be expected to yield fairly realistic results.

A list of the external inputs to the farmers decision subroutine is given in Appendix U.

### 5.4.6.2 The Crop Model

#### 5.4.6.2.1 General

Whereas in the farmers decision model the important decisions necessary for the smooth and effective operation of an APPS are made and the area of the different crops grown is simulated, the crop model computes the yield of these crops, which is a prerequisite to determine the economical feasibility of the system.

As already pointed out earlier the cropping pattern adopted in the model comprises three overlapping irrigated rice crops in the early monsoon, monsoon and late monsoon season. Furthermore, it includes groundnut as the irrigated dryland crop in the dry season as well as the sorghum crop grown under rainfed conditions during monsoon (Figure 5.18).

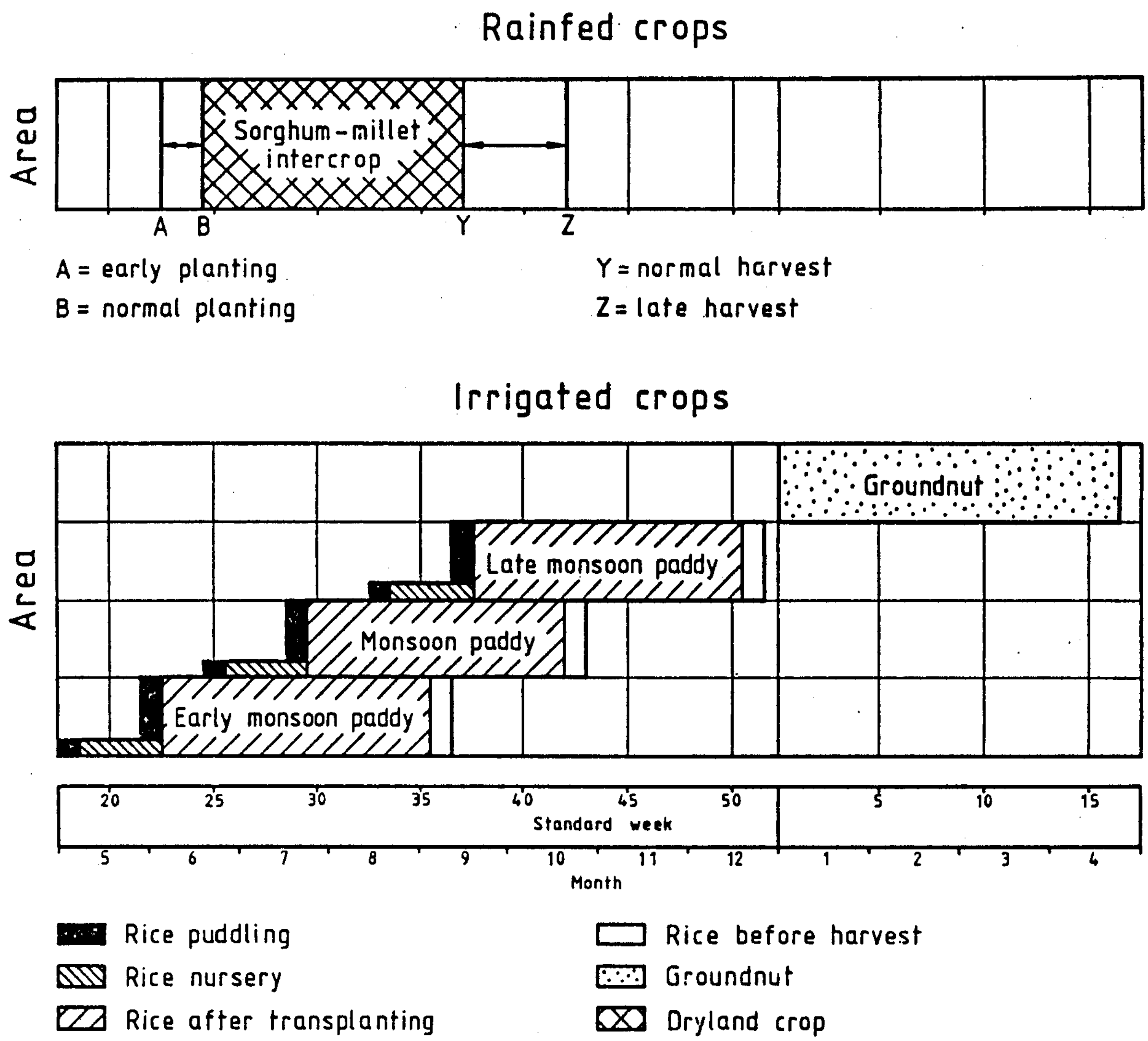



Figure 5.18: Cropping Pattern as Employed in APPSMOD.

This cropping pattern was chosen because rice is an ideal crop to be grown in an APPS during monsoon. In the dry season there is no water retaining or conserving effect in the cultivation of paddy, hence it is economical to grow groundnut which has similar net returns as rice and has a lower water requirement. The sorghum millet intercrop, normally planted in the study area as the traditional rainfed crop, is represented in the model by a sorghum crop.

The simulated cropping pattern closely mimicks the traditional cropping pattern in the study area where paddy irrigation prevails amongst the cultivation of a variety of other irrigated crops such as chillies, tomatoes and sorghum.

In the monsoon season about 78 % of the irrigated area is cultivated with rice [57]. Rice requires markedly more water than other local crops. Thus, in total more than 90 % of the water used for irrigation is supplied to paddy crops. Therefore the other crops being of minor importance were neglected in the model.

A cropping pattern with a high percentage of rice in the monsoon season, and groundnut predominating in the dry season was also suggested by Dangelmaier [44]. Her results were obtained by using a linear programming model which was run with the objective to maximize farmer's income.

The diversity of models to predict crop yield is almost as high as the diversity of crops and the varying conditions under which they are grown. In [62] crop models are classified as follows:

- Crop growth simulation models
- Crop-weather analysis models
- Empirical-statistical models

A crop growth simulation model may be defined as a simplified representation of the physical, chemical and physiological processes underlying plant growth processes. If the basic plant processes - production and distribution of dry matter and water relations - are properly understood and modelled, the entire response of the plant to the environmental conditions can be simulated. Therefore there is no need to differentiate between climatic regions, since the simulation model itself will show the limiting factors for growth. In humid climates with low temperature and radiation levels, the model will generally show the greatest response of yields to increases in total radiation received. In an arid and hot climate it will show the greatest reponse of yields to the distribution and total amount of precipitation.

Crop-weather analysis models are defined in [62] as the product of two or more factors, each representing the simplified functional relationship between a particular plant response (e.g., yield) and the variations in selected variables at different phases of plant development. Conventional statistical procedures are used in such models to evaluate the coefficients relating crop responses to climatological or derived agroclimatological data.

Empirical-statistical models relate one or several variables representing weather or climate, soil characteristics or a time trend to plant yield. The "independent" variables are often temperature or precipitation terms or derived agrometeorological variables such as an index of the atmospheric moisture stress or the soil moisture regime. The weighting coefficients in these equations are by necessity obtained in an empirical manner using standard statistical procedures such as multivariable regression analysis. This statistical approach does not easily lead to an explanation of the cause and effect of the relationships, but is a very practical approach for the assessment or prediction of yields.

The first categorie must be regarded more as a tool to study plant growth processes and the factors influencing them. Their input data requirements are enormous and therefore such models are not considered appropriate to be incorporated in APPSMOD.

In the absence of sufficiently detailed data on crop yields and agro-climatological parameters for the respective periods, reliable empirical-statistical models could not be established.

Therefore a general type of model was selected which, the author feels, falls into the categorie of the crop-weather analysis models. The type of model chosen is a maximum yield model, where the ratio of actual to maximum yield is related to the ratio of actual to maximum evapotranspiration. Incorporation of such a model into APPSMOD is quite easy since actual and maximum evapotranspiration are already simulated in the different water balance models. As inputs, only the maximum yield and the crop response factors are required. The maximum yield data was derived from data collected by the author and other studies carried out in the study area or neighbouring districts (see Appendix B). The yield response factors were taken from [48]. Such a model provides a reasonable estimate of crop yields because:

- by the input of maximum yield a lot of site-specific characteristics are represented such as the level of inputs (fertilizer, pesticides etc.), cultivation practices, variety of crop, maximum radiation, soil type and other general environmental conditions.

- the linear relationship between yield and actual evapotranspiration is very well established [48], [186], [36], [238].

Most plants show different response to water stress during different growth stages. Crop water-use/yield relationships which consider timing of water stress are called dated water production functions. In these functions the effects of stress in the different periods of the growing season are taken into account by different yield response factors. Simplifications are introduced by assuming that the stress effects in each period are independent. The combined effects of stress in several periods are evaluated by postulating that these effects are additive or multiplicative. Several production functions derived on this basis have been used in irrigation optimisation models [186].

The following multiplicative form of a dated water production function was suggested in [186] because it performed better than the additive type in the range of high evapotranspiration deficits:

$$\frac{Y}{Y_{max}} = \prod_{i=1}^{n} \left(1 - k_{yi} \left(1 - \frac{ET_{act}}{ET_{max}}\right)_i\right) \qquad (5.43)$$

where:

| | | | |
|---|---|---|---|
| $Y$ | = | Crop yield | [tons/ha] |
| $Y_{max}$ | = | Maximum crop yield | [tons/ha] |
| $k_{yi}$ | = | Crop response factor | [tons/ha] |
| $i$ | = | Number of growth period | [1,2 .. ] |
| $ET_{act}$ | = | Actual evapotranspiration during period i | [m] |
| $ET_{max}$ | = | Maximum evapotranspiration during period i | [m] |

With modifications this general type of a crop yield model is employed in the agro-economical component of APPSMOD for simulation of sorghum and groundnut yields.

5.4.6.2.2 Groundnut Yield Model

In the model the computation of the ratio of actual to maximum groundnut yield is implemented as follows:

At the beginning of the run the model reads the week when the crop is planted, the duration in days of the entire growing season and the number of the last day of each growth stage from the input file (Table 5.1 and 5.2).

When the model has proceeded to the planting date of groundnut, then the daily actual evapotranspiration computed for the groundnut crop in the respective water balance model is supplied to the crop model and summed up for all growth stages (Table 5.2).

Table 5.1: Growth Stages and Yield Response Factors of Groundnut as Used in the Model

| No. | Growth stage | Duration [48] [d] | Duration Model [d] | Yield Response Factor [-] |
|---|---|---|---|---|
| 0 | Establishment | 10 - 20 | 14 | 0.8 |
| 1 | Vegetative | 25 - 35 | 28 | 0.2 |
| 2 | Flowering | 30 - 40 | 28 | 0.8 |
| 3 | Yield formation (Pod setting and filling) | 30 - 35 | 28 | 0.6 |
| 4 | Ripening | 10 - 20 | 14 | 0.2 |
| Total | | 105 - 150 | 112 | |

The daily maximum evapotranspiration is determined according to Equation 5.44 and added up for each growth stage:

$$ET_{max} = k_{c,gn} \cdot ET_{pot} \qquad (5.44)$$

where:

$k_{c,gn}$ = Crop factor groundnut (Figure 5.19)

While the potential evapotranspiration is supplied from the weather component of APPSMOD, the crop factor in the above equation is calculated using the function between the percentage of the growing season and the crop factor presented in Figure 5.19. The crop factors for groundnut and sorghum were taken from [48], and the crop factors of the rice crop were derived from the results of the water balance studies in rice fields carried out by the author.

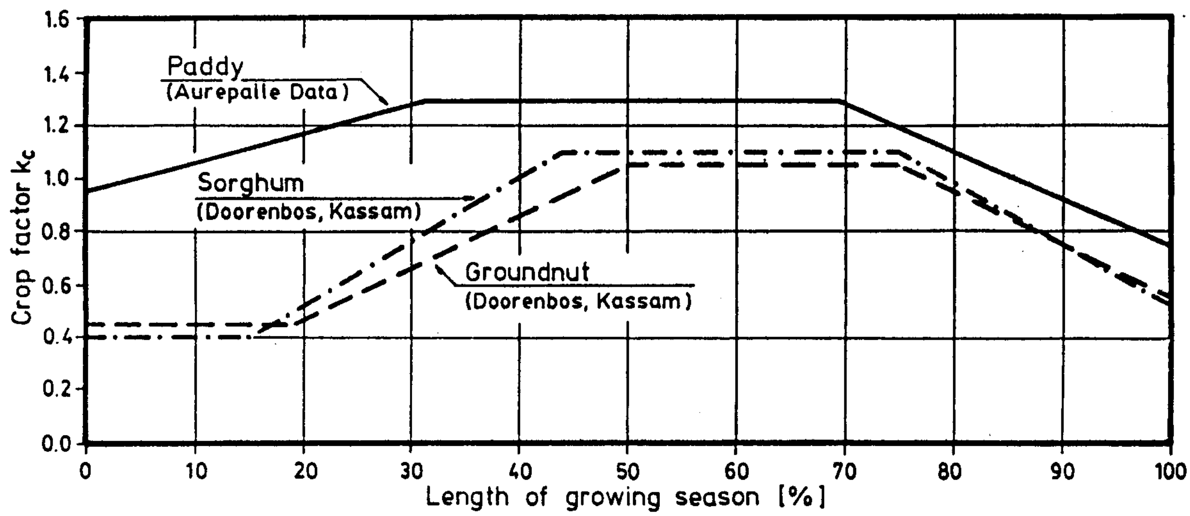



Figure 5.19: Crop Factors of Paddy, Groundnut and Sorghum Plotted over the Growing Period (%).

At the end of each growth stage the evapotranspiration deficit is computed by division of the sums of actual and maximum evapotranspiration and subtraction from unity. Multiplication with the yield response factor for this growth stage and subtraction of the result from unity, yields the ratio of actual to maximum yield for the growth stage.

After the models has advanced through all growth stages in the same manner the yield ratios of all growth stages are multiplied to arrive at the final yield ratio for the groundnut crop for a particular season.

A further input required for the groundnut crop model and the groundnut water balance model is the water available to the plants during the growing season which represents the parameter maximum soil water storage. This parameter is determined based on published values of rooting depth and soil property data (Table 5.2).

Table 5.2: General Data on Crops as Used in the Model

| Crop | Length of growing season | | Date of plant. | Date of harvest | Water requirement season $k_c \cdot ET$ | Rooting depth RD | Avail. soil water $S_a$ (1S) | Plant avail. water $S_a \cdot RD$ (1·S) |
|---|---|---|---|---|---|---|---|---|
| | [w] | [d] | [w] | [w] | [mm] | [m] | [mm/m] | [mm] |
| Sorghum-millet intercrop | 13 | 91 | var | var | 375 [185] | 0.70 [62] | 140 [52] | 98 |
| Early monsoon paddy | 19* | 133 | 18 | 36 | 580 - 900 [243] | 0.25 [62] | 140 [52] | 35 |
| Monsoon paddy | 19* | 133 | 25 | 43 | 580 - 900 [243] | 0.25 [62] | 140 [52] | 35 |
| Late monsoon paddy | 19* | 133 | 33 | 51 | 580 - 900 [243] | 0.25 [62] | 140 [52] | 35 |
| Groundnut | 16 | 112 | 1 | 16 | 400 [185] | 0.50 [48] | 140 [52] | 70 |

var = variable; w = week; * = including nursery puddling

Source: Compiled by the author from [48], [52], [62], [185], [243]

5.4.6.2.3 Sorghum Yield Model

The Sorghum model is, in principle, similar to the groundnut model although different growth periods and yield response factors are employed (Table 5.3). A further difference to the groundnut model is the varying planting data, which is set as mentioned earlier by the model depending on the moisture content of the soil at the beginning of the monsoon.

Table 5.3: Growth Stages of Sorghum and Yield Response Factors

| No. | Growth stage | Duration [48] (d) | Model (d) | Yield Response Factor (-) |
|---|---|---|---|---|
| 0 | Sowing to head initiation (establishment) | 15 - 20 | 14 | 1.00 |
| 1 | Head initiation to emergence (vegetative) | 20 - 30 | 21 | 0.20 |
| 2 | Emergence to seed set (Flowering) | 15 - 20 | 14 | 0.55 |
| 3 | Seed set to physiol. maturity (Yield formation) | 35 - 40 | 21<br>14 | 0.90<br>0.45 |
| 4 | Physiol. maturity to harvest (Ripening) | 10 - 15 | 7 | 0.20 |
| Total | | 95 - 125 | 91 | |

The length of the growth stages and the growing season employed in the model are shorter than the values given by Doorenbos and Kassam [48] to concur with the sorghum variety grown in the study area.

5.4.6.2.4 Rice Yield Model

Traditionally it is considered necessary to submerge a rice crop. Submergence has been found useful since it reduces weed growth, regulates temperature and promotes algal nitrogen fixation. Various depths of submergence ranging from 1 to 15 cm have been proposed by different workers. However, several studies have shown that considerable water is saved by reducing the depth and frequency of submergence. For example 0 to 4 cm of submergence was as effective as 4 to 8 cm in terms of grain production [227]. On the other hand, yields decline when the moisture content of the soil falls below about 75 % of the saturation value [48], [227]. At a moisture content of 50 % of saturation the yield decrease amounts to ca. 60 % and at a level of 30 % no yield at all can be expected. Plants die at soil water contents below 20 % [48] (Figure 5.20).

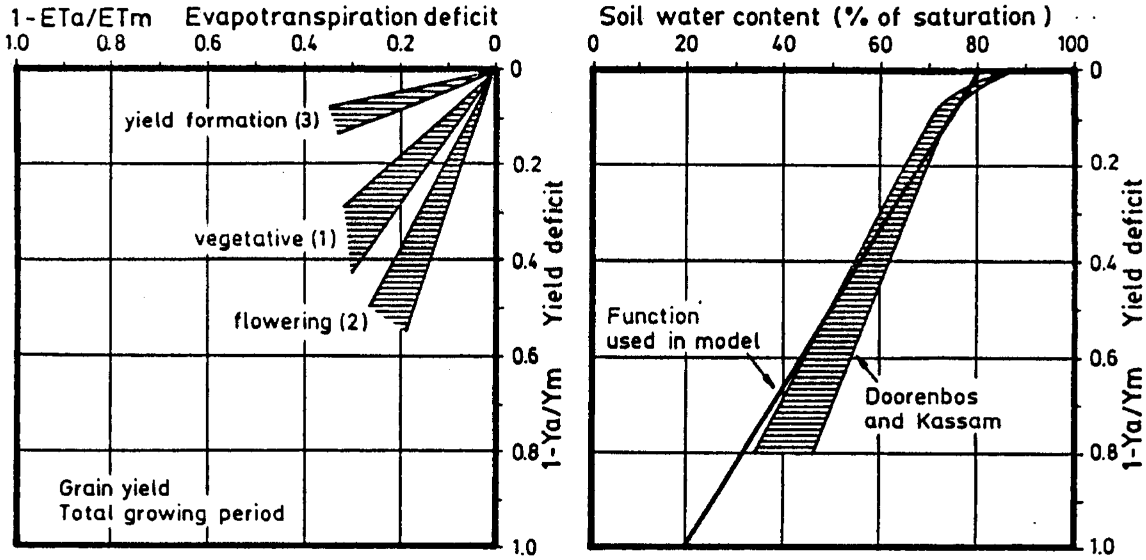



Figure 5.20: Response of Rice Yield to Evapotranspiration Deficit and Soil Water Content [48].

The most sensitive stages of plant development to water deficit are flowering and the second half of the vegetative period (head development). In the flowering stage the yield response is nine times greater, and in the vegetative stage three times greater than in the yield formation stage [48] (Figure 5.20).

Since the relationship between evapotranspiration deficit and yield does not cover the yield loss due to soil water contents lower than saturation, the relationship between soil water content and yield is adopted for the rice yield model (Equation 5.46).

$$\frac{Y}{Y_m} = \frac{\sum_{i=0}^{i=n} \left( \sum_{t=0}^{t=t_i} (k_w \cdot k_{red}) \right)}{\sum_{i=0}^{i=n} (k_w \cdot t_i)} \qquad (5.45)$$

where:

$$k_{red} = \frac{100}{60} \cdot \left( \frac{SM_{pwp} + SM + RC}{SM_{sat}} - 0.2 \right) \qquad (5.46)$$

or:

$$K_{red} = 1 \text{ for: } \quad \frac{SMpwp + SM + RC}{SM_{sat}} > 0.8$$

with:

| | | | |
|---|---|---|---|
| $k_{red}$ | = | Yield reduction factor according to Figure 5.20 | [-] |
| $i$ | = | Number of growth stage | [0 .. 4] |
| $t_i$ | = | Duration of growth stage i | [d] |
| $k_w$ | = | Weighting factor to account for different yield response in each growth stage | [-] |
| $SM_{pwp}$ | = | Soil moisture content at permanent wilting point | [mm] |
| SM | = | Actual plant available soil moisture | [mm] |
| $SM_{sat}$ | = | Soil moisture content at 100% saturation | [mm] |
| RC | = | Deep percolation below root zone | [mm] |

The yield reduction factor is calculated on each day of the growing season by using Equation 5.46 and is weighted with a factor to account for the different response of yield to water deficit in the different growth stages (Equation 5.45).

The different growth stages of rice and their durations are illustrated in Figure 5.21:

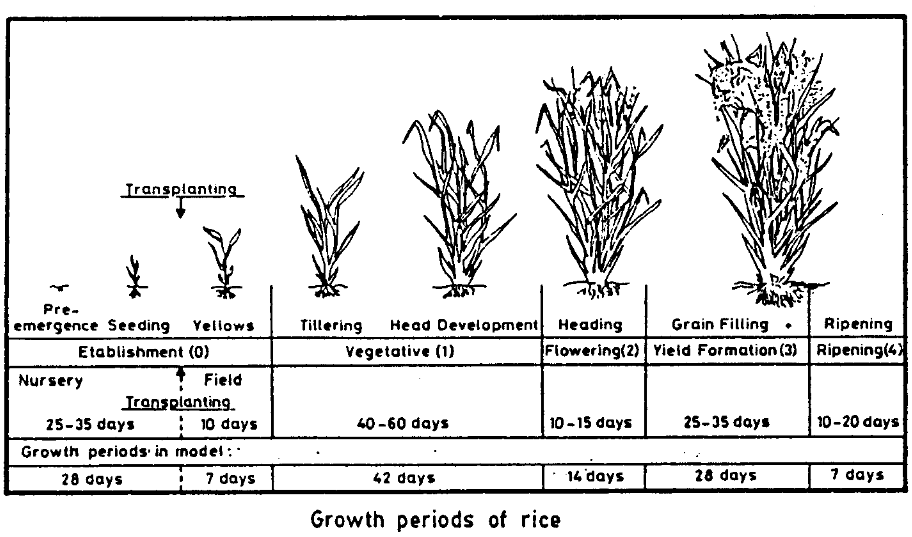



Figure 5.21: Growth Periods of Rice [48] and as Used in Model.

The weighting factors for the yield response in the various growth stages were derived from the relationships between evapotranspiration deficit and yield presented in Figure 5.20.

Table 5.4: Yield Weighting Factors Adopted in APPSMOD

| Growth stage | 0 | 1/1 | 1/2 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| Duration [d] | 35 | 21 | 21 | 14 | 28 | 7 |
| Response Factor | 3.0 | 3.0 | 6.0 | 9.0 | 1.0 | 0.0 |

Other inputs to the rice yield model are the values of soil moisture at 100 % saturation and the soil moisture at the permanent wilting point. Typical values for the loamy-sandy Alfisol prevailing in the study area and rooting depths of 25 cm are 95 mm and 15 mm, respectively [96].

The actual plant available soil moisture and the deep percolation are provided by the paddy water balance model.

Based on the results of the water balance studies in paddy fields conducted by the author and taking into account the distribution of the water depth in paddy fields presented in [48], and furthermore the distribution of the yield response over the growing season, the daily irrigation requirement for the rice crop is determined as:

$$ID_{act} = DI + ET_{max} \tag{5.47}$$

where:

$ID_{act}$ = Irrigation requirement (demand) [mm/d]
DI = Depth index (Figure 5.22) [mm/d]

Due to the coarse nature of the soils in the study area a constant water depth cannot be maintained in the paddy fields. However to create the wet environment paddy needs for proper growth, farmers in the study area provide a considerable quantity of water, in excess of the maximum evapotranspiration, to the crop. The depth index is supposed to account for this quantity (Figure 5.22).

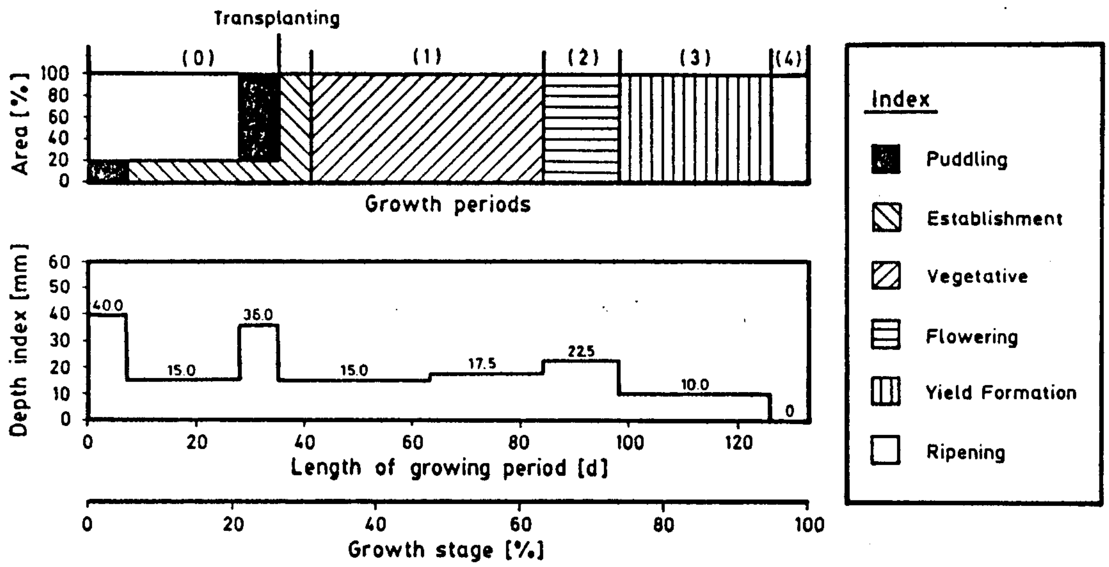



Figure 5.22: Depth Index as a Function of Growth Stage.

5.4.6.3 Economics Model

5.4.6.3.1 General

The prime objective of the economics model component is to evaluate the economic feasibility of the APPT. The economic feasibility can be judged by comparing the benefits and costs of the system.

The costs of APPT include those for planning, construction, operation, maintenance and financing of the project. Another cost to be taken into account is the compensation for ripanan rights for instance, for the reduced surface outflow from the system.

The benefits of the project comprise the incremental net returns from the cultivation of crops and the benefit resulting from the increased ground water discharge from the system. In order to determine the total incremental returns due to APPT, model runs with and without APPT were carried out for identical physical frameworks.

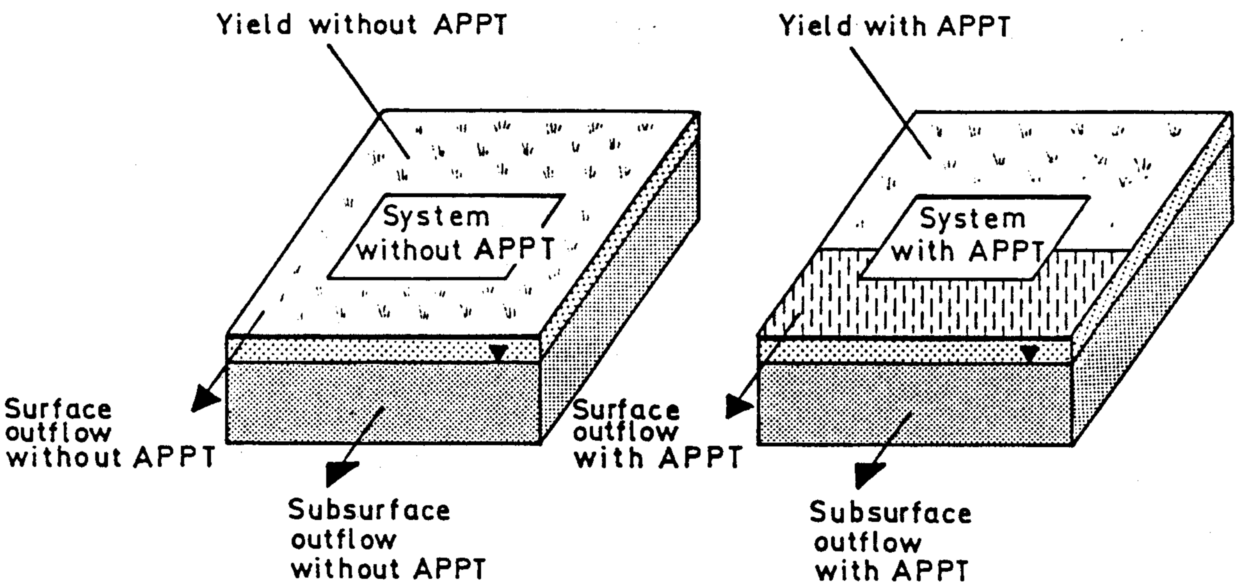



Figure 5.23: Determination of the Incremental Returns Due to APPT

Generally, the investment in a project is reasonable when the present worth of all benefits and costs over the assumed lifespan of the project, discounted with the rate of discount, is equal or greater than zero at the beginning of the investment (Equation 5.48). Of several alternative investments, the investment with the highest present worth is the best [147].

$$NPV = \sum_{j=0}^{T} \frac{B_j - C_j}{(1 + p / 100)^j} >= 0 \qquad (5.48)$$

where:

$$B_j = \Delta Y_j + \Delta BGW_j \qquad (5.49)$$

$$C_j = I_j + O_j + M_j + K_j + \Delta COW_j \qquad (5.50)$$

and:

$$\Delta BGW_j = \Delta GW_j \cdot SY_{gwj} \qquad (5.51)$$

$$\Delta COW_j = \Delta OW_j \cdot SY_{owj} \qquad (5.52)$$

with:

| | | | |
|---|---|---|---|
| NPV | = | Net present value of project | [Rs] |
| $j$ | = | Number of year | [1,2 ..] |
| $B_j$ | = | Benefit | [Rs] |
| $C_j$ | = | Costs at the end of the j th year | [Rs] |
| $T$ | = | Lifespan of the project | [a] |
| $p$ | = | Present worth factor | [%] |
| $\Delta Y_j$ | = | Incremental agricultural net returns due to APPT | [Rs] |
| $\Delta BGW_j$ | = | Incremental net return due to increased GW-discharge | [Rs] |
| $\Delta GW_j$ | = | Increase of GW-discharge | [$m^3$] |
| $SY_{gwj}$ | = | Specific benefit of ground water | [$Rs/m^3$] |
| $\Delta COW_j$ | = | Incremental costs due to reduced surface outflow | [Rs] |
| $\Delta OW_j$ | = | Reduction of surface outflow | [$m^3$] |
| $SY_{owj}$ | = | Specific benefits (costs) of surface water | [$Rs/m^3$] |
| $I_j$ | = | Investments | [Rs] |
| $M_j$ | = | Maintenance costs | [Rs] |
| $O_j$ | = | Cost of operation | [Rs] |
| $K_j$ | = | Capital cost | [Rs] |

#### 5.4.6.3.2 Calculation Procedure

As mentioned above, in order to determine the incremental returns from an APPT always two runs are performed:

- a so called "zero run" which represents a system with only rainfed dryland agriculture on the entire system area, and
- a "non-zero run" which represents the stage of development of the APPT such as a run with terraces and a well; a run with terraces, well and farm pond, or a run with terraces, well and increased height of terrace field bunds.

The type of run to be executed has to be specified in the main input file. If a "zero_run" is to be executed then the commands Yes_zero_run, No_terraces and No_pond have to be given in the input file. In addition all the nodes of the ground water model have to be defined as dryland nodes in the ground water model input file.

If a run with terraces, well and farm pond is to be executed then the commands No_zero_run, Yes_terraces and Yes_pond must be given in the main input file and the nodes of the ground water model must be defined accordingly.

The command Yes_terraces always includes a well. For runs with an increased height of terrace field bunds the parameter maximum surface storage has to be changed from the standard value of 100 mm to the required value (300 mm).

With the above commands all relevant types of runs can be performed. A "zero run" creates an output file in which the following information is stored:

- annual ground water discharge from the system
- annual surface water outflow from the system

This information is read during the subsequent "non_zero_run", allowing computation of the incremental returns due to increased ground water recharge. Given the additional inputs of the specific costs and returns of surface and ground water according to Equations 5.51 and 5.52, the incremental costs due to reduced surface outflow can be calculated.

All cost calculations are automatically adjusted by the model with respect to the type of run. For example, in a run without a farm pond the investment, operating and capital costs for the pond are not taken into account. For a terrace surface water storage higher than 100 mm additional investment costs, etc., are considered.

Also the computation of benefits depends on the type of model run. If the command Yes_zero_run is given then only the benefits from the dryland crop are computed. If it is not given then the incremental benefits are determined by employing Equation 5.49. The term $\Delta Y_j$, in this case, includes the net returns from the rice crops and the irrigated dryland crop minus the returns from the dryland crop for the area which is covered by terraces (Equation 5.55).

The annual benefits and costs (Equation 5.49 and 5.50) are computed in the model with and without the terms ΔBGWj and ΔCOWj in order to demonstrate the effect of taking into consideration such benefit or cost terms.

The modified rainfall file of the Aurepalle rainfall regime includes only 12 years of data. Whereas a lifespan of 36 years was assumed for the APPT. Therefore with n = rainfall years and j = lifespan years, the present worth of benefits minus costs is calculated three times for each rainfall year by employing j = n the first time, j = n+12 the second, and for the third time j = n+2·12.

The main steps for determination of the present worth of benefits and costs are the computation of:

- gross returns from crops
- annual income or benefits from crops
- annual incremental benefits from the system
- investments
- annual capital costs
- annual maintenance costs
- annual operation costs
- annual incremental costs from the system
- the present worth of all benefits and costs (zero run)
- the present worth of all incremental benefits and costs (non-zero run)

For convenience gross returns are calculated in the crop model. Equation 5.53 applies for all crops:

$$GR_{cr} = Y_{cr} \cdot A_{cr} \cdot P_{cr} \qquad (5.53)$$

where:

| | | |
|---|---|---|
| $GR_{cr}$ | = Gross return of crop | [Rs] |
| $Y_{cr}$ | = Yield of crop | [kg/ha] |
| $A_{cr}$ | = Area of crop | [ha] |
| $P_{cr}$ | = Farm gate price of crop | [Rs/kg] |

As far as the annual benefits from crops is concerned, this part of the economics calculations is also executed in the crop model. The income or beneit from a crop is determined by Equation 5.54, which is, in principle valid for all crops. The gross returns, the value of the by-product (fodder) and the value of the inputs are the main parameters:

$$B_{cr} = GR_{cr} - A_{cr} \cdot ( IP_{cr} - BP_{cr} ) \qquad (5.54)$$

where:

| | | |
|---|---|---|
| $B_{cr}$ | = Benefit from crop | [Rs] |
| $IP_{cr}$ | = Value of input for crop | [Rs/ha] |
| $BP_{cr}$ | = Value of by-product from crop | [Rs/ha] |

All further economics calculations were carried out in the main economics model component. The annual incremental benefits from the system were calculated by adopting Equation 5.55:

$$\Delta Y_j = B_{cr,w1} + B_{cr,w2} + B_{cr,w3} + B_{cr,id} - B_{cr,dry,w} \qquad (5.55)$$

where:

| | | |
|---|---|---|
| $B_{cr,w1}$ | = Benefit from wetland crop 1 | [Rs] |
| $B_{cr,w2}$ | = Benefit from wetland crop 2 | [Rs] |
| $B_{cr,w3}$ | = Benefit from wetland crop 3 | [Rs] |
| $B_{cr,id}$ | = Benefit from irrigated dryland crop | [Rs] |
| $B_{cr,dry}$ | = Benefit from dryland crop | [Rs] |
| $B_{cr,dry,w}$ | = Benefit from dryland crop on wetland area | [Rs] |

The investment for construction of the different components of the APPT consist of those for the well and terraces and, depending on the management alternative to be simulated, of the additional investments for terrace field bunds higher than 10 cm and the farm pond.

It is assumed that the land is owned by the farmer and therefore no costs for the aquisition of land or interest are incurred.

The annual capital costs for the above investments are approximated by the expression:

$$K = \frac{I}{2} \cdot \frac{p}{100} \tag{5.56}$$

where:

| | | |
|---|---|---|
| K | = Capital costs | [Rs] |
| I | = Sum of investments according to management alternative | [Rs] |
| p | = Interest rate | [%] |

According to the type of model run to be executed, annual maintenance costs comprise those for maintenance of the well and pump, those for the terraces including field bunds and for the farm pond. In the model the maintenance of the terraces and the field bunds is contained in the inputs for the crop production and therefore not expressed explicitly.

Annual operation costs for the farm pond and terraces are not considered. They are included in the monetary inputs for the cultivation of the crops. The well operation costs can either be determined as follows:

$$O_{well} = \frac{V_{abs,gw}}{Q_{abs,gw}} \cdot c_{pump} \tag{5.57}$$

where:

| | | |
|---|---|---|
| $O_{well}$ | = Operation costs of well | [Rs] |
| $V_{abs,gw}$ | = Annual ground water abstraction from well | [$m^3$] |
| $Q_{abs,gw}$ | = Hourly discharge from pump | [$m^3/h$] |
| $c_{pump}$ | = Hourly pump operation costs | [Rs/h] |

or they can be determined by assuming fixed annual operation costs for the well, which more accurately depicts the situation in the study area where a subsidised fixed rate per season and well is charged for electricity. Using this method the well operation costs can be incorporated in the model by setting the hourly pump operation costs to zero and then adding the fixed annual rate for operation to the maintenance costs of the well.

### 5.4.6.4 Selection and Determination of Agro-Economical Input Data

The procedure to determine the economical feasibility of the APPT described in the preceding sections requires a variety of inputs including:

- yields of crops and farm gate prices to determine gross returns,
- the value of agricultural inputs needed for crop production and the value of by-products from each crop in order to calculate the net income
- the investment, maintenance and operation costs as well as the interest rate for computation of the total costs of the system
- the specific benefits of surface and ground water to quantify in economical terms the impact of the APPT on the water balance of the system.

The yields needed for computation of gross returns are simulated in the various crop models. For these models the input of maximum yields is required. Taking into account reported values of average yields for sorghum, rice and groundnut in the study area (Appendix B) and an interview with an educated farmer (Appendix A), maximum yields under the local conditions were estimated to be in the range of:

- 4500 to 6000 Kg/ha for high yielding rice varieties, which have been adopted by the majority of the farmers (VLS data) [99]. The higher value is valid for the pre-monsoon season (high radiation) with fairly high inputs and efficient irrigation.
- 1750 to 2500 Kg/ha for locally planted groundnut varieties under irrigated conditions in the dry season.
- 600 to 1500 kg/ha for locally cultivated sorghum varieties, where the latter value reflects irrigated conditions.

The final maximum yield values (Table 5.5) were selected during a calibration process described in Section 5.5.

Table 5.5: Calibrated Maximum Yields of Crops as Used in APPSMOD in [Kg/ha]

| Crop | Maximum yield |
|---|---|
| Rice crop 1 (pre-monsoon) | 6000 |
| Rice crop 2 (monsoon) | 5600 |
| Rice crop 3 (late monsoon) | 5600 |
| Groundnut | 1750 |
| Sorghum | 1850 |

All prices and costs determined or selected from the literature were converted to 1986 prices by using an annual escalation rate of 7.5 %, which was derived from data presented in [157].

The farm gate prices adopted in APPSMOD were based on data from the ICRISAT village level studies at Aurepalle [99]. Averaging of the prices for the period from 1982 to 1984 and application of the above escalation rate lead to farm gate prices of 1.8, 4.4, 1.5 Rs/kg for rice, groundnut and sorghum, respectively. Interviews with a small sample of farmers carried out in 1986 indicated similar farm gate prices for rice and sorghum. For groundnut farmers quoted a price of 4.7 Rs/kg, therefore, this figure was used in the model.

The values of the agricultural inputs for the three crops were also calculated from the data collected in the village level studies. Data was only available for the period from 1975 to 1983. Since the input values fluctuated markedly between years and appeared to increase with years, average values were calculated from the years 1981 to 1983 and the results were converted to 1986 prices (Table 5.6).

Table 5.6: Value of Total Inputs (Nutrients, Seed, Pesticides, Machinery, Bullock and Human Labour at 1986 prices)

| | Inputs [Rs/ha] | Inputs* [Rs/ha] |
|---|---|---|
| Sorghum mix | 520 | 298 |
| Groundnut | 2799 | 2403 |
| Paddy | 3992 | 3257 |

* excluding family owned labour and bullocks

Source: Compiled by the author from ICRISAT village level studies data [99].

Values of inputs for groundnut and paddy obtained by the author were about 25% higher (Interview, Appendix A). They presented crop budgets for crops grown with inputs at the upper level of the range applied in the study region. Depreciation and maintenance of structures and equipment were also included in these budgets. Thus the authors results agree with the VLS derived data.

An additional benefit from the cultivation of crops is the value of rice and sorghum straw which can be used as fodder. Groundnut does not produce a by-product of commercial value. In the model by-product outputs of 240 Rs/ha and 630 Rs/ha were included for sorghum and rice fodder, respectively. The respective quantities and prices of the by-products as published in [57] were derived from [99] (Table 5.7).

Table 5.7: Value of By-products from Different Crops at 1986 prices

| Crop | Price [Rs/kg] | Quantity [Rs/kg] | Output [Rs/ha] |
|---|---|---|---|
| Sorghum mix | 0.12 | 2000 | 240 |
| Groundnut | -- | -- | -- |
| Paddy | 0.21 | 3000 | 630 |

Source: VLS Data as presented in [57].

In the present study an interest rate of 10 % was employed. Such an interest rate is also given in [47], [157], [251].

The values of investments, replacement and maintenance costs taken into account in the model are presented in Tables 5.8 and 5.9.

Table 5.8: Determination of Investments, Replacement and Maintenance Costs for a Well (1986 prices)

| Item | Initial Invest-ment [Rs] | Replace-ment costs [Rs] | Year [a] | Maintenance costs per [%] | Maintenance costs year [Rs] |
|---|---|---|---|---|---|
| Well: | | | | | |
| -Pump and engine 5 HP | 6400 A | 6400 | 18 | 1.5 | 128 |
| -Pump shed | 1200 A | | | 0.5 | 6 |
| -Excavation | 23000 A | 2000* | | 0.5 | 115 |
| -Pipe | 800 | 800 | 18 | 0.5 | 4 |
| -Electrical connection | 1140 A | 1140 | 18 | 0.5 | 6 |
| | 32540 | 10340 | | | 259 |

* removing of silt

Source: Investments marked with A from [57] including adjustment to 1986 prices.

Given an interest rate of 10 %, the present worth of the replacement costs occurring in the 18 th year after investment work out to be 1860 Rs. The sum of this value and the inital investment for the well amount to 34400 Rs. This valve is considered in the model as the total investment for the well.

For estimating annual maintenance and repair costs the normal practice is to utilize a percentage of the initial investment costs for the various components of an irrigation system [109]. Investigations in [57] indicated that very little maintenance is done on wells and pumps in the study area. Since labour is also available at low costs, smaller percentage costs for maintenance were emloyed than the values given in [109] (Table 5.8).

Table 5.9: Determination of Investments and Maintenance Costs for Terraces and a Farm Pond (1986 prices)

| Item | Initial Invest-ment [Rs] | Replace-ment costs [Rs] | Year [a] | Maintenance costs per [%] | Maintenance costs year [Rs] |
|---|---|---|---|---|---|
| Terraces: | | | | | |
| - Construction of levelled terraces 1.2 ha | 1284 A | -- | | * | |
| Terrace bunds: | | | | | |
| - Costs to increase height of bunds to 30 cm | 1000 B | -- | | * | |
| Farm pond: | | | | | |
| - Excavation 1200 $m^3$ | 20000 C | -- | | 1.0 | 200 |

* included in agricultural inputs (labour costs)

Sources: A = Water harvesting questionnaire conducted by the author
B = Estimated value
C = Value estimated from questionnaire conducted by the Economics Program of ICRISAT

As mentioned above operating costs are only considered for the well. The well can either be operated with an electric motor or a diesel engine. In the first case annual electricity costs of 300 Rs [57] are taken into account. In the latter case operating costs should be taken into consideration as costs per one hour of pumping. For a 5 HP pump with the price of 1 liter of diesel at 4 Rs [251] the hourly operation costs of the diesel engine are estimated to be 4 Rs/h. In order to determine the annual operation costs according to Equation 5.57 the additional inputs, hourly pump discharge and annual ground water draft, are required. The ground water draft is simulated in the well model. The pump discharge from a common 5 HP pump with about 10 m lift amounts, according to pump tests carried out by the author, to 42 $m^3/h$.

In order to quantify the benefits and costs resulting from the changed surface water and ground water outflow from an APPT, it is necessary to estimate the order of magnitude of the specific benefits of surface and ground water (Equations 5.51 and 5.52).

Considering a net water requirement for rice of 6300 $m^3/ha$ and a net return from rice of 3650 Rs/ha, the specific benefit for ground water works out to be 0.58 $Rs/m^3$. The productivity of surface water is assumed to be lower than that of ground water because in years with high rainfall high surface water losses can occur from a watershed. In the model specific benefits of surface and ground water of 0.5 and 0.25 $Rs/m^3$ were employed.

The agro-economical input data adopted in the model is summarized in Appendix U.

## 5.5 Calibration and Verification of the Model

Gauging the performance of a simulation model involves comparing the outputs generated by the model with those produced by the physical system being modelled. However any measure of model performance can only, at best, be as good as the input data and the observations of the physical system.

Since the physical system, in this case the Agronomically Productive Percolation System, represented only a concept and was therefore not actually monitored as a whole, a comparison of the performance of the entire system with the performance of the model was not possible.

It was, however, possible to compare the performance of some elements of the APPT for which data had been collected with the performance of the respective model components.

In the absence of long-term records of simulated and measured data, mathematical procedures to optimize parameters such as the method of least squares of deviation were not employed.

Since most of the parameters employed had physical significance the only viable means of calibration was to vary some of the input parameters within a plausible range. The intent was not to vary the input parameters too far beyond the measured or otherwise documented data.

Verification of the weather component was described in chapter 5.4.1 (Figure 5.6).

Some subroutines were adopted from the watershed model described in chapter 2 without significant changes. These included the catchment water balance model comprising the components runoff, infiltration, evapotranspiration and soil moisture movement. Further testing of these components was not required (chapter 2.5.6; Table 2.10).

The wetland component was verified against the data collected during the water balance studies in paddy fields (chapter 3). Depending on the rainfall during the different cropping seasons, the simulated ground water recharge in the rice terraces varied between roughly 50 and 75 % of the water applied which coincides with the measured values of 64.4 and 67.4 % (chapter 3, Table 3.2). No data was available to validate the simulation of the surface water outflow from the terraces because of the dry conditions during the observation period.

Also no data existed to validate the farm pond model. However, monitoring of irrigation and percolation tanks in the study watershed and modelling of the tank water balance in the watershed model provided helpful information (Figures 2.4 and 2.5).

Calibration of the crop models with measured data was only possible by comparing reported average yields and coefficients of variation of crops with the mean average yields and variation coefficients computed by the model for the simulation period. A satisfactory match of average yields and coefficients of variation (Table 5.10) was achieved by employing the maximum yield values presented in Table 5.5.

Only the dependency of yields on the water deficit was taken into account in the simulation, whereas in reality pests, diseases and other environmental factors influence yields. For irrigated crops the simulated coefficients of variation were therefore smaller than the corresponding coefficients of measured yields, while the one's for the dryland crops were of a similar value, because here the dependancy of yields on water deficits is more pronounced.

Table 5.10: Comparison of Simulated and Reported Yields

| Crops | Simulated Average (kg/ha) | Simulated Cv. (%) | Reported Average (kg/ha) | Reported Source | Reported Cv. (%) | Reported Source |
|---|---|---|---|---|---|---|
| Sorghum | 438 | 40 | 394-478 | [57] | 45 | [99] |
| Groundnut | 1633 | 3 | 1750 | * | 24 | [99] |
| Rice (pre-monsoon) | 4214 | 18 | ca. 4500 | * | | |
| (monsoon) | 4211 | 9 | ca. 4200 | * | 23 | [99] |
| (post-monsoon) | 4452 | 5 | ca. 4500 | * | | |

* various sources (Appendix A and B)

Although the maximum yield value of the sorghum crop was set very high (1850 kg/ha) the simulation results proved to be good. A modification of the reported yield response factors [48] would probably have led to the same results.

Further measures taken to verify the model were the computation of the water balance error of the entire system and plausibility checks.

The water balance error proved to be lower than 0.1 % of the volume of the annual rainfall (Appendix W). There are two reasons for this error. The first one lies in the variable surface area of the farm pond and the terraces and the second in the numerical errors of the ground water model. The latter one can be again split in two error components. Firstly the error occurring because of the set ground water balance error threshold of 1 mm, at which the iteration procedure is stopped to save running time and the numerical error which occurs when the model has to cope with relatively steep gradients as a result of an extreme rainfall event. This error was found to be greatest when the ground water aquifer overflows and baseflow is generated. Taking into account the low level of the combined water balance error and the uncertainty of a lot of parameters and assumptions made in the model and weighting it against the running time and additional programming effort saved, then the observed water balance error can be considered negligible.

The plausibility checks comprised of plotting and printing out results on daily, weekly, monthly and annual bases. Particular care was taken to test the performance of the ground water model by plotting ground water contour maps for different management alternatives and seasons in order to study the pre-monsoon, monsoon and post-monsoon water levels for dry and wet years and their dependency on the management of the system (Appendix TT).

In addition ground water level hydrographs simulated for the bottom boundary of the APPT (Figure 6.1 and 6.2) were compared with well hydrographs measured in the Aurepalle watershed (Appendix F). The water level hydrographs of observation wells 6, 1, 28 in Appendix F and the simulated ground water level for the APPT show a very similar pattern. The two peaks in the monsoon season of 1984 and the late single peak in 1985 as well as the absence of a significant water level rise in 1986 are clearly visible in simulated as well as measured hydrographs. The magnitude of the water level fluctuations however depends largely on the specific yield of the aquifer. While in the model a constant specific yield of 2.5 % was chosen for the entire APPT which was derived from pump tests carried out in the Aurepalle watershed, the variation of the specific yield between wells can be quite pronounced [155]. Furthermore the rainfall and boundary conditions vary a lot between wells. Therefore the measured ground water level hydrographs can only be used to check the plausibility of the simulated values.

## 5.6 Sensitivity Analysis

An extensive sensitivity analysis was conducted in order to firstly assess the effect of inaccurracies in estimation or determination of input parameters on the water balance and the economical feasibility of the system. Secondly it was conducted to evaluate the performance of the system under various physical environments. The parameters studied comprised:

Management parameter:

- Risk factor

Meteorological parameter:

- ET-sensitivity factor

Soil parameters:

- SCS curve number
- Plant available water of soils
- Hydraulic conductivity of terrace soil

Subsoil parameters:

- Hydraulic conductivity of the aquifer - Gradient of the ground water table at the lower boundary - Depth of aquifer

Economic parameters:

- Maximum yields
- Farm gate prices
- Discount rate

Other parameters:

- Area of the system
- Percolation rate of the farm pond
- Capacity of the tank

In addition to a run carried out with the standard input data, a minimum of two further runs were executed for each parameter with input values reduced and increased by 20 % .

In order to determine the effect of changing parameters on the incremental benefit of an APPT, the above mentioned model runs were conducted for both management alternative A (only drylands) and management alternative D (drylands plus terraces plus a farm pond).

Different risk factors were adopted to determine the most beneficial management strategy.

Further runs with different hydraulic conductivities of the aquifer and terrace soil were performed to investigate the impact of changes, of an order of magnitude, of these important parameters on the results.

Discount rates were varied with the aim of estimating the internal rate of return from the additional investments for the APPT.

As far as the parameters plant available water of soils, maximum yields and farm gate prices were concerned only the effects of a change of yield or prices of all crops at the same time were examined to reduce the number of model runs.

A detailed list of all runs carried out is given in Appendix V. A comprehensive quantitative overview of the impact of variation of parameters on the mean annual water balance and the net present value of the system with and without APPT is presented in Appendix W.

The results of the sensitivity analysis are dicussed and summarized below (following the sequence of parameters studied as given in Appendix V):

The risk factor does not influence a system with only dryland but has an impact on a system with terraces, since this factor has a direct bearing on the decision on the area to be cultivated which in turn influences the water balance and the economic performance. With an increasing risk factor (beginning from 0) the cultivated area increases slightly, therefore, the surface water retention of the system also increases. Due to the enhanced ground water demand the ground water outflow only decreases marginally. The net present value increases with increasing risk factor but the increase is negligible for risk factors higher than 0.4. Since the farmer can only take into account non-dependable resources with the maximum value of the dependable resources (chapter 5.4.6.1 "Farmers Decision Making") higher risk factors above 0.4 only lead to a marginal increase in the cultivated area. Without this condition the increase of the cultivated area would be more pronounced and for risk factors above 0.4 the frequency of crop failures would be greater and thus cause reduced net present values.

It is obvious that a change in the hydraulic conductivity of the aquifer has no effect on the net present value of a system composed of only drylands. The surface outflow is influenced in so far as a low hydraulic conductivity causes low ground water discharge from the system and in years with high rainfall the aquifer overflows resulting in baseflow which is defined as a portion of the surface outflow.

In a system with terraces and a farm pond the impact of the hydraulic conductivity on the water balance and the economic performance is more pronounced. Since at low hydraulic conductivities less ground water is discharged from the system, a larger area can be cultivated and thus the water retention in the system and the actual evapotranspiration increase. The high productive evapotranspiration is also reflected in an increased net present value. In quantitative terms reduction of the hydraulic conductivity by 20 %, which is certainly less than the accuracy of measurement of this parameter, leads to a reduction of the ground water discharge by 6 % and an increase of the net present value by 19 % . This parameter appears to be one of the most sensitive parameters as far as the impact on the economic performance is concerned.

The influence of a variation in the specific yield of the aquifer on the water balance and the net present value proves to be very low for a system without APPT. For a system with APPT an increase of the specific yield of the aquifer leads to an increased storage capacity which supports in turn a larger cultivated area, an improved surface water retention, higher productive evapotranspiration and higher economic returns. A 20 % increase of specific yield generates a 16 % larger net present value.

As described for the last two parameters above, the effect of the ground water table gradient at the lower boundary of the system on the water balance and economics of a system with only drylands is not very pronounced. However, in the management alternative D a reduction of the gradient by 20 % reduces the ground water discharge from the system by 6 %. The actual evapotranspiration increases by the volume of reduced discharge, while the surface outflow from the system remains unaffected. The net present value increases by 29 %. Thus the slope of the ground water table also falls into the categorie of highly sensitive parameters. It can be inferred from the results that at gradients of 0.2 % the net present value becomes greater than zero.

The results of a variation in the aquifer depth indicate that a depth of 12 m, in combination with the standard input data and the Aurepalle rainfall regime, is sufficient to prevent an overflow of the aquifer and thus losses through baseflow. There is only a negligible impact on the actual evapotranspiration and the net present value for depths higher than 12 m. Below 10 m the baseflow increases markedly which is compensated for by a decrease of the ground water discharge and a decrease in actual evapotranspiration resulting in a moderate reduction of the net present value.

By increasing or reducing the area the water balance of a system with only dryland (expressed in percent) is not affected. However in volumetric terms all parameters of the water balance increase or decrease at the same rate as the area of the system is changed. Consequently, a change of area by ±20 % causes a change in the net present value of ±20 % .

For a system with terraces and a farm pond the percentage wise water balance is also influenced by the size of the system. The percentage of surface outflow of the total water input increases in relation to the enlarged area, while the percentage of subsurface outflow decreases. The percentage of the actual evapotranspiration remains almost unaffected. Since the costs for the well were kept constant for all runs and since an increased area leads to a higher input of water to the system which allows cultivation of a greater area, the relative costs of irrigation decrease. For a certain physical framework there will be an optimum area which can be served by a single well. This fact is indicated by the net present value which increases with increasing area, but at a decreasing rate. For an area of approximatly double that of the standard value no further increase in the net present value can be expected. For the conditions at Aurepalle a system area of 18 ha can be recommended.

The curve number is a parameter representing the infiltration and runoff characteristics of the system. In general a higher curve number results in increased runoff and therefore increase of the surface outflow and losses from the system. Consequently the actual evapotranspiration decreases as well as the net present value. This phenomenon is valid for a system containing only dryland and systems including terraces and a farm pond. For the given rainfall pattern the runoff increases over-proportionally with curve number. Thus a reduction of the curve number has a lesser impact on the water balance of the system than an increase of the same order. Since the size of the farm pond and in turn the investments were not changed for runs with varying curve numbers, an increase of the curve number by 20 % caused a 340 % higher surface outflow. This can be clearly attributed to the insufficent capacity of the surface water retaining structures. The tremendous reduction in the net present value further indicates that an investment to construct such structures would be profitable for areas with high surface runoff.

For a system with only dryland, variation of the parameter total plant available water of soils had little effect on the mean annual surface outflow but a marked effect on the mean annual ground water discharge, the actual evapotranspiration and the net present value. An increase of 20 % of the plant available water caused a reduction of the annual ground water discharge by 19 % . The volume of reduction is equal to the volumetric increase of actual evapotranspiration. The higher evapotranspiration from crops is in turn reflected in an increase of the net present value by 20 %.

As far as the water balance is concerned the variation of the plant available water shows a similar effect on the system with terraces and a farm pond. However an increase of the plant available water causes a reduction of the net present value. This can probably be attributed to the fact that the soil is on average less saturated because the same amount of daily irrigation is supplied. Since the saturation is correlated with yields, a lower saturation causes lower yields and consequently a lower net present value. This phenomenon is certainly a result of the fact that all but one parameter are kept constant in this sensitivity analysis.

Apart from the parameter evapotranspiration, the following parameters do not have an impact on the water balance of a system with only dryland.

The net present value of a system with terraces and a farm pond proved to be relatively insensitive to variations of the hydraulic conductivity of the terrace soil. This is due to the fact that the increased conductivity causes a slight reduction of the surface outflow from the system. The increased conductivity however also results in greater infiltration leading to a higher ground water table and in turn higher ground water discharge. The increase of the ground water discharge compensates the reduction of surface outflow and the actual evapotranspiration stays constant.

A variation of the percolation rate of the farm pond by ±20 % only results in negligible variations of the overall mean annual water balance and consequently has little effect on the economic performance of the system. The main reason lies in the fact that the water collected in the farm pond is first used to meet the irrigation demand of the terraces, that the daily volume of irrigation is much higher than the losses through percolation and therefore the holding time of the water in the farm pond is fairly short for the Aurepalle rainfall pattern.

The results of the sensitivity analysis for the farm pond capacity parameter indicate a logical reduction of surface outflow when a larger farm pond is built. Thus more water can be applied to the terraces, the ground water recharge increases as well as the ground water discharge. The sensitivity of the surface and subsurface outflow to a change of farm pond capacity is only moderate and the sensitivity of the actual evapotranspiration even less. For example a reduction of the capacity by 510 $m^3$ increases the surface outflow by only 410 $m^3$. One can infer from this result that on average the farm pond is filled less than once a year.

As far as the behaviour of the net present value is concerned the model indicates a higher profitability with a larger farm pond. However in these runs the variation of costs due to the changed farm pond capacity was not considered. Taking this into account a 20 % smaller farm pond would increase the net present value by a similar percentage. This suggests that construction of a farm pond in an area as represented by the standard input data and at a cost of 7.8 Rs/$m^3$ is uneconomical.

It is obvious that the parameters maximum yield and farm gate prices of crops do not influence the water balance of the system. A 20 % rise of farm gate prices results in an increase of the net present value of the project by 49 % . An equivalent increase of crop yield has an identical effect. An over-estimation of the expected yield or drop in prices could therefore easily lead to a failure of such a project.

The runs with different discount rates indicated an internal rate of return of between 4 to 5 % for the system with additional terraces and farm a pond (standard input data). However the sensitivity analysis indicates that the internal rate of return can be markedly higher, when the system is placed in a more favourable physical framework.

In order to study the influence of an over or under-estimation of the potential evapotranspiration a factor was introduced by which the potential evapotranspiration could be modified. In the case of the system with only dryland, a 20 % under-estimation of potential evapotranspiration results in a 6 % lower actual evapotranspiration, a 22 % increased surface runoff and a 22 % greater subsurface outflow. The 20 % lower potential evapotranspiration leads to a 109 % higher net present value.

The effect of the variation of the potential evapotranspiration on the water balance in a system with terraces and farm pond is of the same order while the effect on the incremental net present value (+ 12 %) is much lower than in the dryland system. This can be attributed to the fact that the irrigated crops (high level of water supply) respond less to additional moisture than dryland crops (low level of water supply).

## 5.7 Production Runs

In order to test the performance of the APPT for different climatological frameworks the APPSMOD was run with four different rainfall input files, each representing a particular rainfall regime. Since the model requires 12 year-rainfall files, the original Anantapur, Hyderabad and Warangal rainfall records had to be modified. For Anantapur and Hyderabad, where rainfall records of more than thirty years were available to the author, a 12 year-rainfall sequence had to be selected. The selection was based on the criteria to obtain rainfall records with mean annual rainfall and standard deviation similar to those of the original time series. The three best matching time series were plotted and the time series with the most plausible distribution of wet and dry years was chosen. For Warangal only a 9 year rainfall record existed. To create a 12 years-file the years 3, 6 and 9 of the original sequence were appended at the end of the file. The specifications of the original and modified rainfall files are presented in Table 5.11. The distribution of the annual totals of precipitation are illustrated for all selected 12 year-records in Appendix C.

Table 5.11: Specifications of the Original and Modified Rainfall Records

| Stations | Original record from - to (years) | Mean (mm) | Std.dev. (mm) | Modified record from - to | Mean (mm) | Std.dev. (mm) |
|---|---|---|---|---|---|---|
| Aurepalle | 76/77-86/87 | 602.7 | 181.1 | 12 years | 634.2 | 202.4 |
| Anantapur | 50/51-83/84 | 565.3 | 134.0 | 53/54-64/65 | 589.0 | 135.3 |
| Hyderabad | 36/37-69/70 | 766.7 | 157.2 | 40/41-51/52 | 737.7 | 151.8 |
| Warangal | 75/76-83/84 | 994.3 | 257.0 | 12 years | 1021.4 | 281.7 |

For each of the rainfall regimes the model was run four times in order to determine the best management alternative. These runs included:

1. Run without APPT - Management altern. A
2. Run with Terraces (bund height 100 mm) - Management altern. B
3. Run with Terraces (bund height 300 mm) - Management altern. C
4. Run with Terraces and Farm Pond - Management altern. D

All runs were carried out with the standard input data (Appendix U). It should be noted that this procedure was not entirely correct since under the different rainfall regimes the cropping patterns would also differ. Another problem was presented by the use of the same crop response factors for all the rainfall regimes. It can therefore be assumed that especially in the case of the sorghum crop, yields would be over-estimated in high rainfall areas. On analyzing the results of the production runs this aspect should be borne in mind.

The results generated by the model are presented and discussed separately for each of the rainfall regimes.

A. Aurepalle Rainfall Regime:

Mean annual results:
The results for the Aurepalle rainfall regime indicate that the actual evapotranspiration increases with increasing sophistication of the system (Table 5.12). In terms of surface water retention management alternative D is far superior to the other alternatives. Compared to management alternative A the surface water outflow is reduced by more than 50 %, whereas the ground water outflow from the system is about equal for both alternatives. The actual evapotranspiration for management alternatives B and C is almost as high as that of alternative D, which suggests that the crops are well supplied by the available surface and ground water although

the surface water, retention is not as effective as in the system with a farm pond.

At an interest rate of 10 %, which is a rate that is frequently used in India to evaluate the economics of irrigation systems ([47], [157], [251]), the net present values obtained with management alternatives B, C and D were below zero. The sensitivity analysis indicated an internal rate of return between 4 and 5 % for management alternative D. The net present value of the system operated according to management alternative D was much lower than that of alternatives B and C (Internal rate of return close to 6 %). This was probably due to the high investment costs for construction of the farm pond. Obviously the increased supply of water to the paddy fields does not result in much higher yields and returns from the system, but results in a higher ground water recharge and therefore also higher ground water discharge than for management alternatives B and C (Table 5.12).

It can be concluded that it is not advisable to construct a farm pond or tank in an area where ponds are filled only occasionally and construction costs are in the order of 8 Rs/$m^3$. It is estimated that in the Aurepalle area, tanks and farm ponds are only economically feasible when favourable construction conditions allow construction of such structures at costs below 4 Rs/$m^3$.

Table 5.12: Effect of Management Alternative on Water Balance and Net Present Value
Rainfall Regime Aurepalle

| Management Alternative<br>Parameter | Unit | A | B | C | D |
|---|---|---|---|---|---|
| Mean actual ET | % | 79.0 | 82.5 | 82.6 | 82.9 |
| Mean surface outflow | % | 6.8 | 5.9 | 5.1 | 3.0 |
| Mean GW-outflow | % | 13.4 | 11.1 | 11.9 | 13.3 |
| Change of storage | % | 0.8 | 0.5 | 0.4 | 0.8 |
| Net present value | 1000 Rs | - | -9.6 | -8.5 | -25.7 |

Annual results:
Further information on the effects of water management alternatives on the economics and water balance of an APPT, yield the analysis of the annual data simulated for the Aurepalle rainfall regime (Tables 5.13, 5.14 and 5.15).

The results obtained for management alternative A (Table 5.13, 5.14) indicate a similar annual variation in the catchment and system water balance parameters as presented in chapter 2 (Figure 2.13) with a high coefficient of variation, especially for catchment surface runoff and recharge, as well as system surface outflow.

The high fluctuations of dryland crop yields and income (Family owned labour and bullocks considered on the cost side) provide an idea of the problems with which a dryland farmer has to cope within the semi-arid study area (Table 5.13, 5.14).

Whereas no difference can be found in the variation of the dryland water balance parameters between the two management alternatives A and D, the variation of the system water balance parameters seems to be slightly higher for management alternative D than for management alternative A.

Table 5.13: Annual Simulation Results for Aurepalle Rainfall Regime, Management Alternative A, 1976-77 to 1987-88

| Parameter | Unit | Year 76-77 | 77-78 | 78-79 | 79-80 | 80-81 | 81-82 |
|---|---|---|---|---|---|---|---|
| Rainfall | mm | 716 | 538 | 980 | 545 | 538 | 884 |
| Pan class A | mm | 2662 | 2835 | 2586 | 2793 | 2739 | 2735 |
| Runoff CA | $m^3$ | 3010 | 8315 | 17444 | 898 | 4643 | 10299 |
| Act. ET CA | $m^3$ | 83255 | 66967 | 93390 | 81520 | 71629 | 85770 |
| Recharge CA | $m^3$ | 11518 | 13967 | 30898 | 5619 | 0 | 39982 |
| Rainfall | $m^3$ | 107475 | 80640 | 147060 | 81795 | 80760 | 132615 |
| Act. ET | $m^3$ | 83255 | 66969 | 93390 | 81520 | 71629 | 85770 |
| Surf. outflow | $m^3$ | 3010 | 8315 | 17444 | 898 | 4643 | 11338 |
| Subs. outflow | $m^3$ | 13484 | 13288 | 26558 | 11944 | 2561 | 29377 |
| Stor. change | $m^3$ | -7726 | 7932 | -9668 | 12567 | -1927 | -8057 |
| Yield Sg | kg/ha | 405 | 267 | 409 | 347 | 527 | 730 |
| Income Sg | Rs | 4919 | 1808 | 5007 | 3608 | 7650 | 12218 |
| NPV | Rs | 6350 | 8472 | 13814 | 17314 | 24059 | 33854 |

| Parameter | Unit | Year 82-83 | 83-84 | 84-85 | 85-86 | 86-87 | 87-88 |
|---|---|---|---|---|---|---|---|
| Rainfall | mm | 454 | 477 | 554 | 612 | 330 | 980 |
| Pan class A | mm | 2882 | 2918 | 2894 | 2849 | 2977 | 2597 |
| Runoff CA | $m^3$ | 2643 | 393 | 5054 | 6521 | 210 | 17444 |
| Act. ET CA | $m^3$ | 65879 | 71774 | 62862 | 75782 | 50473 | 93084 |
| Recharge CA | $m^3$ | 0 | 0 | 13839 | 9910 | 0 | 30182 |
| Rainfall | $m^3$ | 68145 | 71595 | 83085 | 91755 | 49575 | 147060 |
| Act. ET | $m^3$ | 65877 | 71774 | 62862 | 75782 | 50473 | 93084 |
| Surf. outflow | $m^3$ | 2643 | 393 | 5054 | 6521 | 210 | 17444 |
| Subs. outflow | $m^3$ | 8001 | 1990 | 9854 | 9498 | 3669 | 22521 |
| Stor. change | $m^3$ | 8367 | 2562 | -5315 | 46 | 4777 | -14011 |
| Yield Sg | kg/ha | 179 | 400 | 233 | 399 | 694 | 669 |
| Income Sg | Rs | -181 | 4808 | 1041 | 4785 | 11405 | 10856 |
| NPV | Rs | 33722 | 36907 | 37534 | 40154 | 45831 | 50743 |

CA : Catchment; Sg : Sorghum; NPV : Net present value

Although the yields fluctuations of the irrigated crops were found to be much lower than that of the sorghum dryland crop, the fluctuations of the income from the irrigated crops proved to be higher than that of the dryland crop. This can be attributed to the fact that the area of dryland crops did not vary in contrast to the irrigated area and the coefficient of variation for rainfall was smaller than the variation of runoff and recharge used for irrigation.

Table 5.14: Mean Annual Simulation Results for Aurepalle Rainfall Regime, Management Alternatives A and D 1976-77 to 1987-88

| Parameter | Unit | Management alternative A Value | A Cv % | D Value | D Cv % |
|---|---|---|---|---|---|
| Rainfall | mm | 634 | 33 | 634 | 33 |
| Pan class A | mm | 2789 | 5 | 2789 | 5 |
| Runoff CA | $m^3$ | 6406 | 94 | 6374 | 94 |
| Act. ET CA | $m^3$ | 75199 | 17 | 74824 | 17 |
| Recharge CA | $m^3$ | 12993 | 106 | 12928 | 106 |
| Rainfall | $m^3$ | 95130 | 33 | 95130 | 33 |
| Act. ET | $m^3$ | 75199 | 17 | 78905 | 18 |
| Surf. outflow | $m^3$ | 6493 | 94 | 2838 | 124 |
| Subs. outflow | $m^3$ | 12729 | 71 | 12614 | 78 |
| Stor. change | $m^3$ | -709 | -- | -773 | -- |
| Yield T1 | kg/ha | -- | -- | 4214 | 19 |
| Income T1 | Rs | -- | -- | 676 | 71 |
| Yield T2 | kg/ha | -- | -- | 4211 | 10 |
| Income T2 | Rs | -- | -- | 495 | 105 |
| Yield T3 | kg/ha | -- | -- | 4451 | 5 |
| Income T3 | Rs | -- | -- | 1944 | 93 |
| Yield Gn | kg/ha | -- | -- | 1632 | 3 |
| Income Gn | Rs | -- | -- | 2156 | 85 |
| Yield Sg | kg/ha | 438 | 42 | 438 | 42 |
| Income Sg | Rs | 5660 | 72 | 4528 | 72 |
| Income system | Rs | -- | -- | 8758 | 59 |
| NPV | Rs | -- | -- | -25640 | -- |

CA : Catchment; Sg : Sorghum; NPV : Net present value
T1, T2, T3 : Terrace areas No. 1, 2, 3; Gn : Groundnut

Among the different rice crops the late monsoon crop produced the least variation in income, because at this time of the year the rainfall is much more dependable.

A comparison of the annually arising costs and benefits for the total system, including dryland and terraces shows a higher cash surplus for the farmer in all years and a lower variation than in the case of only dryland (Table 5.14, 5.15). This suggests that the additional investments into terraces and a dugwell lead to a more stable income for the farmer.

Table 5.15: Annual Simulation Results for Aurepalle Rainfall Regime, Management Alternative D, 1976-77 to 1987-88

| Parameter | Unit | Year 76-77 | 77-78 | 78-79 | 79-80 | 80-81 | 81-82 |
|---|---|---|---|---|---|---|---|
| Rainfall | $m^3$ | 107475 | 80640 | 147060 | 81795 | 80760 | 132615 |
| Act. ET | $m^3$ | 87372 | 72293 | 99919 | 84523 | 72748 | 92990 |
| Surf. outflow | $m^3$ | 0 | 4848 | 8512 | 0 | 1913 | 6485 |
| Subs. outflow | $m^3$ | 13728 | 11432 | 28584 | 9060 | 3101 | 28778 |
| Stor. change | $m^3$ | -6375 | 7933 | -10045 | 11788 | -2998 | -4362 |
| Yield T1 | kg/ha | 5113 | 3788 | 5007 | 4930 | 5030 | 2961 |
| Income T1 | Rs | 1168 | 432 | 706 | 1792 | 569 | 197 |
| Yield T2 | kg/ha | 4796 | 0 | 0 | 4418 | 3836 | 0 |
| Income T2 | Rs | 1186 | 0 | 0 | 918 | 89 | 0 |
| Yield T3 | kg/ha | 4357 | 4485 | 4737 | 4483 | 4186 | 4715 |
| Income T3 | Rs | 2352 | 3768 | 4131 | 471 | 313 | 5124 |
| Yield Gn | kg/ha | 1589 | 1604 | 1600 | 1635 | 1709 | 1596 |
| Income Gn | Rs | 1401 | 1541 | 4723 | 733 | 262 | 4468 |
| Yield Sg | kg/ha | 405 | 267 | 409 | 347 | 527 | 730 |
| Income Sg | Rs | 3935 | 1446 | 4006 | 2886 | 6120 | 9775 |
| Income system | Rs | 9542 | 6688 | 13066 | 6300 | 6852 | 19063 |
| NPV | Rs | -53308 | -47581 | -38982 | -36372 | -37075 | -31588 |

| Parameter | Unit | Year 82-83 | 83-84 | 84-85 | 85-86 | 86-87 | 87-88 |
|---|---|---|---|---|---|---|---|
| Rainfall | $m^3$ | 68145 | 71595 | 83085 | 91755 | 49575 | 147060 |
| Act. ET | $m^3$ | 68410 | 72392 | 66740 | 78589 | 51867 | 99012 |
| Surf. outflow | $m^3$ | 0 | 0 | 0 | 3357 | 0 | 8943 |
| Subs. outflow | $m^3$ | 6275 | 1350 | 11260 | 9437 | 2702 | 25663 |
| Stor. change | $m^3$ | 6540 | 2147 | -15219 | -372 | 4994 | -13442 |
| Yield T1 | kg/ha | 4594 | 2857 | 3511 | 4538 | 4197 | 4041 |
| Income T1 | Rs | 1104 | 178 | 222 | 721 | 629 | 391 |
| Yield T2 | kg/ha | 3820 | 0 | 0 | 0 | 4186 | 0 |
| Income T2 | Rs | 176 | 0 | 0 | 0 | 104 | 0 |
| Yield T3 | kg/ha | 4346 | 4360 | 4669 | 4389 | 3957 | 4737 |
| Income T3 | Rs | 446 | 224 | 2395 | 340 | 282 | 3486 |
| Yield Gn | kg/ha | 1620 | 1713 | 1620 | 1622 | 1675 | 1606 |
| Income Gn | Rs | 722 | 131 | 1926 | 2171 | 254 | 4512 |
| Yield Sg | kg/ha | 179 | 400 | 232 | 399 | 694 | 669 |
| Income Sg | Rs | -145 | 3847 | 833 | 3828 | 9124 | 8685 |
| Income system | Rs | 1803 | 3880 | 4876 | 6560 | 9893 | 16574 |
| NPV | Rs | -30142 | -30756 | -28447 | -27475 | -28227 | -25640 |

CA : Catchment; Sg : Sorghum; NPV : Net present value
T1, T2, T3 : Terrace areas No. 1, 2, 3; Gn : Groundnut

B: Anantapur Rainfall Regime

The response of the system to changing management alternatives under the Anantapur rainfall regime was, in principle, similar to that for Aurepalle (Table 5.16). However the percentage of the actual evapotranspiration was higher than in the Aurepalle area which was attributed to the more arid conditions in Anantapur. The increase in evapotranspiration was compensated for by a slightly reduced surface and subsurface outflow. The net returns proved to be smaller, by only a small margin, than those obtained for the respective management alternatives in Aurepalle.

Table 5.16: Effect of Management Alternative on Water Balance
and Net Present Value
Rainfall Regime Anantapur

| Management Alternative Parameter | Unit | A | B | C | D |
|---|---|---|---|---|---|
| Mean actual ET | % | 81.7 | 84.9 | 85.0 | 85.5 |
| Mean surface outflow | % | 6. 0 | 5.6 | 5.0 | 2.7 |
| Mean GW-outflow | % | 12.3 | 9.6 | 10.2 | 11.8 |
| Change of storage | % | 0.0 | -0.1 | -0.2 | 0.0 |
| Net present value | 1000 Rs | - | -9.4 | -9.3 | -26.7 |

C. Hyderabad Rainfall Regime

The management alternative C also appeared to be the most economically profitable one for the Hyderabad rainfall regime. As far as the water balance was concerned the percentage of evapotranspiration was lower than that for the Anantapur and Aurepalle rainfall regimes. The surface water retention in terraces and the farm pond appeared to be better than for the other areas above (Table 5.16). This could be due to a better distributed and less erratic rainfall pattern. On average the net present value was not higher than for the areas with less mean annual rainfall. This could be due to the fact that the yields and returns from the dryland are higher and that therefore the incremental returns from the APPT are reduced. Another explanation could be that the results are slightly distorted, because the distribution of the annual rainfall varies between the different rainfall regimes. For example a rainfall file with relatively low rainfall at the beginning of a time series could lead to similar net present values as a rainfall file with relatively high rainfall at the beginning of the series although, the mean annual rainfall of both files differs.

Table 5.17: Effect of Management Alternative on Water Balance
and Net Present Value
Rainfall Regime Hyderabad

| Management Alternative Parameter | Unit | A | B | C | D |
|---|---|---|---|---|---|
| Mean actual ET | % | 76.0 | 80.5 | 80.8 | 80.9 |
| Mean surface outflow | % | 6.6 | 5.3 | 3.8 | 2.5 |
| Mean GW-outflow | % | 17.4 | 14.3 | 15.6 | 16.5 |
| Change of storage | % | 0.0 | -0.1 | -0.2 | 0.1 |
| Net present value | 1000 Rs | - | -12.5 | -9.8 | -28.1 |

D. Warangal Rainfall Regime

In contrast to the small differences in the water balance and economic performance of the APPT's under the three rainfall regimes above the results for the Warangal rainfall regime were very different. The surface water outflow was four to nine times higher than that in the other areas, which could be attributed to the much more frequent rainfall, resulting in consistently wetter antecedent rainfall conditions and consequently much higher runoff. Although the percentage of actual evapotranspiration was much lower than in the other areas, the cultivated area and the net present value were much higher.

The high surface outflow under the Warangal rainfall regime presents a much higher potential for ground water recharge and subsequent use for irrigation than under the remaining rainfall regimes (Table 5.18).

Table 5.18: Effect of Management Alternative on Water Balance and Net Present Value Rainfall Regime Warangal

| Management Alternative Parameter | Unit | A | B | C | D |
|---|---|---|---|---|---|
| Mean actual ET | % | 50.4 | 56.4 | 56.5 | 56.4 |
| Mean surface outflow | % | 26.3 | 23.6 | 23.5 | 22.7 |
| Mean GW-outflow | % | 23.4 | 20.1 | 20.8 | 21.2 |
| Change of storage | % | -0.1 | -0.1 | -0.8 | -0.3 |
| Net present value | 1000 Rs | - | 40.4 | 42.8 | 21.1 |

For identical APPT's and thus equal investments the additional water retention due to an APPT added up to 5500 $m^3$ and 3600 $m^3$ for the Warangal and Aurepalle rainfall regimes, respectively (Difference between surface outflow from system with management alternative D and A). The difference between these two values does not appear to be very high, however, when taking into account that the evaporative demand of the rice crop in the Warangal area is lower than in Aurepalle and the rainfall alone covers a major portion of the water requirement, then it becomes clear that with the extra amount of water a substantially larger area can be cultivated. The end result is a much better display of economical performance. Thus APPT's appear to be more economical in areas with an annual rainfall of above 750 mm/year.

E. General Considerations

The effect of different rainfall regimes on the economical performance of an APPT can also be demonstrated through a comparison of the on average cultivated area of the various crops grown (Table 5.19). It is interesting to note that a smaller area is planted in Aurepalle than in Anantapur in the monsoon, although Aurepalle receives the higher mean annual rainfall. This can be attributed to the earlier peak of the monsonn rainfall in Anantapur. While relatively small differences in the cultivated area can be observed for the dry season groundnut crop, the increase of the rice area with increasing annual rainfall is much more pronounced. Here also it is clearly visible that application of APPT's is far more economical in higher rainfall areas.

Table 5.19: Effect of Rainfall Regime on Acreages for Different Crops and Management Alternative D

| Rainfall Regime | Crops | | | |
|---|---|---|---|---|
| | T1 (ha) | T2 (ha) | T3 (ha) | GN (ha) |
| Aurepalle | 0.15 | 0.08 | 0.41 | 0.42 |
| Anantapur | 0.15 | 0.16 | 0.15 | 0.40 |
| Hyderabad | 0.18 | 0.29 | 0.70 | 0.50 |
| Warangal | 0.26 | 0.77 | 1.27 | 0.71 |

T1 : Early monsoon rice
T2 : Monsoon rice
T3 : Late monsoon rice
GN : Groundnut dry season

An APPS should be efficient in recharging water and at the same time be a profitable irrigation system. These, however are objectives which point in opposite directions. The farmer operating the system tries to maximize his income by using the available water in the most efficient way. The aim of an authority promoting agronomically productive percolation systems is to increase the ground water discharge to maximize the positive effect of the system on the water balance of a watershed.

The model runs described above were carried out with the aim to achieve maximum benefits for the farmer, because this represents the only viable way to ensure that the APPS's are permanently well maintained and work efficiently. Measures to further increase the ground water discharge from the system would be to limit the area under cultivation. Thus the water application and consequently the ground water recharge per unit of area would be higher.

Model runs including the condition that the farmer is only allowed to cultivate a limited area indicate that the ground water discharge from a system with terraces and a farm pond could be increased beyond the discharge from a system with only dryland. For example, limiting the maximum area to 1.0 ha does not increase the ground water discharge in the Warangal rainfall regime significantly. From a maximum area below 0.6 ha the ground water discharge from a system with APPT is higher than that from a system without. The reduction in area, however results in a tremendously reduced net present value (Table 5.20).

Table 5.20: Effect of a Limited Cropping Area on the Water Balance and Economics for Management Alternative D; Warangal Rainfall Regime, Standard Input Data

| Management Alternative<br>Maximum Area<br>Parameter | ha<br>Unit | A | D<br>0.1 | D<br>1.0 | D<br>> |
|---|---|---|---|---|---|
| Mean actual ET | % | 50.4 | 51.3 | 55.5 | 56.4 |
| Mean surface outflow | % | 26.3 | 24.1 | 22.8 | 22.7 |
| Mean GW-outflow | % | 23.4 | 24.6 | 22.0 | 21.2 |
| Change of storage | % | 0.0 | 0.0 | -0.3 | -0.3 |
| Net present value | 1000 Rs | 255.2 | -94.3 | 1.8 | 21.1 |

In areas with high rainfall such as Warangal limitation of the cropping area would be acceptable, since the net present value is markedly above zero for a discount rate of 10 % . However it would be difficult to implement and control such a restriction.

From an economical point of view limitation of the cultivated area would not be feasible under low rainfall regimes. To increase the ground water discharge from the system another alternative for a watershed authority would be to subsidize the construction of farm ponds, since the management alternative D yielded lower net present values, but higher ground water discharge from the system under all the rainfall regimes.

# 6 CONCLUSIONS

The conclusions concerning the agro-hydrogeological inventory of the study watershed and the hydrological aspects of paddy irrigation described in chapters 2.6 and 3.5, respectively, resulted in the formulation of the concept of Agronomically Productive Percolation Systems (APPS). The conclusions drawn from the attempt to validate the APPS concept using modelling techniques are summarized below.

The quantitative results generated by the model have to be interpreted with caution because of the many assumptions made and the lack of more detailed data to validate the model. However the results have provided a basis for the understanding of the mechanisms inherent in an APPS:

## A. Findings Derived from the Sensitivity Analysis

The following findings were derived from the sensitivity analysis. They are valid for a system with a farm pond and terraces characterized by the standard input data (Aurepalle conditions):

1. The internal rate of return for the additional construction of terraces and a farm pond was estimated to be between 4 and 5 %. However, the sensitivity analysis indicated that the internal rate of return could be markedly higher if the system was constructed in a more favourable environment. Especially the subsurface inflow and outflow conditions strongly influence the amount of water available for irrigation and therefore have a strong bearing on the economical performance of the system.

- A 20 % lower hydraulic conductivity of the aquifer improves the incremental net present value by 19 %.

- The system also performs better in areas with a high aquifer storage capacity. A high specific yield results in greater ground water storage, lower water table fluctuations and thus a reduced baseflow in high rainfall years.

- The slope of the ground water table at the bottom boundary also has a strong impact on the profitablity of the system.
  A 20 % reduction in the ground water outflow gradient would increase the net present value by 29 % . At gradients of above 0.2 % the net present value becomes greater than zero.

- Aquifer depths of more than 12 m do not lead to a further reduction of the baseflow and thus do not enhance the economical performance.

- Favourable conditions for an APPT are encountered when the top boundary conditions of the aquifer are such that ground water inflow occurs from upward lying areas.

2. An optimum system area of 18 ha is recommended under the Aurepalle conditions for a system with one traditional dugwell.

3. Construction of farm ponds is more profitable in areas with catchment soils having higher runoff potential or when runoff can be harvested from relatively impermeable rocky outcrop areas, where runoff is generated even on days with fairly low rainfall (between about 10 to 40 mm).

4. The net present value is fairly insensitive to changes in the hydraulic conductivity of the terrace soil due to the compensating effects of surface runoff and ground water discharge.

5. As long as the percolation rate in the farm pond does not rise beyond tens of millimeters then it does not have a significant effect on the water balance and the economics of the APPT.

6. No further increase in size of the farm pond can be recommended for the Aurepalle rainfall pattern. Farm ponds appear to be uneconomical at a cost of about 8 Rs/$m^3$.

7. An overestimation of crop yields and a drop in farm gate prices could easily result in failure of a project since these parameters are highly sensitive. The net present value, for example, fluctuates by 49 % in response to a 20 % variation of yields or prices.

8. The effect of an overestimation of the potential evapotranspiation is less pronounced in a system with APPT than for a system without, because the response to additional water resources is lower at high levels of water supply (irrigation) than at low levels (dryland agriculture). However the impact of a 20 % variation of this parameter on the water balance and economics of the system is not negligible. An increase of 20 % results in a 12 % increase of the net present value.

B. Findings Derived from Production Runs

The conclusions derived from the production runs were drawn as follows:

The management alternative C (Terraces with increased height of field bunds and a dug well) appears to be the best method of management throughout all rainfall regimes as far as runs with standard input data are concerned. In low rainfall areas the additional farm pond required for management alternative D is not filled often enough to generate sufficient additional water resources and consequently does not provide benefits to justify the high investment costs. On the other hand the incremental benefits from the additional water are low in high rainfall areas such as Warangal.

The differences in the water balances and the economical performance of the APPT between the rainfall regimes Aurepalle, Anantapur and Hyderabad are not very pronounced. However, the results obtained for the Warangal rainfall regime reflect the much better economical performance of the system in higher rainfall areas. The main reason for this is the much higher surface runoff which provides the main potential for artificial ground water recharge, increased evapotranspiration from the system and, therefore, higher productivity.

Due to the fairly high subsurface outflow during the wet and dry seasons it is almost impossible to store water for the next premonsoon season. Storage of rainfall over the year was only observed in years with exceptional rainfall (Figures 6.1 and 6.2).

A rainfall pattern with an early peak probably produces higher recharge than a rainfall pattern with a late peak since early rains allow cultivation of larger areas in which runoff can be retained for recharge. Comparison of the results for the Aurepalle and Anantapur rainfall regimes support this observation. The APPT under the Anantapur rainfall regime with lower rainfall but an earlier peak performed almost as well as the APPT in the Aurepalle regime as far as the economics of the system was concerned.

There are compensating effects within the system which tend to even out the resources available to the farmer, although there are still large differences between years. For example in years with high rainfall a larger amount of surface water is lost and also the ground water outflow is higher. Whereas, in years of low rainfall the surface outflow from the system is negligible and the ground water discharge which is a function of the ground water level and in turn of the recharge is reduced.

From the analysis of the areas cultivated in the different croping seasons under the four rainfall regimes it can be inferred that the performance of the APPT could be improved by a better adaption of the standard cropping pattern to individual rainfall patterns.

A limitation of the area under cultivation with the aim to increase the ground water discharge from the system would only be economically feasible under the Warangal rainfall regime. Under these conditions an APPT is productive enough to be able to compensate for the considerable reduction of the net present value.

C. The Effect of APPT's on the Watershed:

Although in this thesis the positive effect of an APPT on the water balance and production of the watershed, within which the APPT is situated, is not quantified in economical terms, the following qualitative remarks can be made:

- Evaporation from a system with APPT is increased which leads to a higher overall productivity of the area.
- Surface water is retained in the upland areas which leads to a better retaining efficiency of surface water retaining systems situated downstream of the APPS, especially in high rainfall years.
- In low rainfall years the APPT generates ground water recharge which can be used for irrigation, whereas no recharge is observed for a system with only drylands (Figures 6.1 and 6.2; years 1980, 1983, 1985, 1986).
- In years with medium to high rainfall the recharge in a system with an APPT is significantly higher than for a system with only dryland.
- As far as the management alternative D is concerned the ground water discharge is not reduced compared to management alternative A (only dryland), while the production of the entire area is raised.
- The ground water storage in the upland areas can be used more efficiently, since in systems with APPT the ground water level before the monsoon season is lower than in systems with only dryland. Thus, more storage capacity is available for the generally higher ground water recharge in systems with an APPT (Figure 6.1 and 6.2).

- The on average higher water levels in the monsoon and post-monsoon season (middle to end of the year) illustrate the higher ground water recharge and discharge from sytems with APPT's during this period (Figure 6.1 and 6.2). The recharge wave generated during the monsoon reaches low lying areas after a delay when water levels there are already declining.

- Medium to low income farmers would mostly benefit from the APPT's because they own the land in the middle and upper reaches of a typical watershed. In contrast, the far more productive land in the valley bottom is mostly owned by high income farmers [44]. Therefore, construction of APPT's in the middle or upper reaches of the watershed would certainly have a positive effect on redistribution of income within the population of the watershed.

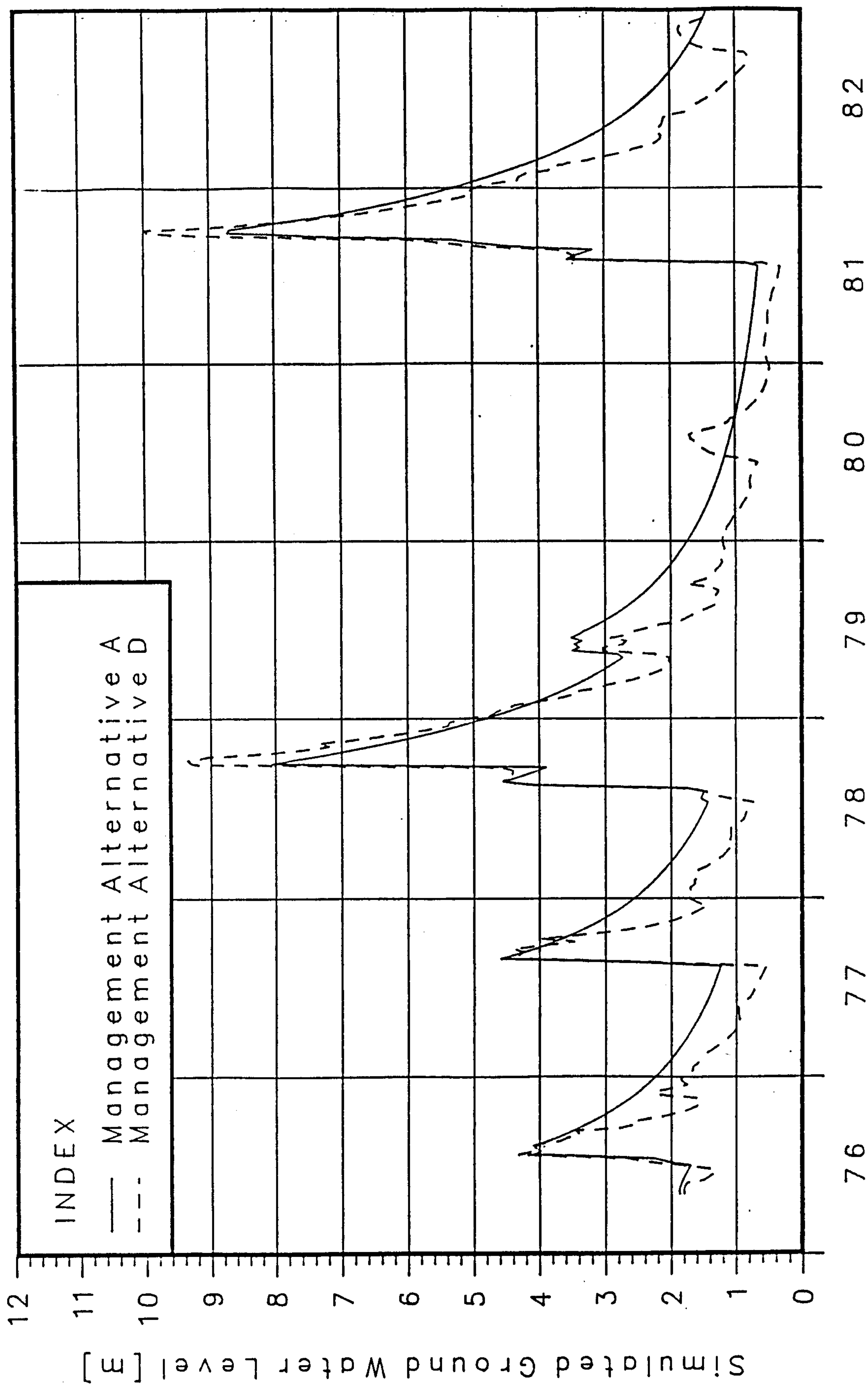



Figure 6.1: Simulated Ground Water Levels at the Outflow Cross-Section of the APPT for Management Altern. A and D, 1976 to 1982

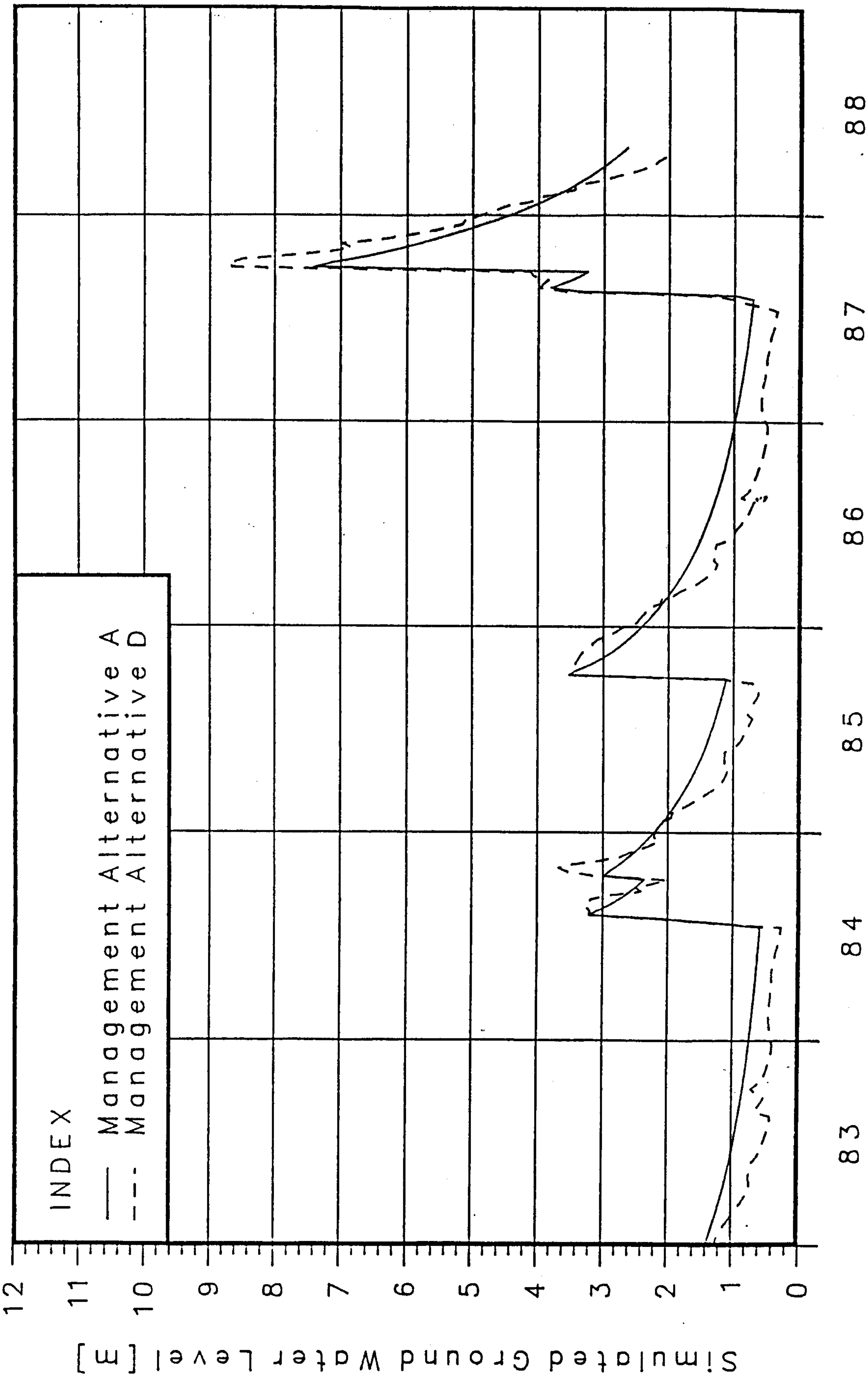



Figure 6.2: Simulated Ground Water Levels at the Outflow Cross-Section of the APPT for Management Altern. A and D, 1983 to 1088

To conclude with a few final remarks, it appears to be apparent from this study that:

- APPT's are generally economically feasible in high rainfall areas with an annual rainfall above 750 mm .
- In areas with an annual rainfall below 750 mm APPT's are economically feasible when favourable conditions are met such as a lower ground water table gradient, a lower hydraulic conductivity of the aquifer, a higher runoff generation than in case of the standard input data and when additional water retaining structures can be constructed at low costs.
- With the sensitivity analysis and production runs a data base has been established which provides a basis to assess and extrapolate the performance of APPT's in areas not covered by the sensitivity analysis and production runs.
- The developed model (APPSMOD) has been successfully used to provide further insight into the main hydrological and economic mechanisms inherent in an APPT.

## 7 FUTURE WORK

Drawing from the experience gained while conducting this project and from the extensive modelling experiments, several recommendations can be made for a continuation of the research in the field of Agronomically Productive Percolation Systems.

The future work can be divided into three main areas encompassing firstly modification of the model, execution of further model runs and construction and monitoring of pilot projects.

One important aspect which has not been considered in the model is the simulation of the rice yield decrease due to submergence. Such an amendment to the model would certainly provide a basis for the estimation of an optimal height for field bunds.

A more complex simulation of the farmers decision making process would certainly be an interesting and challenging area for future research. The first measure could be a generalization of the algorithm presented by the author to enable it to cope with different cropping patterns, followed by a comparison of different decision criteria.

The simulation of the farmers decision making process could be improved by integrating an expert system into the model. Expert systems have been developed for supporting decision making processes in the fields of medicine, environmental pollution, car maintenance, etc. Such intelligent computer programmes even exist for the selection of vines. To support the farmers decision making process the necessary set of relevant facts and rules would have to be established.

The model could be modified for use in extension work as a training tool for the education of local farmers or system operators. The model could be redesigned to stop when a decision is needed, displaying all the necessary information on the existing situation in the APPT, to enable the person being trained to make his own decision. Several decision strategies could be tested by comparing the results. The knowledge gained by the trainees from "trial and error" runs would help them understand how their decision making influences their income and apply this kwowledge on their own farms.

Further model runs could provide a better insight into the behavior of an APPT under different rainfall regimes. For this purpose the sensitivity analysis could also be carried out for the Anantapur, Hyderabad and Warangal rainfall regimes. Additional runs with different well locations would be helpful in determining the best position for the well within the system.

The question of whether it would be better to use all available resources for cultivation of a maximum area in the dry season or to save some water for the following pre-monsoon cropping season could be answered by varying the groundnut resource utilization factor (Appendix U.)

Before implementation of APPS's on a large scale it would be desirable to set up a series of pilot projects in climatologically and physically different areas in order to verify the conclusions based on the modelling results provided in this study. The monitoring of such systems would provide further information from which improved design criteria could be derived. Practical and operational problems in running agronomically productive percolation systems could be detected and solved. Pilot projects would also be helpful to test and adapt technologies to suite the local conditions for catchment, storage and distribution of water within the APPT. Appropriate rice varieties or other crops suitable for growth in APPT's, under conditions of prolonged submergence could also be selected.

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# APPENDIX A: ECONOMIC DATA

Table 1: Harvest Prices of Different Crops for Main Product in Rupees/kg at Aurepalle

| Crop | Variety | Year 1982 | 1983 | 1984 | 82/84 |
|---|---|---|---|---|---|
| Paddy | loc | 1.43 | 1.60 | 1.47 | 1.50 |
| Paddy | HYV | 1.41 | 1.49 | 1.44 | 1.45 |
| Sorghum | loc | 1.16 | 1.23 | 1.30 | 1.23 |
| Millet | loc | 1.05 | 1.19 | 1.12 | 1.12 |
| Castor | loc | 3.05 | 5.66 | 3.91 | 4.21 |
| Castor | HYV | 2.95 | 5.45 | 3.66 | 4.02 |
| Groundnut | | 3.44 | 3.66 | -- | 3.55 |
| Wheat | HYV | 2.40 | 2.60 | 2.51 | 2.50 |

loc: Local variety, HYV: High yielding variety
Source: Compiled by the author from ICRISAT VLS data

Table 2: Net Return Calculation for Groundnut and Paddy for Aurepalle Conditions at 1986 Prices in Rupees/Hectare and Season (Results of Interview with Educated Landlord)

| | Unit | Groundnut | | | Paddy | | |
|---|---|---|---|---|---|---|---|
| Inputs: | | | | | | | |
| Land preparation | [Rs/h] | | 400 | | | 750 | |
| Seed | [Rs/h] | | 1250 | | | 200 | |
| Farmyard manure | [Rs/h] | | 225 | | | 300 | |
| Complex DAP | [Rs/h] | (100 kg) | 325 | | (125 kg) | 400 | |
| N | [Rs/h] | (125 kg) | 275 | | (150 kg) | 330 | |
| Pest control | [Rs/h] | | 150 | | | -- | |
| Nursery plowing | [Rs/h] | | -- | | | 150 | |
| Nursery spreading | [Rs/h] | | -- | | | 50 | |
| Sowing/Transplanting | [Rs/h] | | 125 | | | 600 | |
| Weeding | [Rs/h] | | 300 | | | 200 | |
| Harvest/Threshing | [Rs/h] | | 250 | | | 1000 | |
| Permanent servant | [Rs/h] | | -- | | | 360 | |
| Electricity | [Rs/h] | | 60 | | | 100 | |
| Depreciation and Maintenance | [Rs/h] | | 400 | | | 625 | |
| Total Inputs | [Rs/ha] | | 3760 | | | 5065 | |
| | | low | medium | high | low | medium | high |
| Yield | [kg/ha] | 800 | 1750 | 2500 | 3500 | 4375 | 5600 |
| Harv. price | [Rs/kg] | 5.0 | 4.7 | 4.4 | 1.9 | 1.8 | 1.7 |
| Gross returns Main product | [Rs/ha] | 4000 | 8225 | 11000 | 6650 | 7875 | 9520 |
| By product (Fodder) | [Rs/ha] | -- | -- | -- | 700 | 700 | 700 |
| Total gross returns | [Rs/ha] | 4000 | 8225 | 11000 | 7350 | 8575 | 10220 |
| Net returns | [Rs/ha] | 240 | 4465 | 7240 | 2285 | 3510 | 5155 |

Table 2 indicates higher net returns for groundnut than for paddy in normal to good years. However, it has to be noted that the data on groundnut refers to the dry season and the data on paddy to the monsoon season. The yield and net returns of groundnut would be much lower in the monsoon season due to higher susceptibility to diseases in wet conditions. Thus groundnut can not be considered a serious competitor with rice in the wet season.

# APPENDIX B: YIELDS OF CROPS AND ACREAGES IN STUDY REGION

Table 1: Reported Grain Yields [kg/ha] for Main Crops and Different Sources

| Source | | Crops | | | | | |
|---|---|---|---|---|---|---|---|
| | | Paddy | | Groundnut | | Sorghum | Castor |
| | | Kharif | Rabi | Kharif | Rabi | | |
| Das Gupta | 1984 | 3750 H | 4250 H | 1500 I | 1750 I | 1500 I | 1000 I |
| Engelhardt | 1984 | 3174 H<br>2874 L | 2700 H<br>2874 L | 846 | | 436 | 192 |
| Walker and Subba Rao | 1982 | 2906 H | 3332 H | | | | 256 |
| Venkata Ramana | 1985 | 4138 H | 4533 H | | | 672 | 693 |
| Sharma | 1982 | 2781 *<br>4590 ** | 3092 * | | | | |
| Theune Questionnaire | 1985 | 4180 ** | 4680 ** | 1000 I | 1220 I | 300 | |
| Theune Measurement | 1986 | 4480 | | | | | |
| Sinha | 1985 | 1730 SI<br>5550 RI | 690 SN<br>2550 RN | 1220 SI<br>1760 RI | 770 SN<br>990 RN | 580 SN<br>3100 RN | |

S: State,
R: Research station,
K: Kharif (Monsoon),
R: Rabi (Post-Monsoon),
I: Irrigated,

N: Not irrigated
H: High yielding variety
L: Local variety
*: 60 % High yielding variety
**: 90 % High yielding ariety

Source: Compiled by the author.

From Table 1 can be inferred that yields of rice are generally 12 % higher in the post-monsoon season than in the monsoon season.

Table 2: Grain Yields of Selected Crops in Aurepalle Village in kg/ha (ICRISAT Village Level Studies (VLS))

| Crop | | Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | Av. |
| Paddy | HYV | 2203 | 1567 | 3231 | 3296 | 3796 | 2927 | 2921 | 3842 | 3834 | 4137 | 3175 |
| Paddy | loc | 1572 | 2228 | 3789 | 2964 | 3231 | 1681 | 1867 | 3009 | 2792 | 2438 | 2557 |
| Groundnut | | -- | 1730 | 850 | 741 | 803 | 767 | 894 | 948 | 1050 | -- | 973 |
| Sorghum | HYV | -- | 132 | 640 | 258 | -- | 338 | 872 | 151 | -- | 62 | 350 |
| Sorghum | loc | 217 | 242 | 346 | 553 | 380 | 249 | 171 | 460 | 402 | 296 | 332 |
| Millet | loc | 209 | 194 | 343 | 498 | 284 | 350 | 435 | 403 | 450 | 214 | 338 |
| Castor | HYV | -- | -- | -- | -- | -- | -- | 322 | 283 | 318 | 314 | 309 |
| Castor | loc | 196 | 95 | 584 | 250 | 174 | 169 | 71 | 155 | 65 | 85 | 184 |
| Wheat | HYV | -- | 864 | -- | -- | 890 | 867 | 1367 | 1243 | 1560 | 915 | 1101 |

HYV: High yielding variety,
loc: Local variety
Source: Compiled by the author from ICRISAT VLS Data.

Table 2 shows that crop yields have increased over the years, probably due to higher use of fertilizer, better management and improved crop varieties.

Table 3: Area of Different Crops in Aurepalle in Hectares during 1975 to 1984

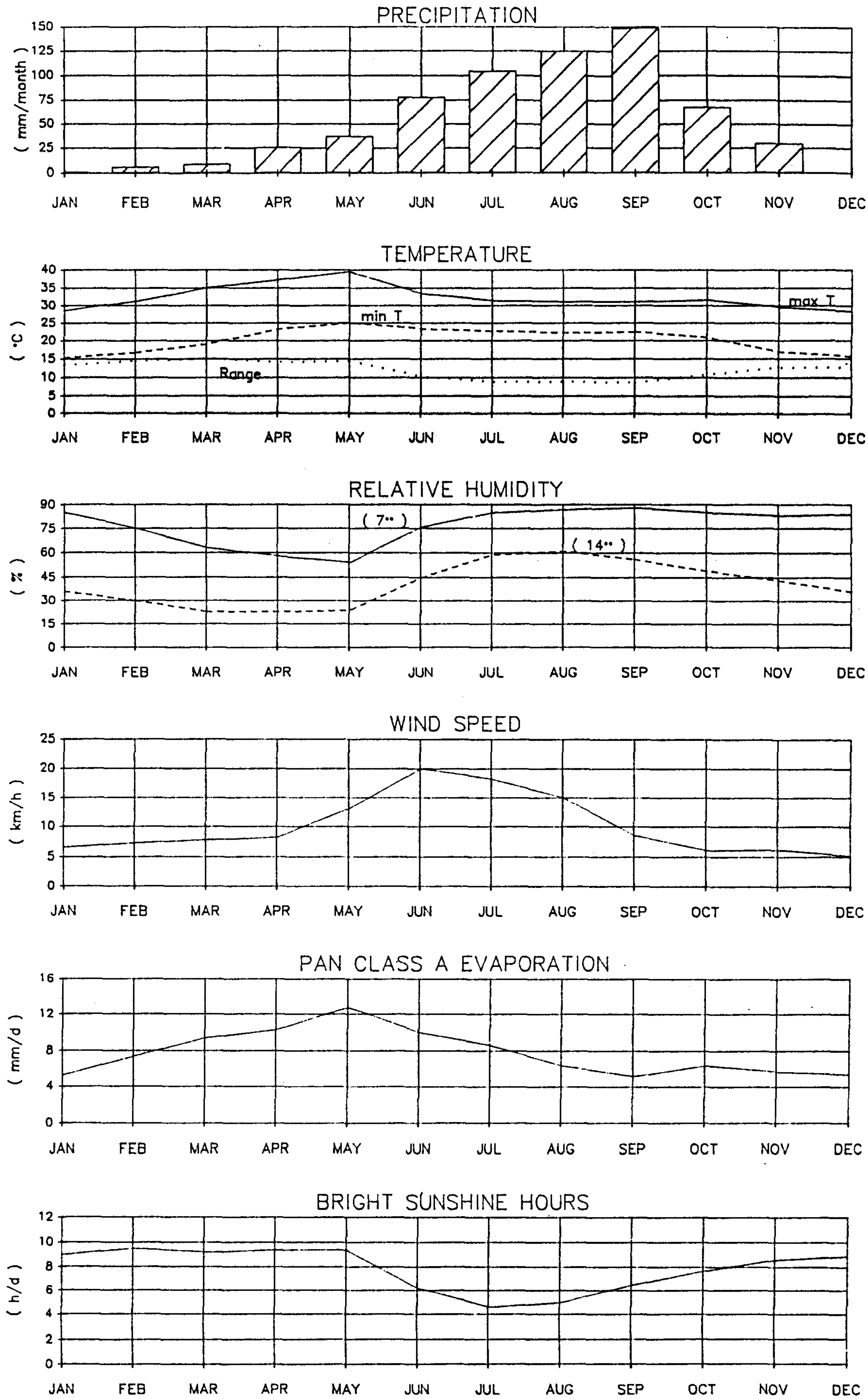
| Crop | | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 |
| Paddy | loc | 9.6 | 7.4 | 6.1 | 7.5 | 9.1 | 4.2 | 4.5 | 3.0 | 2.6 | 1.2 |
| Paddy | HYV | 15.5 | 16.3 | 17.2 | 18.2 | 17.2 | 15.4 | 17.7 | 12.2 | 19.1 | 19.0 |

Loc: Local variety, HYV: High yielding variety.
Source: Compiled by the author from ICRISAT VLS data.

Table 3 indicates that farmers have adopted high yielding varieties of paddy.

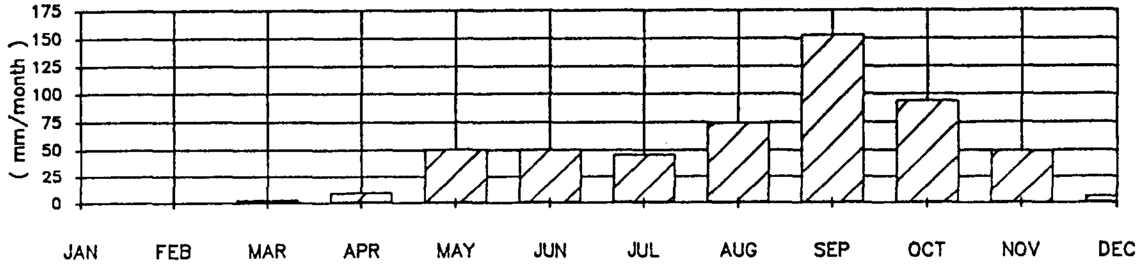
# APPENDIX C: METEOROLOGICAL DATA OF AUREPALLE, ANANTAPUR, ICRISAT, HYDERABAD AND WARANGAL

# METEOROLOGICAL DATA AUREPALLE

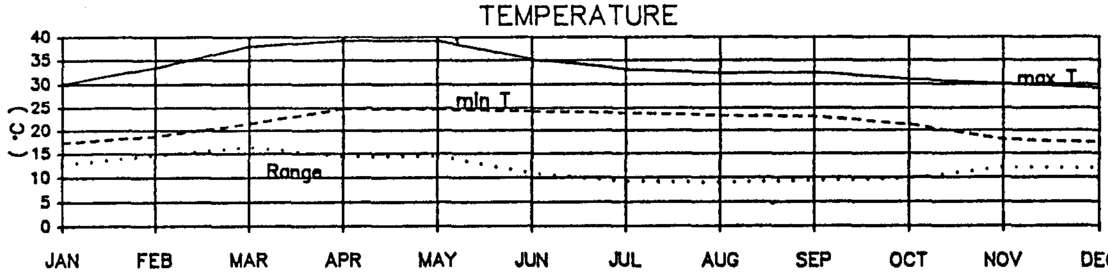


# METEOROLOGICAL DATA ANANTAPUR

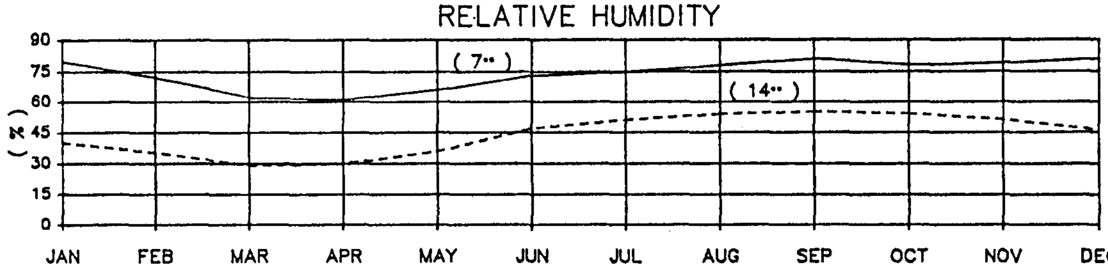
## PRECIPITATION



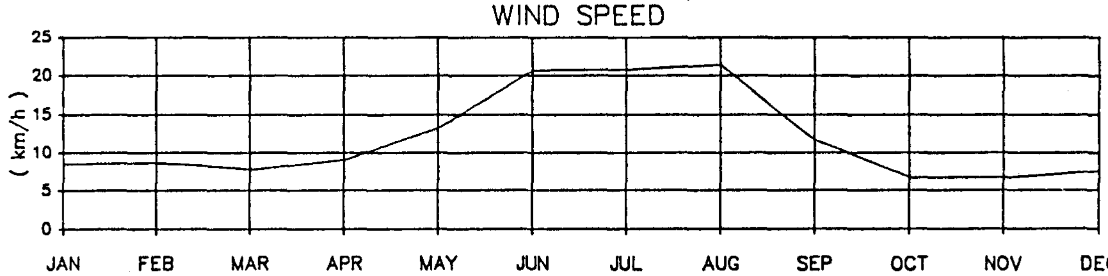

## TEMPERATURE



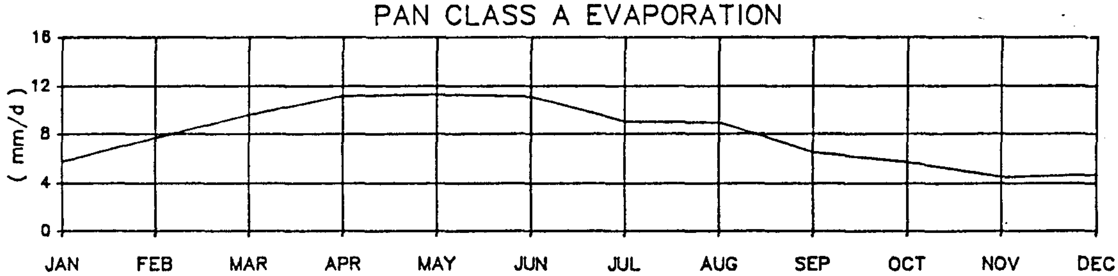

## RELATIVE HUMIDITY



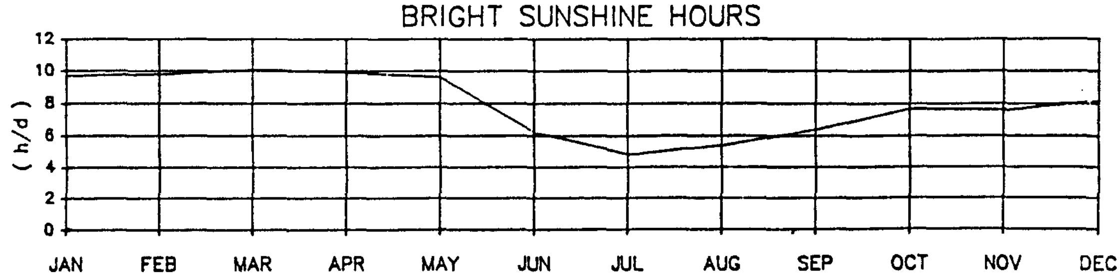

## WIND SPEED




## PAN CLASS A EVAPORATION

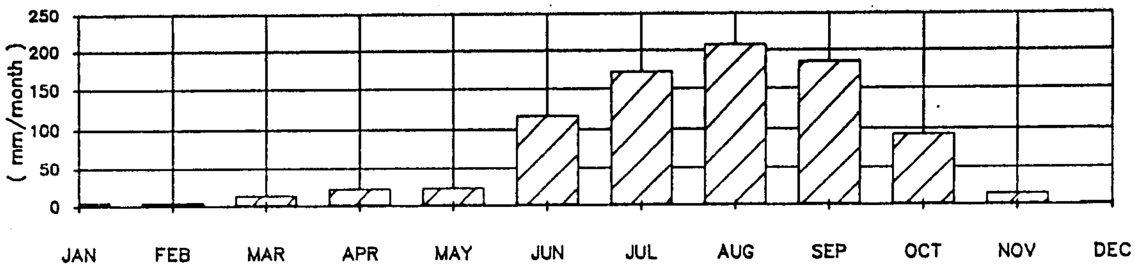



## BRIGHT SUNSHINE HOURS

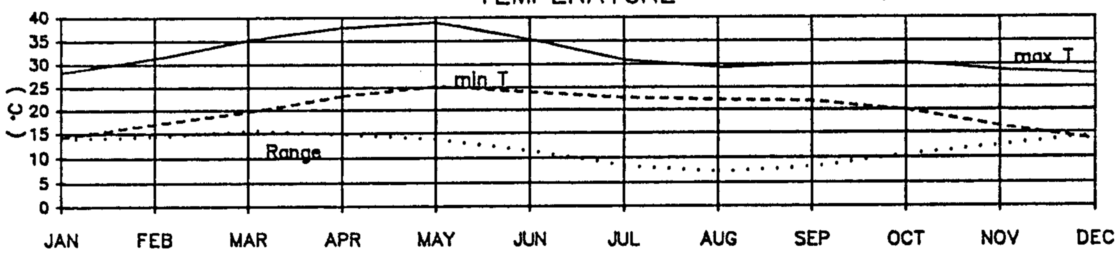


# METEOROLOGICAL DATA ICRISAT

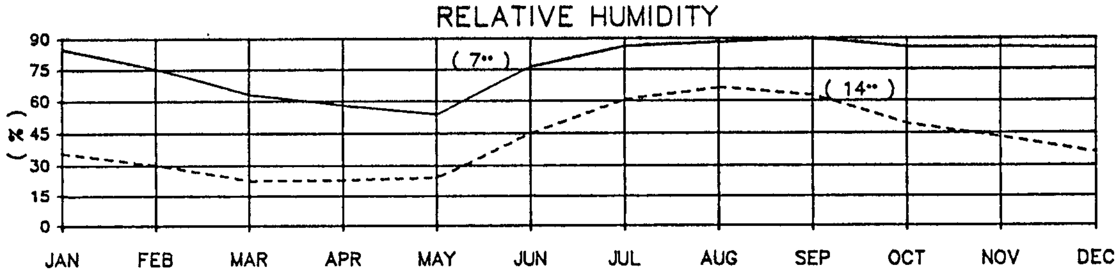
## PRECIPITATION



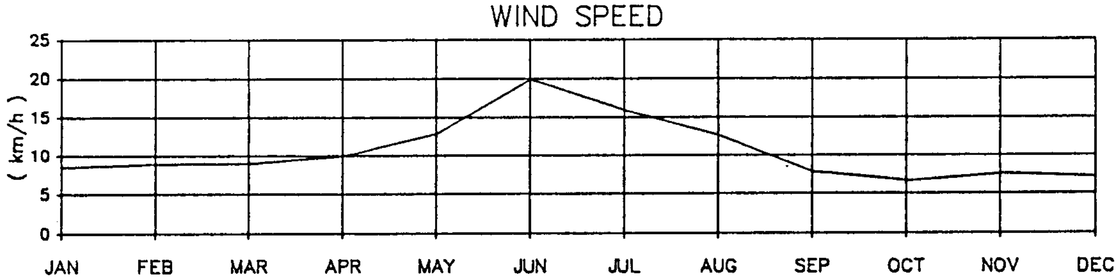

## TEMPERATURE



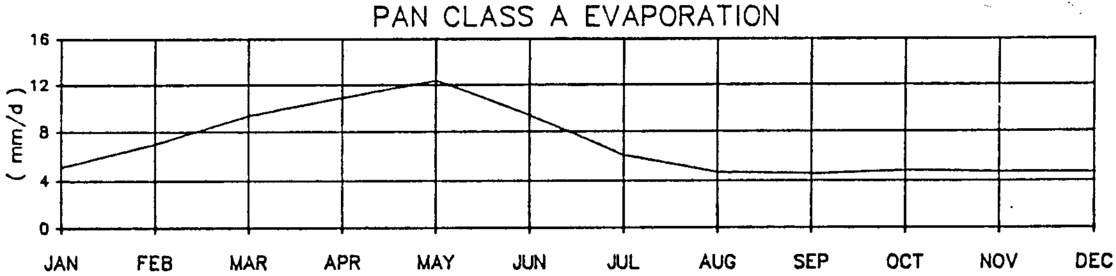

## RELATIVE HUMIDITY



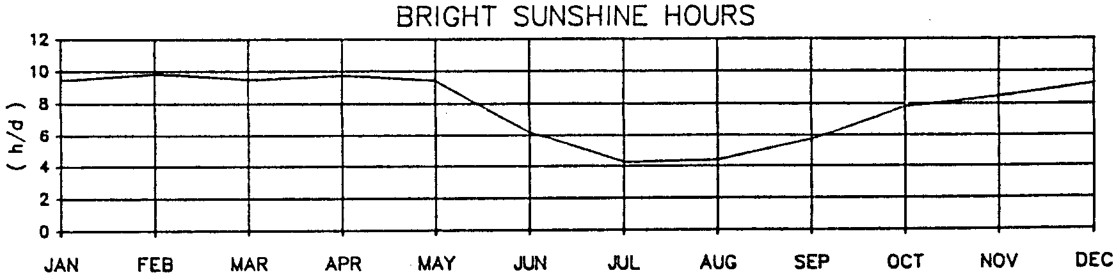

## WIND SPEED

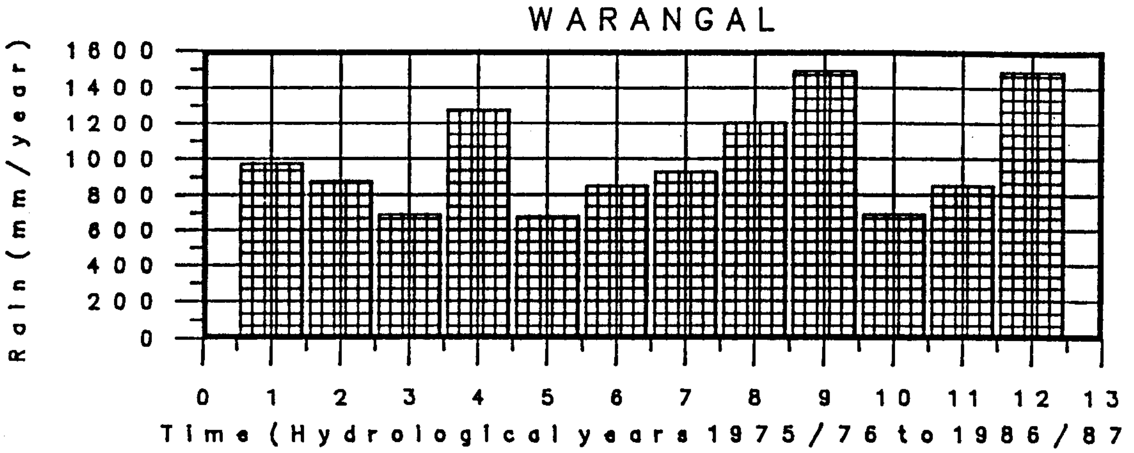


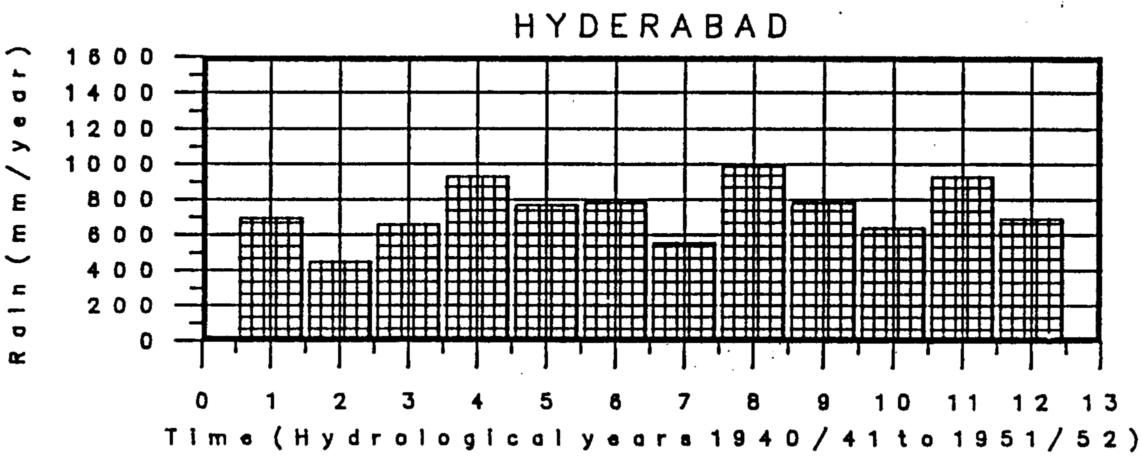

## PAN CLASS A EVAPORATION

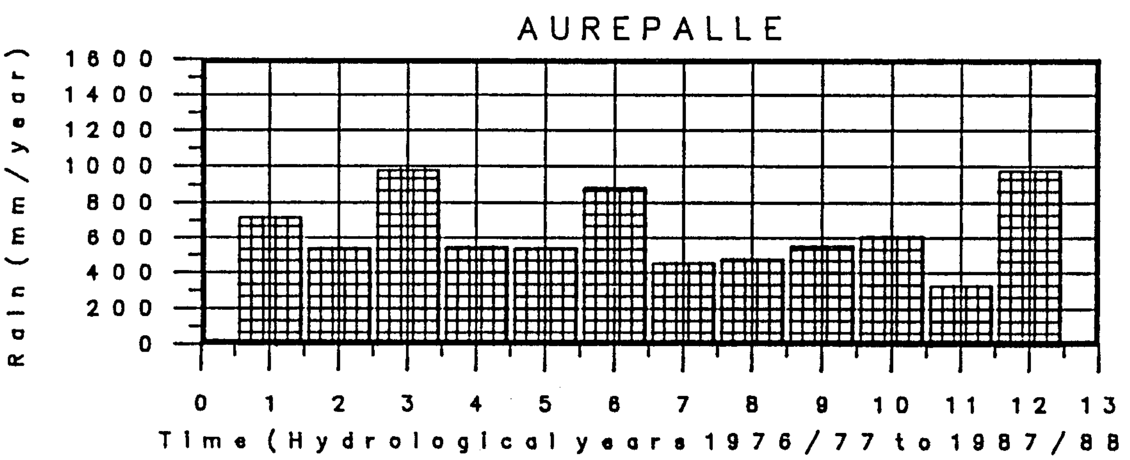


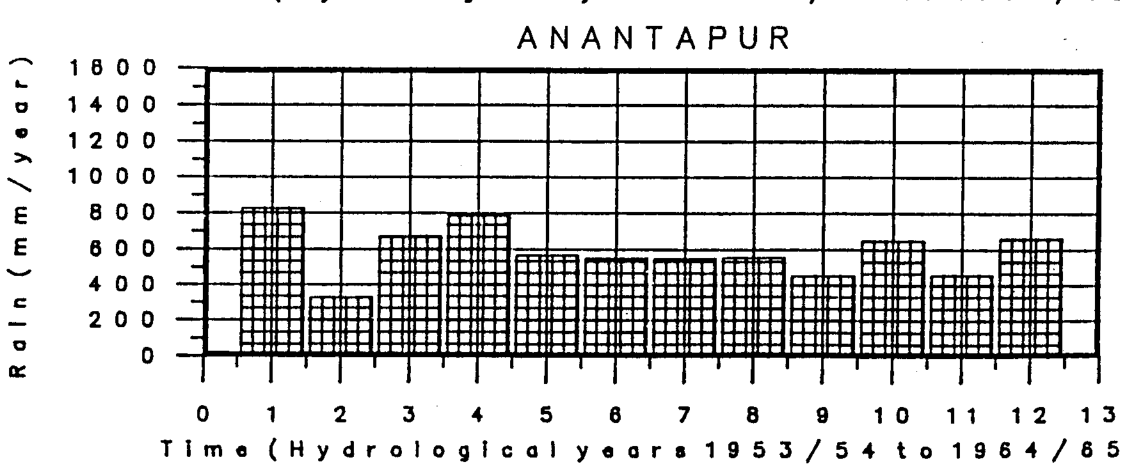

## BRIGHT SUNSHINE HOURS




WARANGAL
Rain (mm/year)
0 200 400 600 800 1000 1200 1400 1600
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time (Hydrological years 1975/76 to 1986/87)


HYDERABAD
Rain (mm/year)
0 200 400 600 800 1000 1200 1400 1600
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time (Hydrological years 1940/41 to 1951/52)


AUREPALLE
Rain (mm/year)
0 200 400 600 800 1000 1200 1400 1600
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time (Hydrological years 1976/77 to 1987/88)


ANANTAPUR
Rain (mm/year)
0 200 400 600 800 1000 1200 1400 1600
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time (Hydrological years 1953/54 to 1964/65)

# APPENDIX D: DEFINITION OF STANDARD WEEKS

"The Standard Weeks"

| Week No. | Month | Dates | Week No. | Month | Dates |
|---|---|---|---|---|---|
| 1 | January | 01-07 | 27 | July | 02-08 |
| 2 | | 08-14 | 28 | | 09-15 |
| 3 | | 15-21 | 29 | | 16-22 |
| 4 | | 22-28 | 30 | | 23-29 |
| 5 | | 29-04 | 31 | | 30-05 |
| 6 | February | 05-11 | 32 | August | 06-12 |
| 7 | | 12-18 | 33 | | 13-19 |
| 8 | | 19-25 | 34 | | 20-26 |
| 9 | | 26-01 | 35 | | 27-02 |
| 10 | March | 05-11 | 36 | September | 03-09 |
| 11 | | 12-18 | 37 | | 10-16 |
| 12 | | 19-25 | 38 | | 17-23 |
| 13 | | 26-01 | 39 | | 24-30 |
| 14 | April | 02-08 | 40 | October | 01-07 |
| 15 | | 09-15 | 41 | | 08-14 |
| 16 | | 16-22 | 42 | | 15-21 |
| 17 | | 23-29 | 43 | | 22-28 |
| 18 | | 30-06 | 44 | | 29-04 |
| 19 | May | 07-13 | 45 | November | 05-11 |
| 20 | | 14-20 | 46 | | 12-18 |
| 21 | | 21-27 | 47 | | 19-25 |
| 22 | | 28-03 | 48 | | 26-02 |
| 23 | June | 04-10 | 49 | December | 03-09 |
| 24 | | 11-17 | 50 | | 10-16 |
| 25 | | 18-24 | 51 | | 17-23 |
| 26 | | 25-01 | 52 | | 24-31 |

# APPENDIX E: SAMPLE OF WELL AND WATER HARVESTING QUESTIONNAIRE

Well questionnaire

Watershed: Investigator: Date:

| Well identification: | | Soil profile: | | Coding: |
|---|---|---|---|---|
| Code | | Top soil | ________ m _ | |
| Location code | | Alluvium | ________ m _ | |
| Description of location | | High fract. granite | ________ m _ | |
| Owner's name | | Low fract. granite | ________ m _ | |
| Village | | Bedrock | ________ m _ | |

| Well design: | | Top | Bot |
|---|---|---|---|
| Shape | | | |
| Construction | | | |
| Depth | ( m ) | | |
| Width | ( m ) | | |
| Length | ( m ) | | |

Other geological features close to well:

| Water lifting: | | Suc | Del |
|---|---|---|---|
| Lifting device | | | |
| No. of pumpsets | | | |
| Horse power | ( HP ) | | |
| Diameter of pipe | (inch) | | |
| Length of pipe | ( m ) | | |
| Height of pumpset | ( m ) | | |
| Height of del. pipe | ( m ) | | |

| Water quality: | |
|---|---|
| Salinity | |
| Other problems | |

| Well performance: | | low | med. | high |
|---|---|---|---|---|
| Farmer's estimation | | | | |
| Acres irrigated | | M | DS | PM |
| Paddy | (acre) | | | |
| Range of paddy area | (acre) | | | |
| ID-crops | (acre) | | | |
| Daily pumping | (hrs ) | | | |
| Time of pumping: morn. | (hrs ) | | | |
| Time of pumping: even. | (hrs ) | | | |
| Pump. days season | (days) | | | |
| Average water level | ( m ) | | | |
| Drawdown | ( m ) | | | |
| Recovery after 3 days without pumping | ( m ) | | | |
| Overflowing | | | | |

| Constraints: | |
|---|---|
| Land | |
| Water | |

| Recharge by tank: | | Full | Half | Nearly empty |
|---|---|---|---|---|
| Water level in well when tank is | ( m ) | | | |
| Distance to tank | ( m ) | | | |

| Quality of obtained data: | | |
|---|---|---|
| Low | Med | High |

Remarks:

ID - crops = Irrigated Dryland crops M = Monsoon DS = Dry Season PM = Pre-Monsoon

# QUESTIONNAIRE
# RAINWATER HARVESTING IN PADDY FIELDS

PLOT IDENTIFICATION | | CODE

Farmer's name : ____________________ ____
Location of well : ____________________ ____
Well number : ____________________ ____

MICRO ENVIRONMENT YES = 1 NO = 0

Upland paddy : ____________________ ____
Lowland paddy : ____________________ ____
Soil type : ____________________ ____
Soil depth : ____________________ ____

IRRIGATION PRACTICES PM M

How Many days in Pre-Monsoon and Monsoon 1985 did you use wellwater for irrigation ? ____________ d ____ ____
How many days in Pre-Monsoon and Monsoon 1985 did you use tankwater for irrigation ? ____________ d ____ ____
How many days in Pre-Monsoon and Monsoon 1985 did you use rainwater for irrigation ? ____________ d ____ ____
How many days in Pre-Monsoon and Monsoon 1985 did you use runoff for irrigation ? ____________ d ____ ____
What is the maximum depth of irrigation ? ____________ mm ____ ____
What is the minimum depth of irrigation ? ____________ mm ____ ____
What is the depth of submergence before pumping ? ________ mm ____ ____

HARVESTING PRACTICES qualitatively YES = 1 NO = 0

Do you harvest rainwater in your paddy fields ? ________ ____ ____
How do you harvest rainwater in your paddy fields ? ________ ____ ____
____________________________________________
Why don't you harvest rainwater in your paddy fields ? ____ ____ ____
____________________________________________
____________________________________________
Do you harvest runoff from upper lying areas ? ________ ____ ____
Do you divert water from gullies to your fields ? ________ ____ ____
Why don't you harvest runoff ? ____________ ____ ____
____________________________________________
____________________________________________
Do you retain all the rainwater ? ____________ ____ ____
Do you retain all the rain- and runoff water ? ________ ____ ____
Do you retain rainwater in terraces with ID-crops ? ________ ____ ____
Wy don't you retain rainwater in terraces with ID-crops? __ ____ ____
____________________________________________
____________________________________________

HARVESTING PRACTICES quantitatively YES = 1 NO = 0 PM M

| | | PM | M |
|---|---|---|---|
| On how many days was rainwater harvested in 1985 ? ________ | d | ____ | ____ |
| Up to what depth do you store rainwater ? ________ | mm | ____ | ____ |
| How long does the water stay in the field ? ________ | d | ____ | ____ |
| How many acres o paddy did you cultivate in 1985 ? ________ | acr | ____ | ____ |
| How many days in 1985 did you not pump due to rain ? ________ | d | ____ | ____ |
| How many days in 1985 did you pump less than normal due to rain ? ________ | d | ____ | ____ |
| How many acres wetland do you have ? ________ | acr | ____ | ____ |

ALTERNATIVES YES = 1 NO = 0

| | | PM | M |
|---|---|---|---|
| Could you harvest more rainwater through increase of bund height ? ________ | | ____ | ____ |
| What wouldbe the maximum permissible depth of submergence that yield is not influenced ? ________ | mm | ____ | ____ |
| Do you think that rainwater stored in uncultivated terraces can be used for irrigation ? ________ | | ____ | ____ |
| Do you think that rainwater stored in uncultivated terraces would recharge your well ? ________ | | ____ | ____ |

COSTS AND MAINTENANCE PM M

| | | PM | M |
|---|---|---|---|
| What are the costs per acre for construction of terraces and field bunds ? ________ | Rs | ____ | ____ |
| What are the annual costs per acre for maintenance of terraces and field bunds ? ________ | Rs | ____ | ____ |

YIELDS AND NET RETURNS

What are the average yields and net returns per acre of following crops ?

| | | PM | M | | PM | M |
|---|---|---|---|---|---|---|
| Paddy | t | ____ | ____ | Rs | ____ | ____ |
| Groundnut | t | ____ | ____ | Rs | ____ | ____ |
| Castor | t | ____ | ____ | Rs | ____ | ____ |
| Sorghum | t | ____ | ____ | Rs | ____ | ____ |
| Millet | t | ____ | ____ | Rs | ____ | ____ |
| Tomatoes | t | ____ | ____ | Rs | ____ | ____ |
| Chillies | t | ____ | ____ | Rs | ____ | ____ |

QUALITY OF DATA Low ____ Med ____ High ____

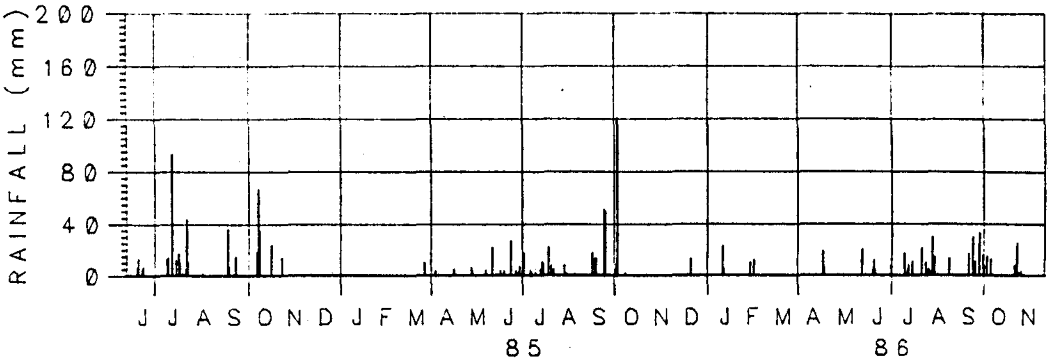
REMARKS:

PM = Pre-Monsoon M = Monsoon Rs = Rupiees

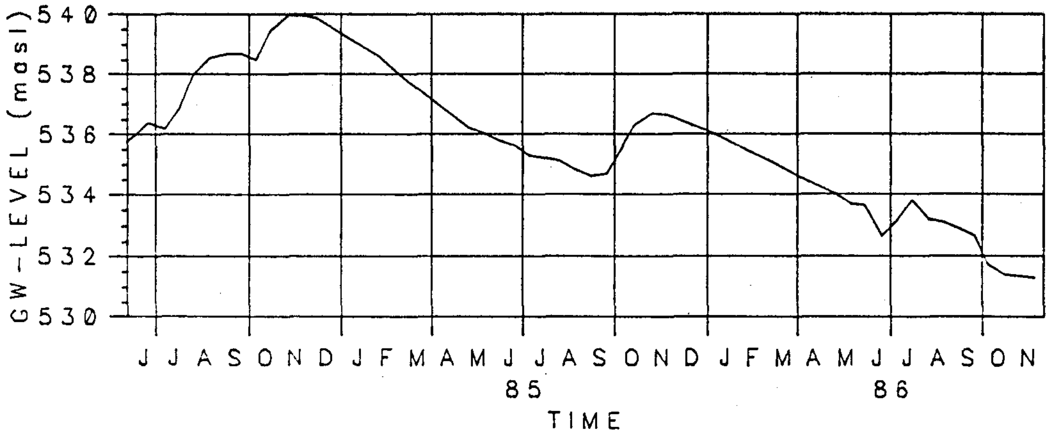
# APPENDIX F: SELECTED WELL HYDROGRAPHS

F1

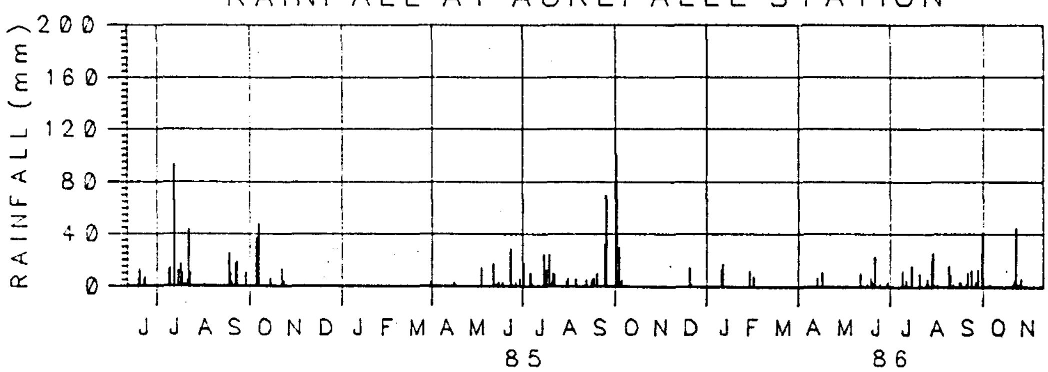
RAINFALL AT SITARAMANAGAR STATION



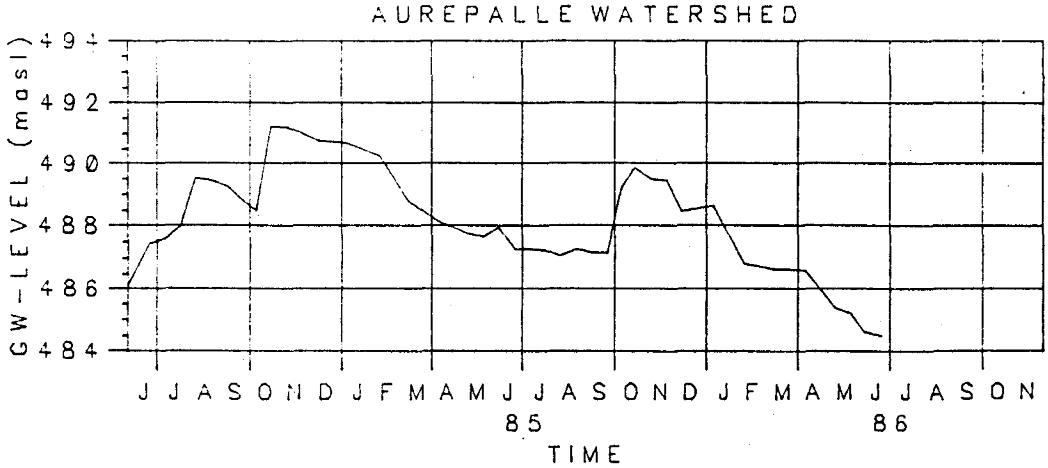

OBSERVATION WELL No.1
AUREPALLE WATERSHED



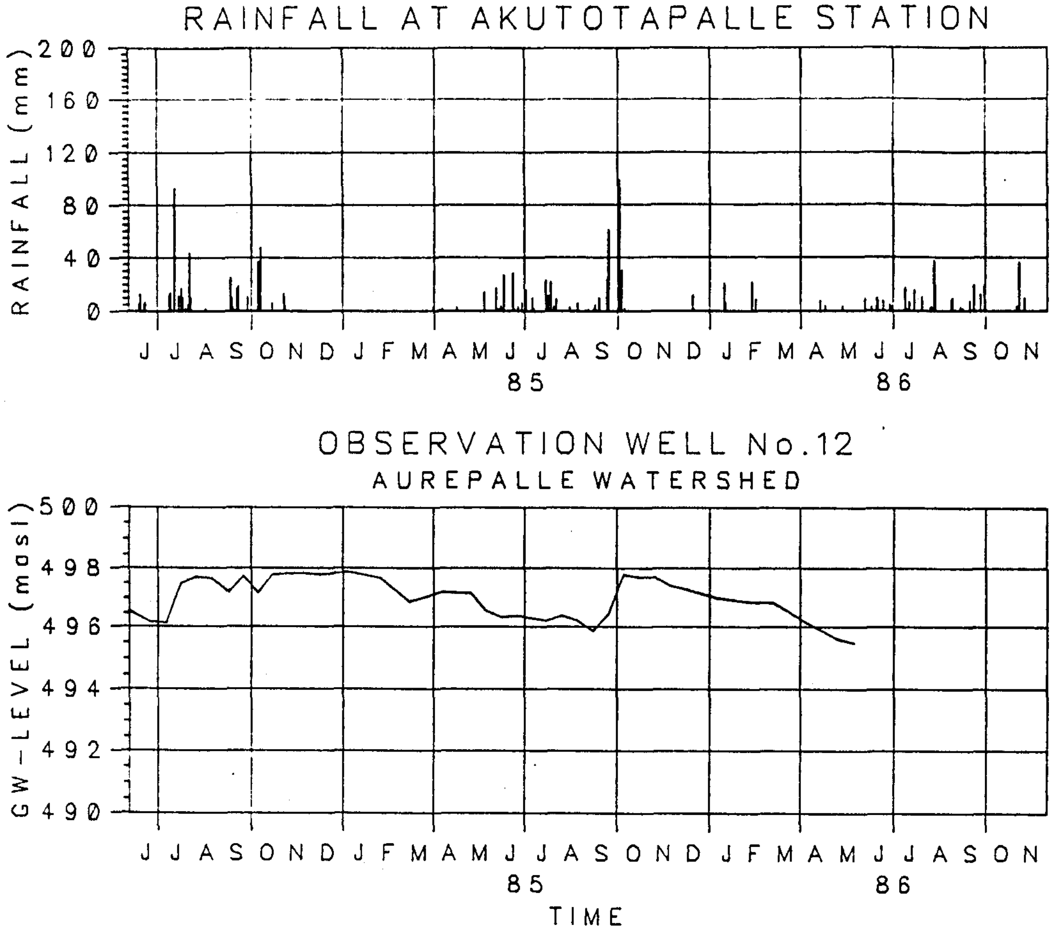

RAINFALL AT AUREPALLE STATION

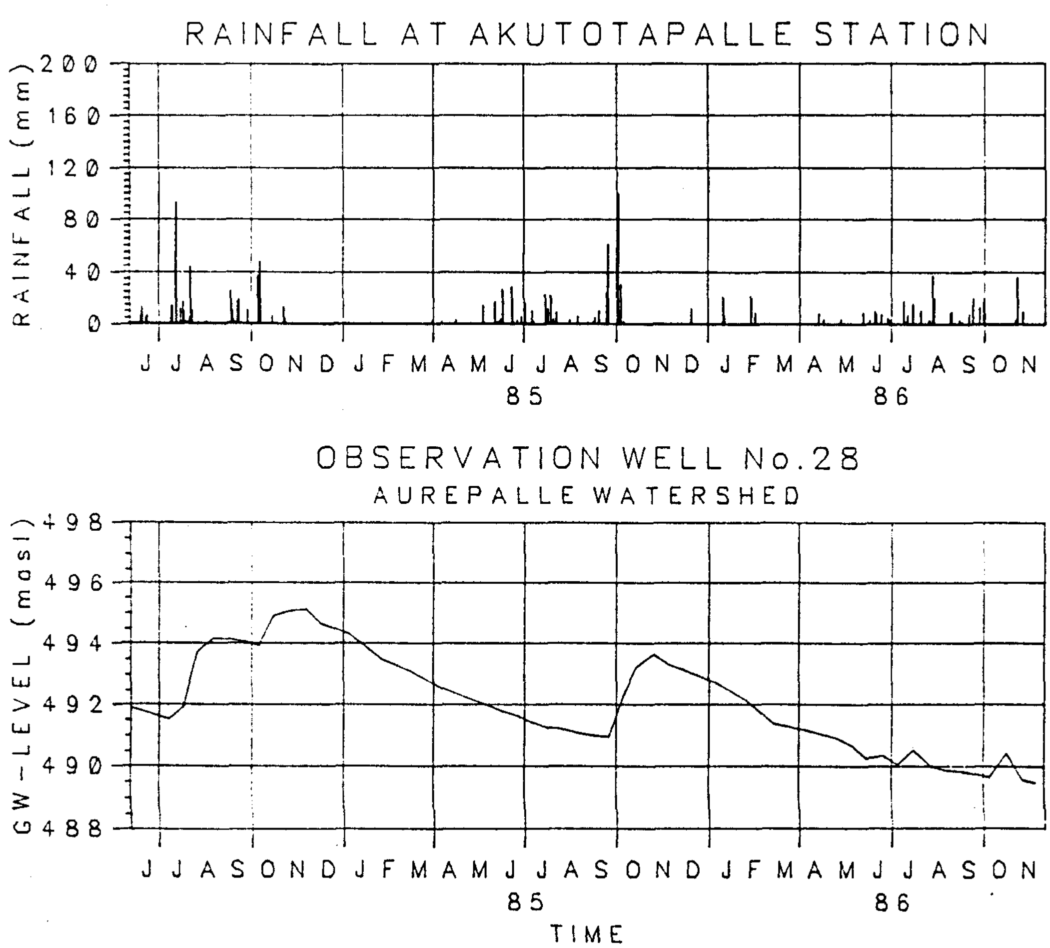



OBSERVATION WELL No. 6
AUREPALLE WATERSHED

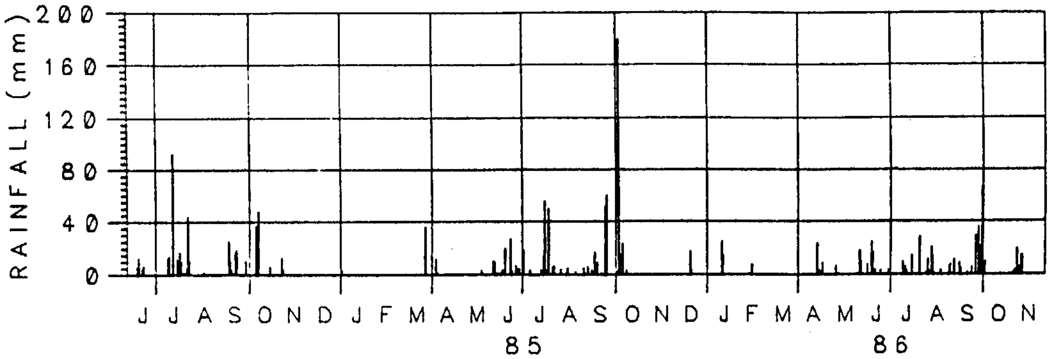


F2


RAINFALL AT AKUTOTAPALLE STATION
RAINFALL (mm)
200
160
120
80
40
0
J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
85
86
OBSERVATION WELL No.12
AUREPALLE WATERSHED
GW-LEVEL (masl)
500
498
496
494
492
490
J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
85
86
TIME

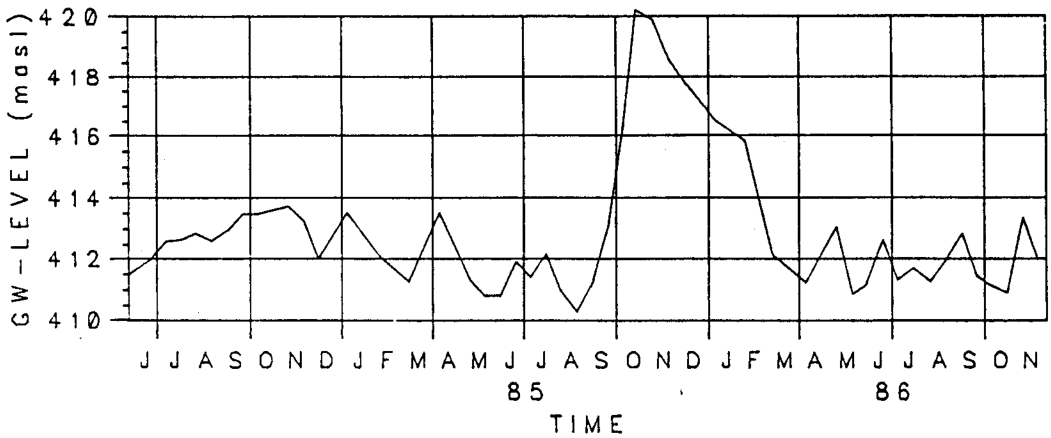

RAINFALL AT AKUTOTAPALLE STATION
RAINFALL (mm)
200
160
120
80
40
0
J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
85
86
OBSERVATION WELL No.28
AUREPALLE WATERSHED
GW-LEVEL (masl)
498
496
494
492
490
488
J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
85
86
TIME

RAINFALL AT KALKUNDA STATION

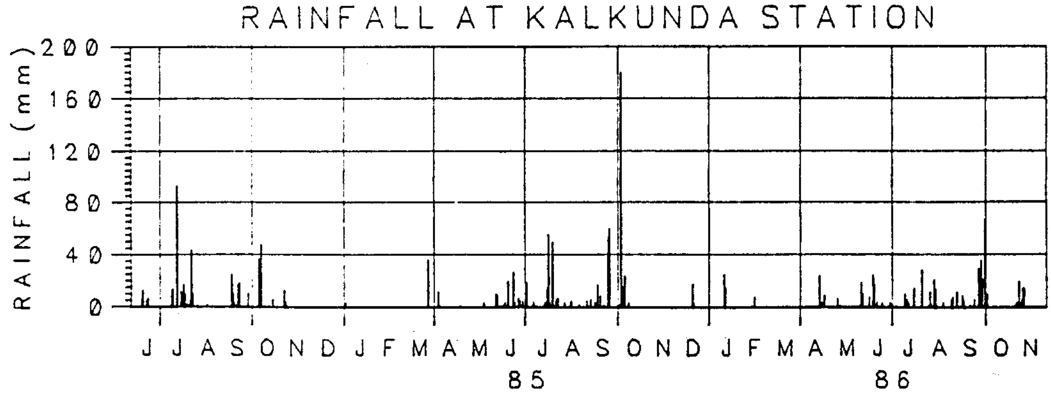



OBSERVATION WELL No.37

AUREPALLE WATERSHED

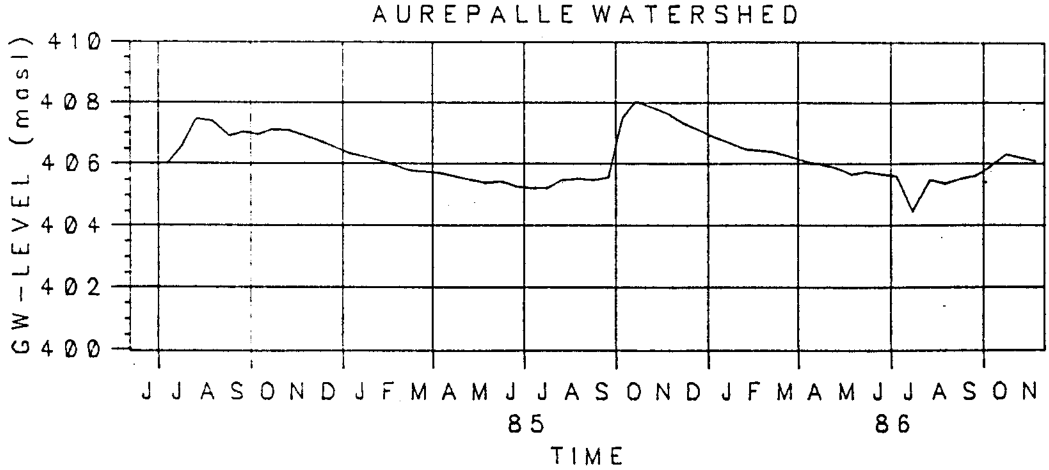



RAINFALL AT KALKUNDA STATION




OBSERVATION WELL No.44

AUREPALLE WATERSHED

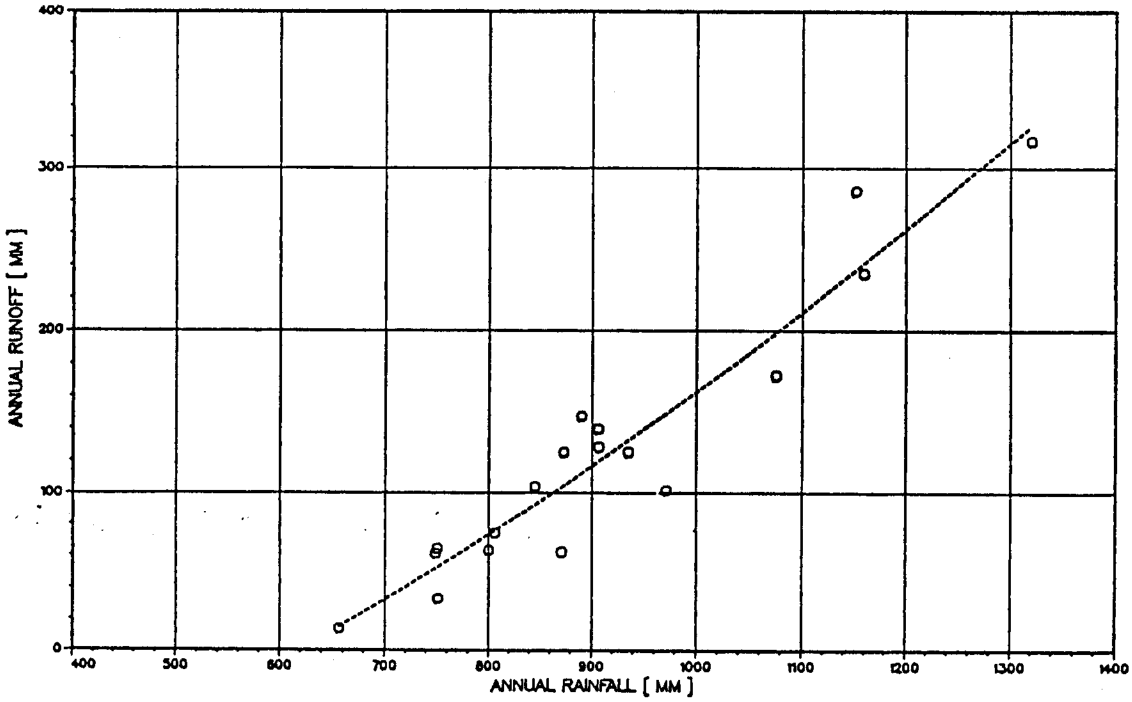


# APPENDIX G: RAINFALL AND RUNOFF IN TELENGANA REGION, ANDHRA PRADESH, INDIA

RAINFALL – RUNOFF – RELATIONSHIP

TELENGANA REGION, ANDHRA PRADESH, INDIA

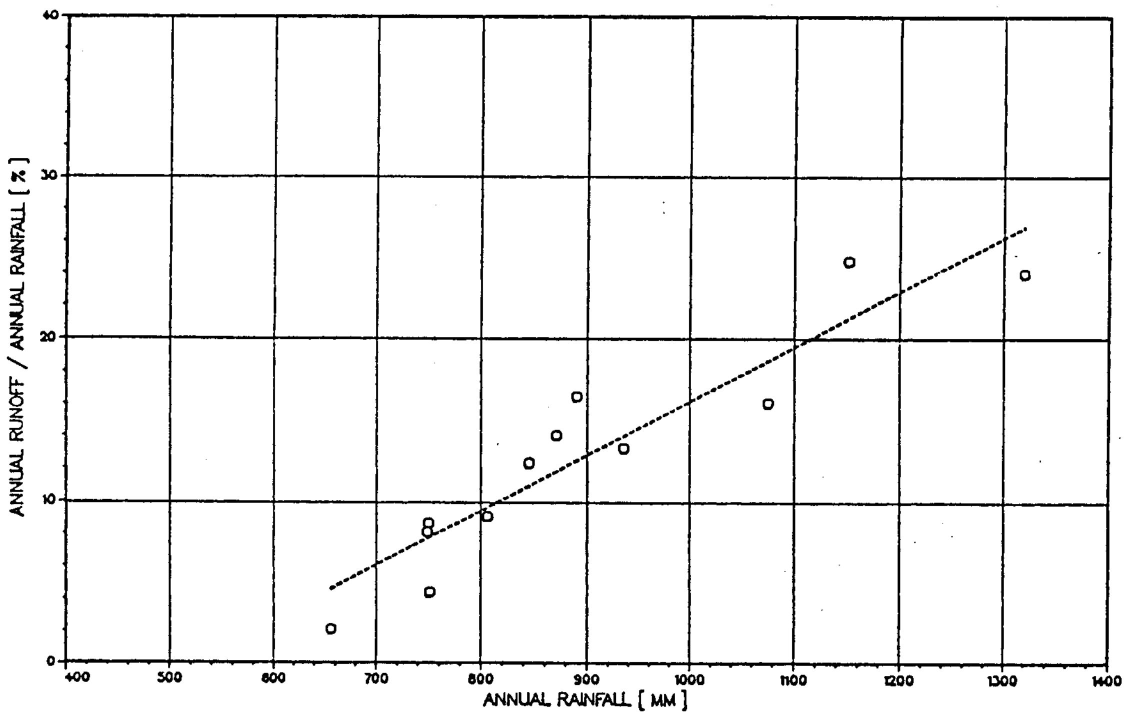
CATCHMENT AREAS BETWEEN 4.7 AND 1308 $KM^2$




RUNOFF AS A PERCENTAGE OF RAINFALL

TELENGANA REGION, ANDHRA PRADESH, INDIA

CATCHMENT AREAS BETWEEN 4.7 AND 1308 $KM^2$



# APPENDIX J: RESULTS OF INFILTRATION TESTS

## Infiltration test No.1

Plot: Gopal Reddy | Subplot: 001
Soil: Red loamy sand | Crop: Irrigated rice
Initial soil moisture: Near saturation

| Time [ h ] | Duration [ min ] | Infiltration [mm/h] |
|---|---|---|
| 10 00 | 30 | 8.0 |
| 11 00 | 90 | 8.0 |
| 12 00 | 150 | 2.0 |
| 13 00 | 210 | 3.0 |
| Average: | | 5.25 |

## Infiltration test No.2

Plot: Gopal Reddy | Subplot: 006
Soil: Red loamy sand | Crop: Irrigated rice
Initial soil moisture: Near saturation

| Time [ h ] | Duration [ min ] | Infiltration [mm/h] |
|---|---|---|
| 9 25 | 5 | 1.8 |
| 9 35 | 15 | 1.5 |
| 10 00 | 40 | 0.5 |
| 10 45 | 85 | 0.8 |
| 12 55 | 215 | 0.6 |

## Infiltration test No.3

Plot: Gopal Reddy | Subplot: 008
Soil: Red loamy sand | Crop: Irrigated rice
Initial soil moisture: Near saturation

| Time [ h ] | Duration [ min ] | Infiltration [mm/h] |
|---|---|---|
| 9 19 | 1 | 30.0 |
| 9 28 | 10 | 18.0 |
| 10 00 | 42 | 15.0 |
| 10 30 | 72 | 13.5 |
| 11 00 | 102 | 15.0 |
| 11 30 | 132 | 12.0 |
| 12 00 | 162 | 12.0 |
| 12 30 | 192 | 13.5 |
| 14 30 | 312 | 12.0 |
| 15 00 | 342 | 12.0 |
| 15 30 | 372 | 13.5 |
| 16 00 | 402 | 13.5 |

Infiltration test No.4

Plot: Gopal Reddy
Soil: Black loamy sand
Initial soil moisture:

Subplot: 019
Crop: Fallow after irrigated rice
Near field capacity

| Time [ h ] | Duration [ min ] | Infiltration [mm/h] |
|---|---|---|
| 15 14 | 1 | 168 |
| 15 25 | 12 | 51 |
| 15 40 | 27 | 45 |
| 16 00 | 47 | 45 |
| 16 30 | 77 | 39 |
| 17 00 | 107 | 39 |
| 17 30 | 137 | 36 |
| 18 00 | 167 | 36 |

Infiltration test No.5

Plot: Gopal Reddy
Soil: Red sandy soil
Initial soil moisture:

Dryland area
Crop: Fallow after irrigated rice
Near permanent wilting point

| Time [ h ] | Duration [ min ] | Infiltration [mm/h] |
|---|---|---|
| 8 53 | 1 | 1240 |
| 8 58 | 6 | 480 |
| 9 10 | 18 | 400 |
| 9 30 | 38 | 305 |
| 10 00 | 68 | 310 |
| 10 30 | 98 | 295 |
| 11 00 | 128 | 280 |
| 11 30 | 158 | 260 |
| 12 00 | 188 | 270 |
| 12 30 | 218 | 280 |

# APPENDIX K: RESULTS OF PONDING TESTS

## Ponding test No. 1

Plot: Gopal Reddy    Subplot: 001
Soil: loamy Sand    Crop: Irrigated rice

| Time [h] | Water Level [cm] | Total Loss [mm/h] | *ET* Loss [mm/h] | Perc. + Seep. Loss [mm/h] |
|---|---|---|---|---|
| 9 30 | 2.60 | | | |
| 10 30 | 2.00 | 6.00 | 0.70 | 5.30 |
| 11 30 | 1.40 | 6.00 | 0.80 | 5.20 |
| 12 30 | 0.70 | 7.00 | 1.00 | 6.00 |
| 13 30 | 0.10 | 6.00 | 0.90 | 5.10 |
| Average: | | 6.25 | 0.85 | 5.40 |

* ET estimated from lysimeter data *

## Ponding test No. 2

Plot: Gopal Reddy    Subplot: 004
Soil: Red loamy sand    Crop: Irrigated rice

| Time [h] | Water Level [cm] | Total Loss [mm/h] | *ET* Loss [mm/h] | Perc. + Seep. Loss [mm/h] |
|---|---|---|---|---|
| 16 00 | 4.20 | | | |
| 17 00 | 3.95 | 2.50 | 0.50 | 2.00 |
| 18 00 | 3.75 | 2.00 | 0.20 | 1.80 |
| Average: | | 2.25 | | 1.90 |

* ET loss estimated from Lysimeter data *

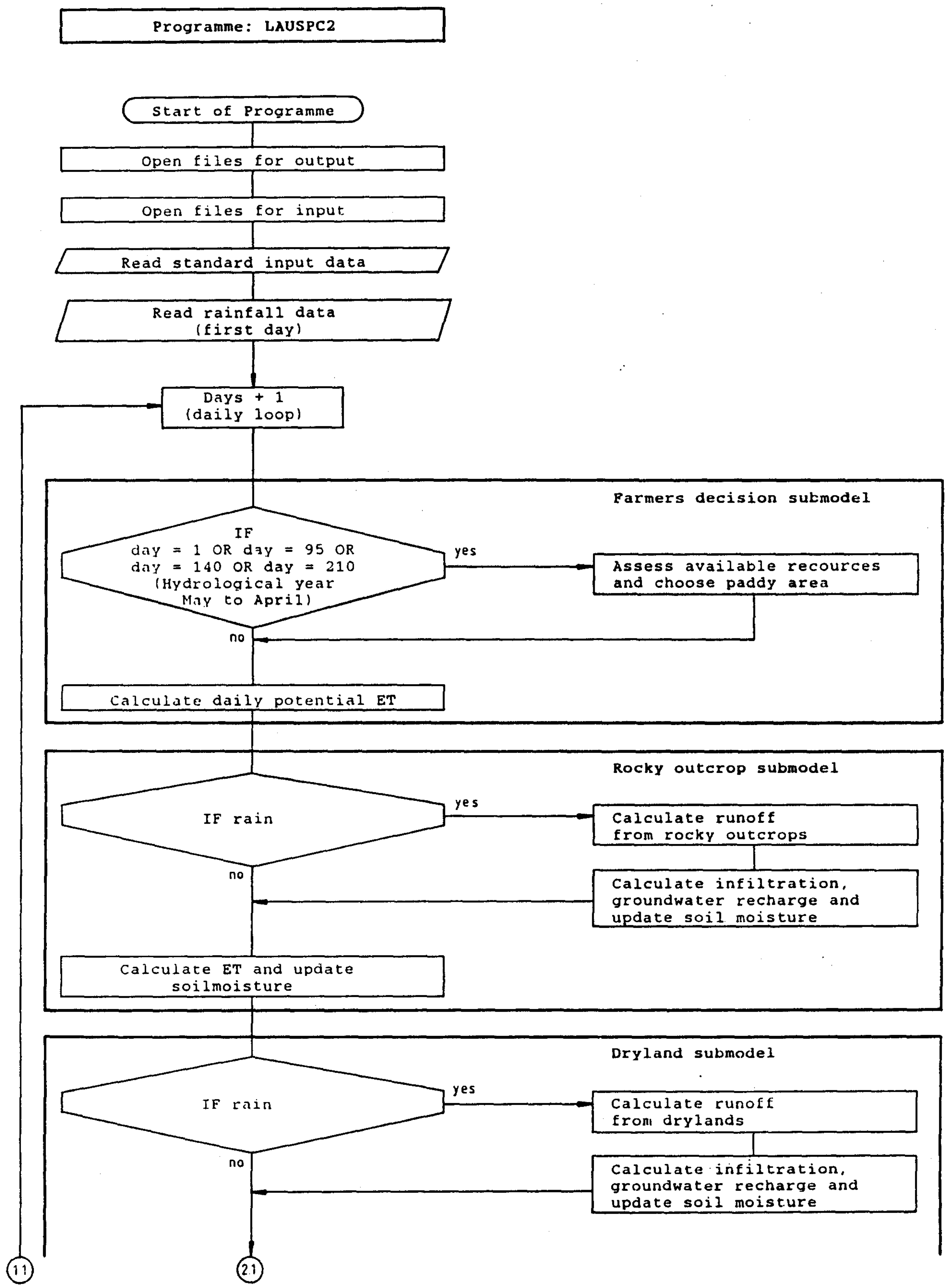
## Ponding test No. 3

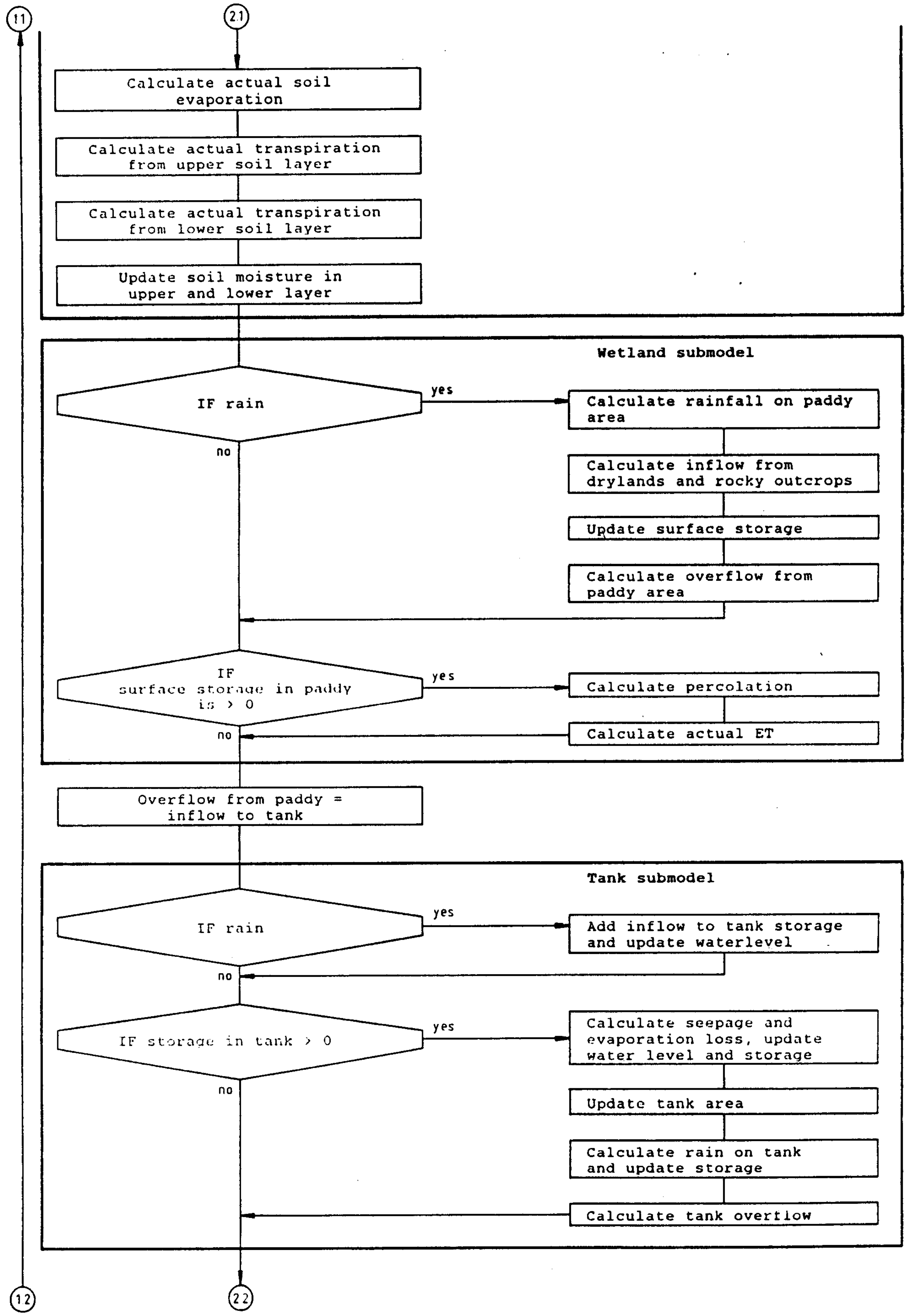
Plot: Gopal Reddy    Subplot: 008
Soil: Red loamy sand    Crop: Irrigated rice

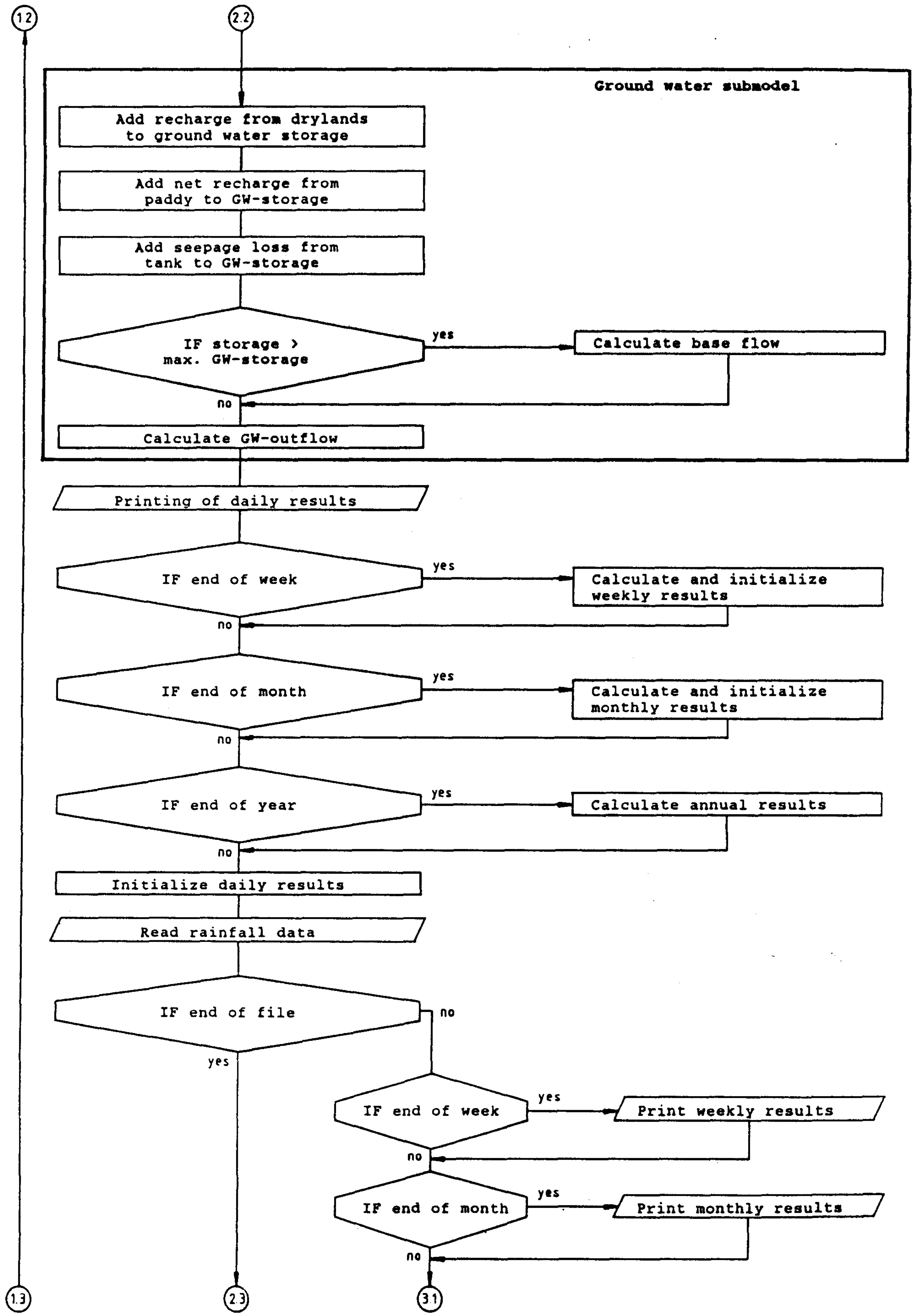
| Time [h] | Water Level [cm] | Total Loss [mm/h] | *ET* Loss [mm/h] | Perc. + Seep. Loss [mm/h] |
|---|---|---|---|---|
| 9 38 | 2.40 | | | |
| 9 45 | 2.00 | 34.3 | negl. | 34.3 |
| 10 00 | 1.35 | 26.0 | negl. | 26.0 |
| 10 06 | 0.95 | 40.0 | negl. | 40.0 |
| 10 15 | 0.30 | 43.3 | negl. | 43.3 |
| 10 20 | 0.00 | 36.0 | negl. | 36.0 |
| Average: | | 34.3 | | 34.3 |

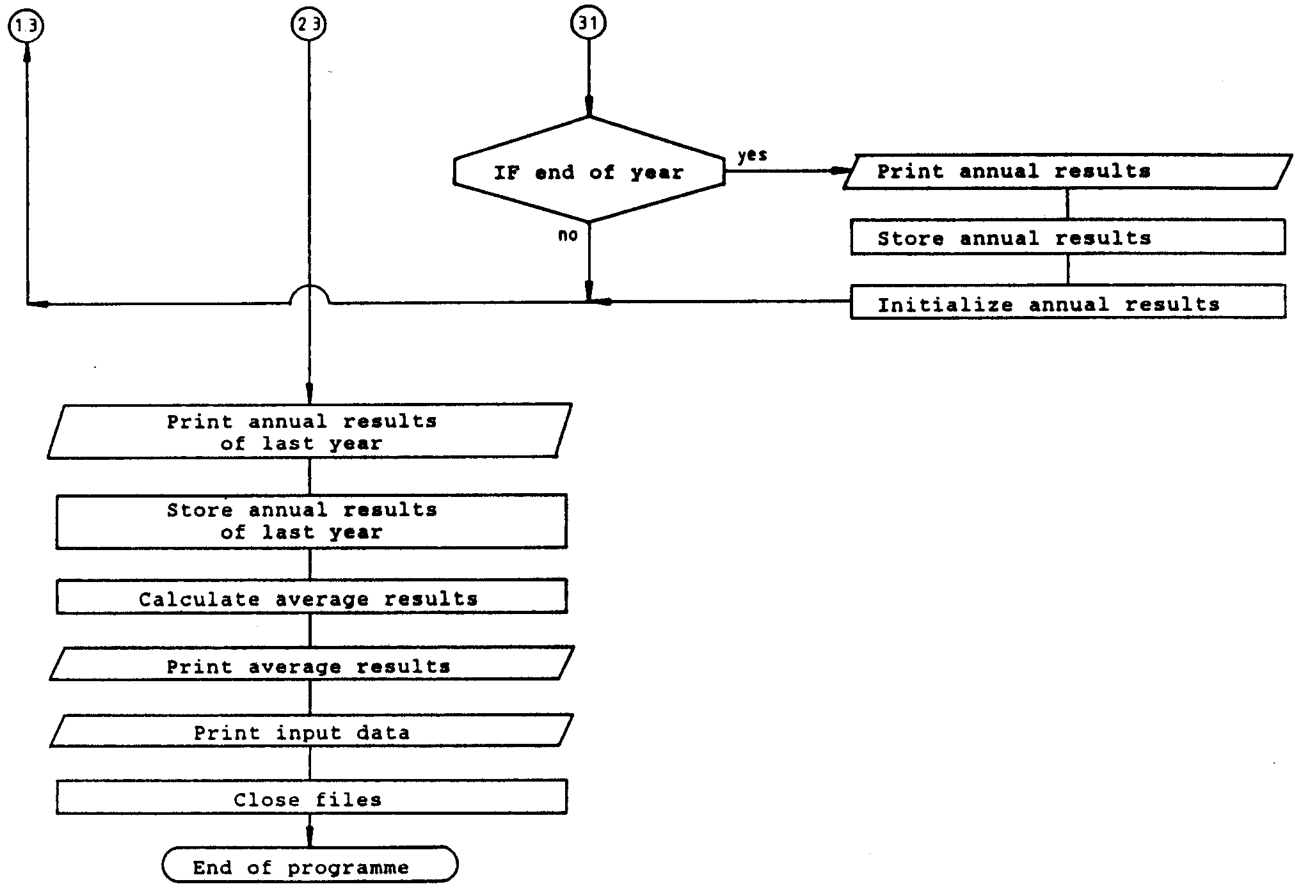
* ET losses neglected because of short duration of the test *

APPENDIX S: SIMPLIFIED FLOW CHART OF PROGRAMME LAUSPC2


Programme: LAUSPC2
Start of Programme
Open files for output
Open files for input
Read standard input data
Read rainfall data (first day)
Days + 1 (daily loop)
Farmers decision submodel
IF day = 1 OR day = 95 OR day = 140 OR day = 210 (Hydrological year May to April)
yes
Assess available recources and choose paddy area
no
Calculate daily potential ET
Rocky outcrop submodel
IF rain
yes
Calculate runoff from rocky outcrops
Calculate infiltration, groundwater recharge and update soil moisture
no
Calculate ET and update soilmoisture
Dryland submodel
IF rain
yes
Calculate runoff from drylands
Calculate infiltration, groundwater recharge and update soil moisture
no
11
21


11
21
Calculate actual soil evaporation
Calculate actual transpiration from upper soil layer
Calculate actual transpiration from lower soil layer
Update soil moisture in upper and lower layer
Wetland submodel
IF rain
yes
no
Calculate rainfall on paddy area
Calculate inflow from drylands and rocky outcrops
Update surface storage
Calculate overflow from paddy area
IF surface storage in paddy is > 0
yes
no
Calculate percolation
Calculate actual ET
Overflow from paddy = inflow to tank
Tank submodel
IF rain
yes
no
Add inflow to tank storage and update waterlevel
IF storage in tank > 0
yes
no
Calculate seepage and evaporation loss, update water level and storage
Update tank area
Calculate rain on tank and update storage
Calculate tank overflow
12
22


1.2
2.2
Ground water submodel
Add recharge from drylands to ground water storage
Add net recharge from paddy to GW-storage
Add seepage loss from tank to GW-storage
IF storage > max. GW-storage
yes
Calculate base flow
no
Calculate GW-outflow
Printing of daily results
IF end of week
yes
Calculate and initialize weekly results
no
IF end of month
yes
Calculate and initialize monthly results
no
IF end of year
yes
Calculate annual results
no
Initialize daily results
Read rainfall data
IF end of file
no
yes
IF end of week
yes
Print weekly results
no
IF end of month
yes
Print monthly results
no
1.3
2.3
3.1


13
23
31
IF end of year
yes
no
Print annual results
Store annual results
Initialize annual results
Print annual results of last year
Store annual results of last year
Calculate average results
Print average results
Print input data
Close files
End of programme

APPENDIX T: ANNUAL SIMULATION RESULTS OF LAUSPC2

ANNUAL RESULTS OF SIMULATION OF THE WATER BALANCE OF THE AUREPALLE SUB-WATERSHED 3 FOR THE YEARS 1976 TO 1987

AUREPALLE HYDROLOGICAL YEAR 1976/1977

| | | |
|---|---|---|
| TOT RAIN | MM | 716.50 |
| | CUM | 4427970.50 |
| TOT RUNOFF ROCKY | MM | 19.45 |
| | CUM | 22948.28 |
| | % | 2.71 |
| TOT ETP ROCKY | CUM | 639334.75 |
| | % | 75.62 |
| TOT RECH ROCKY | CUM | 183186.98 |
| | % | 21.67 |
| TOT RUNOFF DRYL. | MM | 8.01 |
| | CUM | 35770.73 |
| | % | 1.12 |
| TOT AETP DRYL. | MM | 631.93 |
| | CUM | 2854850.20 |
| | % | 88.20 |
| TOT EVLOSSUL DRYL. | % | 30.10 |
| TOT TRLOSSUL DRYL. | % | 34.08 |
| TOT TRLOSSLL DRYL. | % | 35.82 |
| TOT RECH DRYL. | MM | 50.02 |
| | CUM | 235216.95 |
| | % | 6.98 |
| TOT INFLOW PADDY | CUM | 370913.06 |
| TOT OVERFL PADDY | CUM | 15218.38 |
| | % | 4.10 |
| TOT EVLOSS PADDY | CUM | 693068.81 |
| TOT INFL ETP PAD | CUM | 105432.16 |
| | % | 28.43 |
| TOT PELOSS PADDY | CUM | 250069.39 |
| | % | 67.42 |
| TOTAL PADDY OVFL | % | 0.34 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 1.30 |
| | CUM | 8022.10 |
| TOT INFLOW TANK | CUM | 7196.28 |
| | % | 0.16 |
| TOT RAIN TANK | CUM | 604.06 |
| | % | 7.74 |
| TOT EVAP TANK | CUM | 815.93 |
| | % | 10.46 |
| TOT PERC TANK | CUM | 6984.41 |
| | % | 89.54 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 1.26 |
| | CUM | 7800.34 |
| | % | 0.18 |
| WATERSHED RECH | MM | 110.60 |
| | CUM | 683479.88 |
| | % | 15.44 |
| WATERSHED ETP | MM | 677.68 |
| | CUM | 4188069.80 |
| | % | 94.58 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE HYDROLOGICAL YEAR 1977/1978

| | | |
|---|---|---|
| TOT RAIN | MM | 537.60 |
| | CUM | 3322368.20 |
| TOT RUNOFF ROCKY | MM | 77.85 |
| | CUM | 91860.77 |
| | % | 14.48 |
| TOT ETP ROCKY | CUM | 364091.16 |
| | % | 57.39 |
| TOT RECH ROCKY | CUM | 178416.09 |
| | % | 28.13 |
| TOT RUNOFF DRYL. | MM | 40.13 |
| | CUM | 194034.80 |
| | % | 7.46 |
| TOT AETP DRYL. | MM | 475.35 |
| | CUM | 2241751.00 |
| | % | 88.42 |
| TOT EVLOSSUL DRYL. | % | 43.50 |
| TOT TRLOSSUL DRYL. | % | 22.02 |
| TOT TRLOSSLL DRYL. | % | 34.48 |
| TOT RECH DRYL. | MM | 48.00 |
| | CUM | 233409.66 |
| | % | 8.93 |
| TOT INFLOW PADDY | CUM | 420917.25 |
| TOT OVERFL PADDY | CUM | 296799.47 |
| | % | 70.51 |
| TOT EVLOSS PADDY | CUM | 638456.81 |
| TOT INFL ETP PAD | CUM | 36275.17 |
| | % | 8.62 |
| TOT PELOSS PADDY | CUM | 88035.77 |
| | % | 20.92 |
| TOTAL PADDY OVFL | % | 8.93 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 6.29 |
| | CUM | 38860.73 |
| TOT INFLOW TANK | CUM | 257938.77 |
| | % | 7.76 |
| TOT RAIN TANK | CUM | 28004.19 |
| | % | 9.79 |
| TOT EVAP TANK | CUM | 39308.82 |
| | % | 13.75 |
| TOT PERC TANK | CUM | 170157.14 |
| | % | 59.51 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 76476.95 |
| | % | 26.75 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 46.27 |
| | CUM | 285942.94 |
| | % | 8.61 |
| WATERSHED RECH | MM | 114.71 |
| | CUM | 708879.38 |
| | % | 21.34 |
| WATERSHED ETP | MM | 531.33 |
| | CUM | 3283607.80 |
| | % | 98.83 |
| WATERSHED OVERFLOW | % | 2.30 |

AUREPALLE HYDROLOGICAL YEAR 1978/1979

| | | |
|---|---|---|
| TOT RAIN | MM | 980.40 |
| | CUM | 6058872.00 |
| TOT RUNOFF ROCKY | MM | 151.48 |
| | CUM | 178747.34 |
| | % | 15.45 |
| TOT ETP ROCKY | CUM | 828720.31 |
| | % | 71.63 |
| TOT RECH ROCKY | CUM | 149404.33 |
| | % | 12.91 |
| TOT RUNOFF DRYL. | MM | 90.75 |
| | CUM | 409941.25 |
| | % | 9.26 |
| TOT AETP DRYL. | MM | 723.24 |
| | CUM | 3279302.80 |
| | % | 73.77 |
| TOT EVLOSSUL DRYL. | % | 35.95 |
| TOT TRLOSSUL DRYL. | % | 29.84 |
| TOT TRLOSSLL DRYL. | % | 34.21 |
| TOT RECH DRYL. | MM | 155.15 |
| | CUM | 673623.75 |
| | % | 15.82 |
| TOT INFLOW PADDY | CUM | 1055292.00 |
| TOT OVERFL PADDY | CUM | 618009.06 |
| | % | 58.56 |
| TOT EVLOSS PADDY | CUM | 749367.88 |
| TOT INFL ETP PAD | CUM | 234678.02 |
| | % | 22.24 |
| TOT PELOSS PADDY | CUM | 202605.02 |
| | % | 19.20 |
| TOTAL PADDY OVFL | % | 10.20 |
| TOT GWINFL TANK | CUM | 459271.38 |
| TOT INFLADD TANK | CUM | 86802.30 |
| TOTAL PERCL PT | MM | 11.86 |
| | CUM | 73315.28 |
| TOT INFLOW TANK | CUM | 1003965.19 |
| | % | 16.57 |
| TOT RAIN TANK | CUM | 61614.83 |
| | % | 5.78 |
| TOT EVAP TANK | CUM | 95764.55 |
| | % | 8.99 |
| TOT PERC TANK | CUM | 191186.38 |
| | % | 17.94 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 762460.88 |
| | % | 71.55 |
| TOT STORBAL TANK | CUM | 16168.25 |
| WATERSHED RUNOFF | MM | 172.42 |
| | CUM | 1065580.00 |
| | % | 17.59 |
| WATERSHED RECH | MM | 208.76 |
| | CUM | 1290134.75 |
| | % | 21.29 |
| WATERSHED ETP | MM | 801.48 |
| | CUM | 4953155.50 |
| | % | 81.75 |
| WATERSHED OVERFLOW | % | 12.58 |

AUREPALLE HYDROLOGICAL YEAR 1979/1980

| | | |
|---|---|---|
| TOT RAIN | MM | 545.30 |
| | CUM | 3369954.80 |
| TOT RUNOFF ROCKY | MM | 11.65 |
| | CUM | 13743.23 |
| | % | 2.14 |
| TOT ETP ROCKY | CUM | 466950.84 |
| | % | 72.57 |
| TOT RECH ROCKY | CUM | 162759.94 |
| | % | 25.29 |
| TOT RUNOFF DRYL. | MM | 3.25 |
| | CUM | 14323.83 |
| | % | 0.60 |
| TOT AETP DRYL. | MM | 553.84 |
| | CUM | 2542217.00 |
| | % | 101.57 |
| TOT EVLOSSUL DRYL. | % | 40.76 |
| TOT TRLOSSUL DRYL. | % | 31.11 |
| TOT TRLOSSLL DRYL. | % | 28.13 |
| TOT RECH DRYL. | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| TOT INFLOW PADDY | CUM | 248508.33 |
| TOT OVERFL PADDY | CUM | 1420.87 |
| | % | 0.57 |
| TOT EVLOSS PADDY | CUM | 511748.22 |
| TOT INFL ETP PAD | CUM | 80197.91 |
| | % | 32.27 |
| TOT PELOSS PADDY | CUM | 166889.56 |
| | % | 67.16 |
| TOTAL PADDY OVFL | % | 0.04 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 0.22 |
| | CUM | 1348.34 |
| TOT INFLOW TANK | CUM | 72.52 |
| | % | 0.00 |
| TOT RAIN TANK | CUM | 1440.70 |
| | % | 95.21 |
| TOT EVAP TANK | CUM | 2690.96 |
| | % | 177.83 |
| TOT PERC TANK | CUM | 14990.51 |
| | % | 990.64 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 0.24 |
| | CUM | 1513.22 |
| | % | 0.04 |
| WATERSHED RECH | MM | 55.99 |
| | CUM | 345988.34 |
| | % | 10.27 |
| WATERSHED ETP | MM | 570.16 |
| | CUM | 3523607.00 |
| | % | 104.56 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE HYDROLOGICAL YEAR 1980/1981

| | | |
|---|---|---|
| TOT RAIN | MM | 538.40 |
| | CUM | 3327312.00 |
| TOT RUNOFF ROCKY | MM | 30.74 |
| | CUM | 36278.14 |
| | % | 5.71 |
| TOT ETP ROCKY | CUM | 559267.50 |
| | % | 88.03 |
| TOT RECH ROCKY | CUM | 39766.40 |
| | % | 6.26 |
| TOT RUNOFF DRYL. | MM | 8.43 |
| | CUM | 41440.32 |
| | % | 1.57 |
| TOT AETP DRYL. | MM | 516.43 |
| | CUM | 2501406.00 |
| | % | 95.92 |
| TOT EVLOSSUL DRYL. | % | 56.20 |
| TOT TRLOSSUL DRYL. | % | 28.41 |
| TOT TRLOSSLL DRYL. | % | 15.39 |
| TOT RECH DRYL. | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| TOT INFLOW PADDY | CUM | 147172.52 |
| TOT OVERFL PADDY | CUM | 73425.95 |
| | % | 49.89 |
| TOT EVLOSS PADDY | CUM | 296132.78 |
| TOT INFL ETP PAD | CUM | 26371.93 |
| | % | 17.92 |
| TOT PELOSS PADDY | CUM | 47374.64 |
| | % | 32.19 |
| TOTAL PADDY OVFL | % | 2.21 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 1.16 |
| | CUM | 7177.58 |
| TOT INFLOW TANK | CUM | 66248.38 |
| | % | 1.99 |
| TOT RAIN TANK | CUM | 9559.49 |
| | % | 12.61 |
| TOT EVAP TANK | CUM | 11104.80 |
| | % | 14.65 |
| TOT PERC TANK | CUM | 64703.07 |
| | % | 85.35 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 12.27 |
| | CUM | 75807.87 |
| | % | 2.28 |
| WATERSHED RECH | MM | 25.73 |
| | CUM | 159021.69 |
| | % | 4.78 |
| WATERSHED ETP | MM | 544.97 |
| | CUM | 3367911.00 |
| | % | 101.22 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE HYDROLOGICAL YEAR 1981/1982

| | | |
|---|---|---|
| TOT RAIN | MM | 884.10 |
| | CUM | 5463738.00 |
| TOT RUNOFF ROCKY | MM | 97.66 |
| | CUM | 115238.09 |
| | % | 11.05 |
| TOT ETP ROCKY | CUM | 696383.44 |
| | % | 66.75 |
| TOT RECH ROCKY | CUM | 231616.50 |
| | % | 22.20 |
| TOT RUNOFF DRYL. | MM | 51.48 |
| | CUM | 232727.41 |
| | % | 5.82 |
| TOT AETP DRYL. | MM | 653.46 |
| | CUM | 3084749.80 |
| | % | 73.91 |
| TOT EVLOSSUL DRYL. | % | 35.04 |
| TOT TRLOSSUL DRYL. | % | 30.10 |
| TOT TRLOSSLL DRYL. | % | 34.86 |
| TOT RECH DRYL. | MM | 191.87 |
| | CUM | 884524.88 |
| | % | 21.70 |
| TOT INFLOW PADDY | CUM | 555947.75 |
| TOT OVERFL PADDY | CUM | 380122.06 |
| | % | 68.37 |
| TOT EVLOSS PADDY | CUM | 591793.50 |
| TOT INFL ETP PAD | CUM | 144929.23 |
| | % | 26.07 |
| TOT PELOSS PADDY | CUM | 30896.46 |
| | % | 5.56 |
| TOTAL PADDY OVFL | % | 6.96 |
| TOT GWINFL TANK | CUM | 407203.00 |
| TOT INFLADD TANK | CUM | 71095.70 |
| TOTAL PERCL PT | MM | 3.05 |
| | CUM | 18833.38 |
| TOT INFLOW TANK | CUM | 768491.69 |
| | % | 14.07 |
| TOT RAIN TANK | CUM | 51695.89 |
| | % | 6.30 |
| TOT EVAP TANK | CUM | 91405.46 |
| | % | 11.14 |
| TOT PERC TANK | CUM | 184472.13 |
| | % | 22.49 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 532920.12 |
| | % | 64.98 |
| TOT STORBAL TANK | CUM | 11390.00 |
| WATERSHED RUNOFF | MM | 132.72 |
| | CUM | 820187.56 |
| | % | 15.01 |
| WATERSHED RECH | MM | 218.50 |
| | CUM | 1350343.38 |
| | % | 24.71 |
| WATERSHED ETP | MM | 722.38 |
| | CUM | 4464332.00 |
| | % | 81.71 |
| WATERSHED OVERFLOW | % | 9.75 |

AUREPALLE HYDROLOGICAL YEAR 1982/1983

| | | |
|---|---|---|
| TOT RAIN | MM | 454.30 |
| | CUM | 2807574.00 |
| TOT RUNOFF ROCKY | MM | 25.37 |
| | CUM | 29931.54 |
| | % | 5.58 |
| TOT ETP ROCKY | CUM | 412646.00 |
| | % | 76.98 |
| TOT RECH ROCKY | CUM | 93496.45 |
| | % | 17.44 |
| TOT RUNOFF DRYL. | MM | 15.19 |
| | CUM | 69883.47 |
| | % | 3.34 |
| TOT AETP DRYL. | MM | 439.20 |
| | CUM | 2046068.00 |
| | % | 96.68 |
| TOT EVLOSSUL DRYL. | % | 42.40 |
| TOT TRLOSSUL DRYL. | % | 35.85 |
| TOT TRLOSSLL DRYL. | % | 21.75 |
| TOT RECH DRYL. | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| TOT INFLOW PADDY | CUM | 260181.48 |
| TOT OVERFL PADDY | CUM | 84438.03 |
| | % | 32.45 |
| TOT EVLOSS PADDY | CUM | 454684.91 |
| TOT INFL ETP PAD | CUM | 58002.72 |
| | % | 22.29 |
| TOT PELOSS PADDY | CUM | 117740.73 |
| | % | 45.25 |
| TOTAL PADDY OVFL | % | 3.01 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 3.91 |
| | CUM | 24169.01 |
| TOT INFLOW TANK | CUM | 60269.02 |
| | % | 2.15 |
| TOT RAIN TANK | CUM | 7183.54 |
| | % | 10.65 |
| TOT EVAP TANK | CUM | 17092.45 |
| | % | 25.34 |
| TOT PERC TANK | CUM | 61750.12 |
| | % | 91.55 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 10.91 |
| | CUM | 67452.56 |
| | % | 2.40 |
| WATERSHED RECH | MM | 48.08 |
| | CUM | 297156.31 |
| | % | 10.58 |
| WATERSHED ETP | MM | 474.19 |
| | CUM | 2930491.50 |
| | % | 104.38 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE HYDROLOGICAL YEAR 1983/1984

| | | |
|---|---|---|
| TOT RAIN | MM | 477.30 |
| | CUM | 2949714.00 |
| TOT RUNOFF ROCKY | MM | 2.36 |
| | CUM | 2783.05 |
| | % | 0.49 |
| TOT ETP ROCKY | CUM | 512120.00 |
| | % | 90.93 |
| TOT RECH ROCKY | CUM | 48310.95 |
| | % | 8.58 |
| TOT RUNOFF DRYL. | MM | 1.75 |
| | CUM | 8387.02 |
| | % | 0.37 |
| TOT AETP DRYL. | MM | 476.06 |
| | CUM | 2300587.80 |
| | % | 99.74 |
| TOT EVLOSSUL DRYL. | % | 38.73 |
| TOT TRLOSSUL DRYL. | % | 32.73 |
| TOT TRLOSSLL DRYL. | % | 28.54 |
| TOT RECH DRYL. | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| TOT INFLOW PADDY | CUM | 86140.66 |
| TOT OVERFL PADDY | CUM | 0.00 |
| | % | 0.00 |
| TOT EVLOSS PADDY | CUM | 218277.20 |
| TOT INFL ETP PAD | CUM | 28741.56 |
| | % | 33.37 |
| TOT PELOSS PADDY | CUM | 57399.10 |
| | % | 66.63 |
| TOTAL PADDY OVFL | % | 0.00 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 0.00 |
| | CUM | 0.00 |
| TOT INFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT RAIN TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT EVAP TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT PERC TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| WATERSHED RECH | MM | 17.11 |
| | CUM | 105710.05 |
| | % | 3.58 |
| WATERSHED ETP | MM | 490.45 |
| | CUM | 3030985.00 |
| | % | 102.76 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE HYDROLOGICAL YEAR 1984/1985

| | | |
|---|---|---|
| TOT RAIN | MM | 553.90 |
| | CUM | 3423102.00 |
| TOT RUNOFF ROCKY | MM | 50.60 |
| | CUM | 59707.04 |
| | % | 9.14 |
| TOT ETP ROCKY | CUM | 452054.22 |
| | % | 69.16 |
| TOT RECH ROCKY | CUM | 141840.78 |
| | % | 21.70 |
| TOT RUNOFF DRYL. | MM | 25.12 |
| | CUM | 117698.08 |
| | % | 4.53 |
| TOT AETP DRYL. | MM | 474.06 |
| | CUM | 2199645.80 |
| | % | 85.59 |
| TOT EVLOSSUL DRYL. | % | 27.67 |
| TOT TRLOSSUL DRYL. | % | 31.37 |
| TOT TRLOSSLL DRYL. | % | 40.96 |
| TOT RECH DRYL. | MM | 53.63 |
| | CUM | 257353.33 |
| | % | 9.68 |
| TOT INFLOW PADDY | CUM | 327022.50 |
| TOT OVERFL PADDY | CUM | 163141.36 |
| | % | 49.89 |
| TOT EVLOSS PADDY | CUM | 477999.59 |
| TOT INFL ETP PAD | CUM | 47679.94 |
| | % | 14.58 |
| TOT PELOSS PADDY | CUM | 116201.20 |
| | % | 35.53 |
| TOTAL PADDY OVFL | % | 4.77 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 7.29 |
| | CUM | 45053.94 |
| TOT INFLOW TANK | CUM | 118087.41 |
| | % | 3.45 |
| TOT RAIN TANK | CUM | 17864.44 |
| | % | 13.14 |
| TOT EVAP TANK | CUM | 25977.56 |
| | % | 19.11 |
| TOT PERC TANK | CUM | 109974.30 |
| | % | 80.89 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 22.00 |
| | CUM | 135951.86 |
| | % | 3.97 |
| WATERSHED RECH | MM | 108.48 |
| | CUM | 670423.56 |
| | % | 19.59 |
| WATERSHED ETP | MM | 510.63 |
| | CUM | 3155677.00 |
| | % | 92.19 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE HYDROLOGICAL YEAR 1985/1986

| | | |
|---|---|---|
| TOT RAIN | MM | 611.70 |
| | CUM | 3780306.20 |
| TOT RUNOFF ROCKY | MM | 60.61 |
| | CUM | 71514.50 |
| | % | 9.91 |
| TOT ETP ROCKY | CUM | 517232.59 |
| | % | 71.66 |
| TOT RECH ROCKY | CUM | 133058.92 |
| | % | 18.43 |
| TOT RUNOFF DRYL. | MM | 42.50 |
| | CUM | 200405.34 |
| | % | 6.95 |
| TOT AETP DRYL. | MM | 519.94 |
| | CUM | 2475525.20 |
| | % | 85.00 |
| TOT EVLOSSUL DRYL. | % | 45.62 |
| TOT TRLOSSUL DRYL. | % | 28.62 |
| TOT TRLOSSLL DRYL. | % | 25.76 |
| TOT RECH DRYL. | MM | 49.81 |
| | CUM | 234872.31 |
| | % | 8.14 |
| TOT INFLOW PADDY | CUM | 419473.81 |
| TOT OVERFL PADDY | CUM | 261316.22 |
| | % | 62.30 |
| TOT EVLOSS PADDY | CUM | 573673.00 |
| TOT INFL ETP PAD | CUM | 46974.12 |
| | % | 11.20 |
| TOT PELOSS PADDY | CUM | 111183.50 |
| | % | 26.51 |
| TOTAL PADDY OVFL | % | 6.91 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 6.73 |
| | CUM | 41614.97 |
| TOT INFLOW TANK | CUM | 219701.25 |
| | % | 5.81 |
| TOT RAIN TANK | CUM | 27529.45 |
| | % | 11.14 |
| TOT EVAP TANK | CUM | 49008.37 |
| | % | 19.82 |
| TOT PERC TANK | CUM | 177986.09 |
| | % | 71.99 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 20236.25 |
| | % | 8.19 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 40.00 |
| | CUM | 247230.70 |
| | % | 6.54 |
| WATERSHED RECH | MM | 113.06 |
| | CUM | 698715.75 |
| | % | 18.48 |
| WATERSHED ETP | MM | 585.02 |
| | CUM | 3615439.00 |
| | % | 95.64 |
| WATERSHED OVERFLOW | % | 0.54 |

AUREPALLE HYDROLOGICAL YEAR 1986/1987

| | | |
|---|---|---|
| TOT RAIN | MM | 330.50 |
| | CUM | 2042490.12 |
| TOT RUNOFF ROCKY | MM | 3.78 |
| | CUM | 4464.80 |
| | % | 1.14 |
| TOT ETP ROCKY | CUM | 356535.19 |
| | % | 91.42 |
| TOT RECH ROCKY | CUM | 28990.02 |
| | % | 7.43 |
| TOT RUNOFF DRYL. | MM | 0.42 |
| | CUM | 2004.27 |
| | % | 0.13 |
| TOT AETP DRYL. | MM | 330.93 |
| | CUM | 1571152.62 |
| | % | 100.13 |
| TOT EVLOSSUL DRYL. | % | 42.31 |
| TOT TRLOSSUL DRYL. | % | 43.34 |
| TOT TRLOSSLL DRYL. | % | 14.35 |
| TOT RECH DRYL. | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| TOT INFLOW PADDY | CUM | 89448.71 |
| TOT OVERFL PADDY | CUM | 0.00 |
| | % | 0.00 |
| TOT EVLOSS PADDY | CUM | 369009.72 |
| TOT INFL ETP PAD | CUM | 30635.77 |
| | % | 34.25 |
| TOT PELOSS PADDY | CUM | 58812.93 |
| | % | 65.75 |
| TOTAL PADDY OVFL | % | 0.00 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 0.00 |
| TOTAL PERCL PT | MM | 0.00 |
| | CUM | 0.00 |
| TOT INFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT RAIN TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT EVAP TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT PERC TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 0.00 |
| | % | 0.00 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 0.00 |
| | CUM | 0.00 |
| | % | 0.00 |
| WATERSHED RECH | MM | 14.21 |
| | CUM | 87802.95 |
| | % | 4.30 |
| WATERSHED ETP | MM | 371.63 |
| | CUM | 2296697.50 |
| | % | 112.45 |
| WATERSHED OVERFLOW | % | 0.00 |

AUREPALLE AVERAGE RESULTS FROM 1976 TO 1987

| | | |
|---|---|---|
| TOT RAIN | MM | 602.73 |
| | CUM | 3724855.20 |
| TOT RUNOFF ROCKY | MM | 48.32 |
| | CUM | 57019.72 |
| | % | 8.02 |
| TOT ETP ROCKY | CUM | 527757.75 |
| | % | 74.20 |
| TOT RECH ROCKY | CUM | 126440.66 |
| | % | 17.78 |
| TOT RUNOFF DRYL. | MM | 26.09 |
| | CUM | 120601.50 |
| | % | 4.33 |
| TOT AETP DRYL. | MM | 526.77 |
| | CUM | 2463387.00 |
| | % | 87.40 |
| TOT EVLOSSUL DRYL. | % | 39.37 |
| TOT TRLOSSUL DRYL. | % | 31.16 |
| TOT TRLOSSLL DRYL. | % | 29.47 |
| TOT RECH DRYL. | MM | 49.86 |
| | CUM | 229000.06 |
| | % | 8.27 |
| TOT INFLOW PADDY | CUM | 361910.75 |
| TOT OVERFL PADDY | CUM | 172171.94 |
| | % | 47.57 |
| TOT EVLOSS PADDY | CUM | 506746.59 |
| TOT INFL ETP PAD | CUM | 76356.23 |
| | % | 21.10 |
| TOT PELOSS PADDY | CUM | 113382.57 |
| | % | 31.33 |
| TOTAL PADDY OVFL | % | 4.62 |
| TOT GWINFL TANK | CUM | 0.00 |
| TOT INFLADD TANK | CUM | 14354.36 |
| TOTAL PERCL PT | MM | 3.80 |
| | CUM | 23490.48 |
| TOT INFLOW TANK | CUM | 227451.86 |
| | % | 6.11 |
| TOT RAIN TANK | CUM | 18681.51 |
| | % | 7.59 |
| TOT EVAP TANK | CUM | 30288.08 |
| | % | 12.31 |
| TOT PERC TANK | CUM | 89291.28 |
| | % | 36.28 |
| TOT IRR OUTFLOW | CUM | 0.00 |
| | % | 0.00 |
| TOT OVFLOW TANK | CUM | 126554.02 |
| | % | 51.42 |
| TOT STORBAL TANK | CUM | 0.00 |
| WATERSHED RUNOFF | MM | 39.83 |
| | CUM | 246133.38 |
| | % | 6.61 |
| WATERSHED RECH | MM | 94.11 |
| | CUM | 581605.06 |
| | % | 15.61 |
| WATERSHED ETP | MM | 570.90 |
| | CUM | 3528179.20 |
| | % | 94.72 |
| WATERSHED OVERFLOW | % | 3.40 |

# APPENDIX U: STANDARD INPUT DATA USED IN APPSMOD

## General Standard Input Data

Table U.1: Dimensions of System

| Parameter | Unit | Value |
|---|---|---|
| Area | $km^2$ | 0.15 |
| Length | m | 750.00 |
| Width | m | 200.00 |

**Table U.2: Standard Input Data Used in Dryland Component (Catchment)**

| Parameter | Unit | Value |
|---|---|---|
| Plant available water | | |
| soil layer 1 | mm | 35 |
| soil layer 2 | mm | 63 |
| SCS curve number | - | 63 |

Table U.3: Standard Input Data Used in Wetland Component (Terraces)

| Parameter | Unit | Value |
|---|---|---|
| Elevation of terrace above reference plane | m | 14.0 |
| Saturated hydraulic conductivity of soil | mm/d | 50.0 |
| Maximum surface storage | | |
| terrace 1 | mm | 100.0 |
| terrace 2 | mm | 100.0 |
| terrace 3 | mm | 100.0 |
| SCS curve number | - | 63.0 |

Table U.4: Standard Input Data Used in Farm Pond Component

| Parameter | Unit | Value |
|---|---|---|
| Elevation of tank bottom above reference plane | m | 14.0 |
| Max. storage of pond | $m^3$ | 2550.0 |
| Depth | m | 2.5 |
| Percolation rate | mm/d | 15.0 |

Table U.5: Monthly Values of Various Factors and Coefficients.

| Factor | Month Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Light interception | 0.20 | 0.15 | 0.10 | 0.10 | 0.05 | 0.30 | 0.80 | 0.80 | 0.80 | 0.50 | 0.50 | 0.30 |
| Root factor soil layer 1 | 0.80 | 0.80 | 0.90 | 0.90 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.70 | 0.70 | 0.70 |
| Root factor soil layer 2 | 0.20 | 0.20 | 0.10 | 0.10 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.30 | 0.30 | 0.30 |
| Pan coeff. pond evap. | 1.10 | 1.00 | 0.92 | 0.80 | 0.70 | 0.72 | 0.85 | 0.95 | 0.95 | 1.00 | 1.05 | 1.10 |

Standard Input Data Used in Ground Water Component

Table U.6: Standard Input Data for Ground Water Sub-Model.

| Parameter | Unit | Value |
|---|---|---|
| No. of intervals in Y-direction | - | 8.00 |
| Distance between nodes in Y-direction | m | 93.75 |
| No. of intervals in X-direction | - | 4.00 |
| Distance between nodes in X-direction | m | 50.00 |
| Time step | s | 86400.00 |
| Hydraulic conductivity | m/s | 0.000162 |
| Specific yield | - | 0.025 |
| Slope of GW-Table (Outflow cross section) | - | 0.01 |
| Surface slope | - | 0.01 |
| Area of well | $m^2$ | 70.00 |

Table U.7: Maximum Ground Water Levels (m) above Reference Plane for all Nodes.

| | | X - Direction 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Y | 0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| | 1 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| | 2 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| | 3 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| | 4 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |

Table U.8: Initial Ground Water Levels (m) above Reference Plane for all Nodes.

| | | X - Direction 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Y | 0 | 0.85 | 1.48 | 1.86 | 2.30 | 2.62 | 2.84 | 2.99 | 3.07 | 3.10 |
| | 1 | 0.85 | 1.48 | 1.82 | 2.29 | 2.62 | 2.84 | 2.99 | 3.07 | 3.10 |
| | 2 | 0.84 | 1.46 | 1.74 | 2.28 | 2.61 | 2.84 | 2.99 | 3.07 | 3.10 |
| | 3 | 0.85 | 1.48 | 1.82 | 2.29 | 2.62 | 2.84 | 2.99 | 3.07 | 3.10 |
| | 4 | 0.85 | 1.48 | 1.86 | 2.30 | 2.62 | 2.84 | 2.99 | 3.07 | 3.10 |

Table U.9: Definition of Nodes as Wetland, Dryland, Well or Farm Pond Nodes.

| | | X - Direction 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Y | 0 | d | d | d | d | d | d | d | d | d |
| | 1 | d | w | t | d | d | d | d | d | d |
| | 2 | w | w | b | d | d | d | d | d | d |
| | 3 | d | w | d | d | d | d | d | d | d |
| | 4 | d | d | d | d | d | d | d | d | d |

w = Wetland, d = Dryland, b = Brunnen, t = Farm pond (tank)

Standard Input Data Used in Agro-Economical Component

**Table U.10: Standard Crop Input Data**

| Parameter | Unit | Value | | | | |
|---|---|---|---|---|---|---|
| | | Rice1 | Rice2 | Rice3 | Ground-nut | Sorghum |
| Plant avail. water | | | | | | |
| soil layer 1 | mm | 35.0 | 35.0 | 35.0 | 70.0 | 35.0 |
| soil layer 2 | mm | | | | | 63.0 |
| Soil moisture | | | | | | |
| at 100% saturation | mm | 95.0 | 95.0 | 95.0 | n.r. | n.r. |
| at perm. wilt. point | mm | 15.0 | 15.0 | 15.0 | n.r. | r.r. |
| Beginning weeks of Crops | w | 18 | 25 | 33 | 1 | 22 |
| Length of growing periods | d | 132.0 | 133.0 | 133.0 | 112.0 | 91.0 |
| Mean Rainfall in growing season | mm | 350.0 | 370.0 | 190.0 | 37.0 | n.r. |
| Cons. seas. water water use | mm | 669.0 | 669.0 | 598.0 | 476.0 | n.r. |
| Total water use | mm | 2900.0 | 2600.0 | 2300.0 | n.r. | n.r. |

n.r. = Not relevant

Table U.11: Last Days of All Growth Stages of Crops

| | Growth stage | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| Terrace 1 (Rice) | 42 | 63 | 84 | 98 | 126 | 132 |
| Terrace 2 (Rice) | 42 | 63 | 84 | 98 | 126 | 133 |
| Terrace 3 (Rice) | 42 | 63 | 84 | 98 | 126 | 133 |
| Groundnut | 14 | 42 | 70 | 98 | 112 | - |
| Sorghum | 14 | 35 | 49 | 70 | 84 | 91 |

Table U.12: Yield Response Factors ky of Crops for Different Growth Stages

| | Growth stage | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| Paddy (AET version) | 0.7 | 0.7 | 1.0 | 1.0 | 0.3 | 0.0 |
| Paddy (SAT version) | 3.0 | 3.0 | 6.0 | 9.0 | 1.0 | 0.0 |
| Groundnut | 0.8 | 0.2 | 0.8 | 0.6 | 0.2 | - |
| Sorghum | 0.9 | 0.2 | 0.5 | 0.9 | 0.4 | 0.2 |

Table U.13: Standard Agro-Economical Input Data

| Parameter | Unit | Value | | | | |
|---|---|---|---|---|---|---|
| | | Rice1 | Rice2 | Rice3 | Ground-nut | Sorghum |
| Max yield | kg/ha | 6000.0 | 5600.0 | 5600.0 | 1750.0 | 1850.0 |
| Farm gate prices | Rs/kg | 1.8 | 1.8 | 1.8 | 4.7 | 1.5 |
| Agric. Inputs | Rs/ha,seas | 3992.0 | 3992.0 | 3992.0 | 2799.0 | 520.0 |
| By-product | Rs/ha,seas | 630.0 | 630.0 | 630.0 | - | 240.0 |

Table U.14: Investment and Maintenance Costs for Irrigation Structures

| | Unit | Pond | Terraces | Terrace bunds | Well |
|---|---|---|---|---|---|
| Investment | Rs | 20000.0 | 1284.0 | 1000.0 | 34400.0 |
| Maintenance | Rs/Year | 200.0 | 0.0 | - | 300.0 |

Table U.15: Other Relevant Standard Input Data

| Parameter | Unit | Value |
|---|---|---|
| Mean annual rainfall | mm/y | 644.00 |
| Pump discharge | $m^3/h$ | 42.00 |
| Cost of pumping | Rs/h | (2.00) |
| Specific benefit of: | | |
| ground water | $Rs/m^3$ | 0.50 |
| surface water | $Rs/m^3$ | 0.25 |
| Interest rate | % | 10.00 |
| Riskfactor | - | 0.30 |
| Resource use factor groundnut | - | 0.60 |

APPENDIX V: LIST OF RUNS EXECUTED IN SENSITIVITY ANALYSIS

Table V.1: Runs Executed in Sensitivity Analysis

| Parameter | Unit | No. of Run | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| A Risc factor | (-) | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 |
| B Hydraulic conduct. of aquifer | (m/d) | 7.70 | 11.20 | 14.00 | 16.80 | 77.00 |
| C Specific yield of aquifer | (%) | 2.00 | 2.50 | 3.00 | | |
| D Gradient of GW table (boundary cond.) | (%) | 0.80 | 1.00 | 1.20 | | |
| E Depth of aquifer | (m) | 9.60 | 12.00 | 14.40 | | |
| Elevation farm p. | (m) | 12.00 | 14.00 | 16.00 | | |
| Elevation terraces | (m) | 12.00 | 14.00 | 16.00 | | |
| F Area of system | (ha) | 12.00 | 15.00 | 18.00 | | |
| Lenght | (m) | 648.07 | 750.00 | 793.73 | | |
| Width | (m) | 185.16 | 200.00 | 226.78 | | |
| | (m) | 81.01 | 93.75 | 99.22 | | |
| | (m) | 46.29 | 50.00 | 56.70 | | |
| G SCS Curve number | (-) | 50.00 | 63.00 | 76.00 | | |
| | (-) | 50.00 | 63.00 | 76.00 | | |
| H Plant avail. water | | | | | | |
| Sorghum layer 1 | (mm) | 28.00 | 35.00 | 42.00 | | |
| layer 2 | (mm) | 50.40 | 63.00 | 75.60 | | |
| Rice | (mm) | 28.00 | 35.00 | 42.00 | | |
| Groundnut | (mm) | 56.00 | 70.00 | 84.00 | | |
| I Hydraulic conduct. of terrace soil | (mm/d) | 20.00 | 40.00 | 50.00 | 60.00 | 300.00 |
| J Percolation rate of farm pond | (mm/d) | 12.00 | 15.00 | 18.00 | | |
| K Capacity of tank | ($m^3$) | 2040.00 | 2550.00 | 3060.00 | | |

Table V.1: Continued

| Parameter | Unit | No. of Run 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| L Maximum yields | | | | | | |
| Sorghum | (kg/ha) | 1480.00 | 1850.00 | 2220.00 | | |
| Rice season 1 | (kg/ha) | 4800.00 | 6000.00 | 7200.00 | | |
| Rice season 2 | (kg/ha) | 4480.00 | 5600.00 | 6720.00 | | |
| Rice season 3 | (kg/ha) | 4480.00 | 5600.00 | 6720.00 | | |
| Groundnut | (kg/ha) | 1400.00 | 1750.00 | 2100.00 | | |
| M Farmgate Prices | | | | | | |
| Sorghum | (Rs/kg) | 1.20 | 1.50 | 1.80 | | |
| Rice season 1 | (Rs/kg) | 1.44 | 1.80 | 2.16 | | |
| Rice season 2 | (Rs/kg) | 1.44 | 1.80 | 2.16 | | |
| Rice season 3 | (Rs/kg) | 1.44 | 1.80 | 2.16 | | |
| Groundnut | (Rs/kg) | 3.76 | 4.70 | 5.64 | | |
| N Discount rate | (%) | 6.00 | 8.00 | 10.00 | 12.00 | |
| O ET sensitivivty factor | (-) | 0.8 | 1.0 | 1.2 | | |

# APPENDIX W: RESULTS OF SENSITIVITY ANALYSIS OF APPSMOD

Table W.A0: Results of Sensitivity Analysis

| Management alternative | : | A - Only drylands |
|---|---|---|
| Parameter | : | Standard data |
| Mean annual rainfall | $m^3$ | 95130.00 |
| Mean annual actual ET | $m^3$ | 75198.75 |
| Mean annual surf. outflow | $m^3$ | 6492.72 |
| Mean annual GW-discharge | $m^3$ | 12728.70 |
| Mean ann. storage change | $m^3$ | -738.60 |
| Mean ann. water bal. error | $m^3$ | -28.77 |
| Net present value | Rs | 50743.25 |
| Net present value * | Rs | 50743.25 |

* including compensation for reduced outflow

Table W.A1: Results of Sensitivity Analysis

Management alternative : D - Terraces and farm pond
Parameter : Risk factor ( 0.3 = Standard value)

| Risk factor | - | 0.1 | 0.2 | 0.3 |
|---|---|---|---|---|
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78649.40 | 78772.95 | 78904.53 |
| Mean annual surf. outflow | $m^3$ | 2928.59 | 2876.81 | 2838.28 |
| Mean annual GW-discharge | $m^3$ | 12785.59 | 12694.86 | 12614.22 |
| Mean ann. storage change | $m^3$ | -762.07 | -782.62 | -754.67 |
| Mean ann. water bal. error | $m^3$ | 4.34 | 2.77 | 18.31 |
| Net present value * | Rs | -28747.93 | -27040.81 | -25639.81 |
| Net present value ** | Rs | -37640.84 | -36568.62 | -35746.71 |
| **Risk factor** | - | 0.4 | 0.5 | |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | |
| Mean annual actual ET | $m^3$ | 78979.04 | 79061.19 | |
| Mean annual surf. outflow | $m^3$ | 2808.18 | 2800.82 | |
| Mean annual GW-discharge | $m^3$ | 12577.98 | 12500.43 | |
| Mean ann. storage change | $m^3$ | -815.96 | -791.82 | |
| Mean ann. water bal. error | $m^3$ | -51.16 | -24.27 | |
| Net present value | Rs | -24734.43 | -24156.18 | |
| Net present value * | Rs | -35167.45 | -34903.45 | |

* including compensation for reduced outflow

Table W.B0: Results of Sensitivity Analysis

Management alternative : A - Only drylands
Parameter : Hydraulic conductivity of aquifer

| Hydraulic conductivity | m/d | 7.70 | 11.20 | 14.00 |
|---|---|---|---|---|
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 75198.75 | 75198.75 | 75198.75 |
| Mean annual surf. outflow | $m^3$ | 6926.77 | 6599.70 | 6492.72 |
| Mean annual GW-discharge | $m^3$ | 11723.33 | 12432.73 | 12723.70 |
| Mean ann. storage change | $m^3$ | -1307.80 | -934.16 | -738.60 |
| Mean ann. water bal. error | $m^3$ | -26.65 | -35.34 | -28.77 |
| Net present value | Rs | 50743.25 | 50743.25 | 50743.25 |
| Net present value * | Rs | 50743.25 | 50743.25 | 50743.25 |
| **Hydraulic conductivity** | **m/d** | **16.80** | **77.00** | |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | |
| Mean annual actual ET | $m^3$ | 75198.75 | 75198.75 | |
| Mean annual surf. outflow | $m^3$ | 6439.24 | 6406.09 | |
| Mean annual GW-discharge | $m^3$ | 12929.58 | 13628.74 | |
| Mean ann. storage change | $m^3$ | -595.92 | 32.23 | |
| Mean ann. water bal. error | $m^3$ | -33.49 | -71.36 | |
| Net present value | Rs | 50743.25 | 50743.25 | |
| Net present value * | Rs | 50743.25 | 50743.25 | |

* including compensation for reduced outflow

Table W.B1: Results of Sensitivity Analysis

Management alternative : D - Terraces and farm pond
Parameter : Hydraulic conductivity of aquifer

| Hydraulic conductivity | m/d | 7.70 | 11.20 | 14.00 |
|---|---|---|---|---|
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 79748.89 | 79241.14 | 78904.53 |
| Mean annual surf. outflow | $m^3$ | 3567.26 | 3032.09 | 2838.28 |
| Mean annual GW-discharge | $m^3$ | 10601.06 | 11897.02 | 12614.22 |
| Mean ann. storage change | $m^3$ | -1290.36 | -944.57 | -754.67 |
| Mean ann. water bal. error | $m^3$ | -77.57 | 15.19 | 18.31 |
| Net present value | Rs | -15856.19 | -20827.14 | -25639.81 |
| Net present value * | Rs | -29620.17 | -32632.95 | -35746.71 |
| **Hydraulic conductivity** | **m/d** | **16.80** | **77.00** | |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | |
| Mean annual actual ET | $m^3$ | 78597.43 | 76998.54 | |
| Mean annual surf. outflow | $m^3$ | 2709.29 | 2552.01 | |
| Mean annual GW-discharge | $m^3$ | 13198.91 | 15508.92 | |
| Mean ann. storage change | $m^3$ | -651.25 | -118.52 | |
| Mean ann. water bal. error | $m^3$ | -26.88 | -47.99 | |
| Net present value | Rs | -30040.34 | -51390.26 | |
| Net present value * | Rs | -38481.54 | -52435.65 | |

* including compensation for reduced outflow

Table W.C0: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : A - Only drylands | | | |
| Parameter | : Specific yield | | | |
| Specific yield | % | 2.00 | 2.50 | 3.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 75198.75 | 75198.75 | 75198.75 |
| Mean annual surf. outflow | $m^3$ | 7003.41 | 6492.72 | 6406.09 |
| Mean annual GW-discharge | $m^3$ | 12344.35 | 12728.70 | 12722.45 |
| Mean ann. storage change | $m^3$ | -631.02 | -738.60 | -825.65 |
| Mean ann. water bal. error | $m^3$ | -47.53 | -28.77 | -22.94 |
| Net present value | Rs | 50743.25 | 50743.25 | 50743.25 |
| Net present value * | Rs | 50743.25 | 50743.25 | 50743.25 |

* including compensation for reduced outflow

Table W.C1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : D - Terraces and farm pond | | | |
| Parameter | : Specific yield | | | |
| Specific yield | % | 2.00 | 2.50 | 3.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78446.95 | 78904.53 | 79215.57 |
| Mean annual surf. outflow | $m^3$ | 3864.47 | 2838.28 | 2480.92 |
| Mean annual GW-discharge | $m^3$ | 12224.86 | 12614.22 | 12558.74 |
| Mean ann. storage change | $m^3$ | -705.26 | -754.67 | -834.20 |
| Mean ann. water bal. error | $m^3$ | -111.55 | 18.31 | 40.58 |
| Net present value | Rs | -31669.42 | -25639.81 | -21644.28 |
| Net present value * | Rs | -40649.80 | -35746.71 | -32490.43 |

* including compensation for reduced outflow

Table W.D0: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | A - Only drylands | | |
| Parameter | : | Gradient of ground water table | | |
| Gradient | % | 0.80 | 1.00 | 1.20 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 75198.75 | 75198.75 | 75198.75 |
| Mean annual surf. outflow | $m^3$ | 6523.80 | 6492.72 | 6480.20 |
| Mean annual GW-discharge | $m^3$ | 12590.00 | 12728.70 | 12814.67 |
| Mean ann. storage change | $m^3$ | -850.44 | -738.60 | -668.65 |
| Mean ann. water bal. error | $m^3$ | -32.98 | -28.77 | -32.27 |
| Net present value | Rs | 50743.25 | 50743.25 | 50743.25 |
| Net present value * | Rs | 50743.25 | 50743.25 | 50743.25 |

* including compensation for reduced outflow

Table W.D1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Gradient of ground water table | | |
| Gradient | % | 0.80 | 1.00 | 1.20 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 79481.40 | 78904.53 | 78468.94 |
| Mean annual surf. outflow | $m^3$ | 2900.41 | 2838.28 | 2791.80 |
| Mean annual GW-discharge | $m^3$ | 11915.50 | 12614.22 | 13146.60 |
| Mean ann. storage change | $m^3$ | -894.87 | -754.67 | -704.97 |
| Mean ann. water bal. error | $m^3$ | -62.17 | 18.31 | 17.69 |
| Net present value | Rs | -18082.21 | -25639.81 | -31356.53 |
| Net present value * | Rs | -30860.32 | -35746.71 | -39272.17 |

* including compensation for reduced outflow

Table W.E0: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | A - Only drylands | | |
| Parameter | : | Depth of aquifer | | |
| Depth of aquifer | m | 9.60 | 12.00 | 14.40 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 75198.75 | 75198.75 | 75198.75 |
| Mean annual surf. outflow | $m^3$ | 7439.75 | 6492.72 | 6406.09 |
| Mean annual GW-discharge | $m^3$ | 11849.26 | 12728.70 | 12812.30 |
| Mean ann. storage change | $m^3$ | -705.82 | -738.60 | -738.60 |
| Mean ann. water bal. Error | $m^3$ | -63.58 | -28.77 | -25.74 |
| Net present value | Rs | 50743.25 | 50743.25 | 50743.25 |
| Net present value * | Rs | 50743.25 | 50743.25 | 50743.25 |

* including compensation for reduced outflow

Table W.E1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Depth of aquifer | | |
| Depth of aquifer | m | 9.60 | 12.00 | 14.40 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78643.78 | 78904.53 | 78954.05 |
| Mean annual surf. outflow | $m^3$ | 4420.59 | 2838.28 | 2463.59 |
| Mean annual GW-discharge | $m^3$ | 11417.20 | 12614.22 | 12887.58 |
| Mean ann. storage change | $m^3$ | -701.00 | -754.67 | -781.09 |
| Mean ann. water bal. Error | $m^3$ | -52.58 | 18.31 | 43.69 |
| Net present value | Rs | -28618.49 | -25639.81 | -25009.20 |
| Net present value * | Rs | -38693.08 | -35746.71 | -34894.00 |

* including compensation for reduced outflow

Table W.F0: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | A - Only drylands | | |
| Parameter | : | Area of system | | |
| Area of system | ha | 12.00 | 15.00 | 18.00 |
| Mean annual rainfall | $m^3$ | 76104.00 | 95130.00 | 114156.00 |
| Mean annual actual ET | $m^3$ | 60159.00 | 75198.75 | 90238.50 |
| Mean annual surf. outflow | $m^3$ | 5140.62 | 6492.72 | 7836.38 |
| Mean annual GW-discharge | $m^3$ | 10375.44 | 12728.70 | 15140.82 |
| Mean ann. storage change | $m^3$ | -455.77 | -738.60 | -970.39 |
| Mean ann. water bal. Error | $m^3$ | -26.83 | -28.77 | -30.10 |
| Net present value | Rs | 40594.60 | 50743.25 | 60891.90 |
| Net present value * | Rs | 40594.60 | 50743.25 | 60891.90 |

* including compensation for reduced outflow

Table W.F1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Area of system | | |
| Area of system | ha | 12.00 | 15.00 | 18.00 |
| Mean annual rainfall | $m^3$ | 76104.00 | 95130.00 | 114156.00 |
| Mean annual actual ET | $m^3$ | 62999.63 | 78904.53 | 94413.83 |
| Mean annual surf. outflow | $m^3$ | 1824.19 | 2838.28 | 3952.36 |
| Mean annual GW-discharge | $m^3$ | 10713.94 | 12614.22 | 14801.66 |
| Mean ann. storage change | $m^3$ | -489.05 | -754.67 | -1038.33 |
| Mean ann. water bal. Error | $m^3$ | 77.18 | 18.31 | -50.18 |
| Net present value | Rs | -34715.06 | -25639.81 | -21014.03 |
| Net present value * | Rs | -41726.14 | -35746.71 | -32678.80 |

* including compensation for reduced outflow

Table W.G0: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | A - Only drylands | | |
| Parameter | : | SCS curve number CN | | |
| Curve number | - | 50.00 | 63.00 | 76.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 75593.66 | 75198.75 | 73268.85 |
| Mean annual surf. outflow | $m^3$ | 3424.22 | 6492.72 | 15899.42 |
| Mean annual GW-discharge | $m^3$ | 15291.23 | 12728.70 | 5737.44 |
| Mean ann. storage change | $m^3$ | -879.15 | -738.60 | -237.23 |
| Mean ann. water bal. Error | $m^3$ | -58.27 | -28.77 | -12.95 |
| Net present value | Rs | 51201.27 | 50743.25 | 46311.18 |
| Net present value * | Rs | 51201.27 | 50743.25 | 46311.18 |

* including compensation for reduced outflow

Table W.G1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | SCS curve number CN | | |
| Curve number | - | 50.00 | 63.00 | 76.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 79469.48 | 78904.53 | 76032.89 |
| Mean annual surf. outflow | $m^3$ | 1959.65 | 2838.28 | 9622.52 |
| Mean annual GW-discharge | $m^3$ | 12900.82 | 12614.22 | 9118.26 |
| Mean ann. storage change | $m^3$ | -757.04 | -754.67 | -380.31 |
| Mean ann. water bal. Error | $m^3$ | 43.03 | 18.31 | -23.99 |
| Net present value | Rs | -22346.61 | -25639.81 | -38779.23 |
| Net present value * | Rs | -38256.38 | -35746.71 | -37543.01 |

* including compensation for reduced outflow

Table W.H0: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | A - Only drylands | | |
| Parameter | : | Plant available water of soils | | |
| Plant avail. water (% of standard value) | % | 80.00 | 100.00 | 120.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 71975.54 | 75198.75 | 77520.70 |
| Mean annual surf. outflow | $m^3$ | 6642.90 | 6492.72 | 6540.34 |
| Mean annual GW-discharge | $m^3$ | 15846.95 | 12728.70 | 10365.12 |
| Mean ann. storage change | $m^3$ | -718.39 | -738.60 | -725.37 |
| Mean ann. water bal. Error | $m^3$ | -53.79 | -28.77 | -21.53 |
| Net present value | Rs | 41837.68 | 50743.25 | 60951.50 |
| Net present value * | Rs | 41837.68 | 50743.25 | 60951.50 |

* including compensation for reduced outflow

Table W.H1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Plant available water of soils | | |
| Plant avail. water (% of standard value) | % | 80.00 | 100.00 | 120.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 76423.47 | 78904.53 | 80637.96 |
| Mean annual surf. outflow | $m^3$ | 3385.34 | 2838.28 | 2676.00 |
| Mean annual GW-discharge | $m^3$ | 14701.93 | 12614.22 | 10937.86 |
| Mean ann. storage change | $m^3$ | -779.05 | -754.67 | -814.13 |
| Mean ann. water bal. Error | $m^3$ | -159.78 | 18.31 | 64.04 |
| Net present value | Rs | -21455.57 | -25639.81 | -30634.57 |
| Net present value * | Rs | -35872.41 | -35746.71 | -37738.17 |

* including compensation for reduced outflow

Table W.I1: Results of Sensitivity Analysis

Management alternative : D - Terraces and farm pond
Parameter : Hydr. conductivity of terrace soil

| | | | |
|---|---|---|---|
| Hydraulic conductivity | mm/d | 40.00 | 50.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78833.95 | 78904.53 |
| Mean annual surf. outflow | $m^3$ | 2920.98 | 2838.28 |
| Mean annual GW-discharge | $m^3$ | 12542.99 | 12614.22 |
| Mean ann. storage change | $m^3$ | -770.97 | -754.67 |
| Mean ann. water bal. Error | $m^3$ | 61.12 | 18.31 |
| Net present value | Rs | -25690.96 | -25639.81 |
| Net present value * | Rs | -35907.28 | -35746.71 |
| Hydraulic conductivity | mm/d | 60.00 | 300.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78878.31 | 78891.16 |
| Mean annual surf. outflow | $m^3$ | 2762.17 | 2555.72 |
| Mean annual GW-discharge | $m^3$ | 12672.81 | 12841.99 |
| Mean ann. storage change | $m^3$ | -797.62 | -824.31 |
| Mean ann. water bal. Error | $m^3$ | 19.08 | 16.82 |
| Net present value | Rs | -25744.20 | -25544.90 |
| Net present value * | Rs | -35718.24 | -35214.73 |

* including compensation for reduced outflow

Table W.J1: Results of Sensitivity Analysis

Management alternative : D - Terraces and farm pond
Parameter : Percolation rate of farm pond

| | | | | |
|---|---|---|---|---|
| Percolation rate | mm/d | 12.00 | 15.00 | 18.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78904.31 | 78904.53 | 78876.21 |
| Mean annual surf. outflow | $m^3$ | 2855.95 | 2838.28 | 2825.01 |
| Mean annual GW-discharge | $m^3$ | 12585.71 | 12614.22 | 12610.23 |
| Mean ann. storage change | $m^3$ | -796.16 | -754.67 | -818.70 |
| Mean ann. water bal. Error | $m^3$ | -12.14 | 18.31 | -0.16 |
| Net present value | Rs | -25578.14 | -25639.81 | -25533.82 |
| Net present value * | Rs | -35777.31 | -35746.71 | -35664.46 |

* including compensation for reduced outflow

Table W.K1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| **Management alternative** | **:** | **D - Terraces and farm pond** | | |
| **Parameter** | **:** | **Maximum capacity of farm pond** | | |
| Capacity of farm pond | m3 | 2040.00 | 2550.00 | 3060.00 |
| Mean annual rainfall | m3 | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | m3 | 78800.38 | 78904.53 | 78936.50 |
| Mean annual surf. outflow | m3 | 3248.08 | 2838.28 | 2522.33 |
| Mean annual GW-discharge | m3 | 12336.87 | 12614.22 | 12816.73 |
| Mean ann. storage change | m3 | -754.40 | -754.67 | -801.30 |
| Mean ann. water bal. Error | m3 | -9.72 | 18.31 | 53.15 |
| Net present value | Rs | -27004.15 | -25639.81 | -24952.52 |
| Net present value * | Rs | -37433.41 | -35746.71 | -34802.59 |

* including compensation for reduced outflow

Table W.L1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Maximum yields of crops | | |
| Maximum yields ( % of standard value) | % | 80.00 | 100.00 | 120.00 |
| Mean annual rainfall | m3 | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | m3 | 78904.53 | 78904.53 | 78904.53 |
| Mean annual surf. outflow | m3 | 2838.28 | 2838.28 | 2838.28 |
| Mean annual GW-discharge | m3 | 12614.22 | 12614.22 | 12614.22 |
| Mean ann. storage change | m3 | -754.67 | -754.67 | -754.67 |
| Mean ann. water bal. Error | m3 | 18.31 | 18.31 | 18.31 |
| Net present value | Rs | -38080.60 | -25639.81 | -13199.02 |
| Net present value * | Rs | -48187.50 | -35746.71 | -23305.92 |

* including compensation for reduced outflow

Table W.M1: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Farm gate prices | | |
| Farm gate prices ( % of standard value) | % | 80.00 | 100.00 | 120.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 78904.53 | 78904.53 | 78904.53 |
| Mean annual surf. outflow | $m^3$ | 2838.28 | 2838.28 | 2838.28 |
| Mean annual GW-discharge | $m^3$ | 12614.22 | 12614.22 | 12614.22 |
| Mean ann. storage change | $m^3$ | -754.67 | -754.67 | -754.67 |
| Mean ann. water bal. Error | $m^3$ | 18.31 | 18.31 | 18.31 |
| **Net present value** | **Rs** | **-38080.60** | **-25639.81** | -13199.02 |
| **Net present value *** | **Rs** | **-48187.50** | **-35746.71** | -23305.92 |

* including compensation for reduced outflow

Table W.M1: Results of Sensitivity Analysis

| | | | | | |
|---|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | | |
| Parameter | : | Discount rate | | | |
| Discount rate | % | 6.00 | 8.00 | 10.00 | 12.00 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 | 95130.[illegible] |
| Mean annual actual ET | $m^3$ | 78904.53 | 78904.53 | 78904.53 | 78904.5[illegible] |
| Mean annual surf. outflow | $m^3$ | 2838.28 | 2838.28 | 2838.28 | 2838.[illegible] |
| Mean annual GW-discharge | $m^3$ | 12614.22 | 12614.22 | 12614.22 | 12614.[illegible] |
| Mean ann. storage change | $m^3$ | -754.67 | -754.67 | -754.67 | -754.67 |
| Mean ann. water bal. Error | $m^3$ | 18.31 | 18.31 | 18.31 | 18.31 |
| Net present value | Rs | -9816.13 | -19038.83 | -25639.81 | -30544.5[illegible] |
| Net present value * | Rs | -24700.00 | -31127.97 | -35746.71 | -39197.[illegible]1 |

* including compensation for reduced outflow

Table W.00: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | A - Only drylands | | |
| Parameter | : | Sensitivity factor of ET | | |
| Factor | - | 0.80 | 1.00 | 1.20 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 70776.22 | 75198.75 | 79111.57 |
| Mean annual surf. outflow | $m^3$ | 7900.83 | 6492.72 | 5883.72 |
| Mean annual GW-discharge | $m^3$ | 15522.64 | 12728.70 | 10703.60 |
| Mean ann. storage change | $m^3$ | -996.32 | -738.60 | -452.88 |
| Mean ann. water bal. Error | $m^3$ | -66.02 | -28.77 | -21.77 |
| Net present value | Rs | 112814.23 | 50743.25 | 21030.00 |
| Net present value * | Rs | 112814.23 | 50743.25 | 21030.00 |

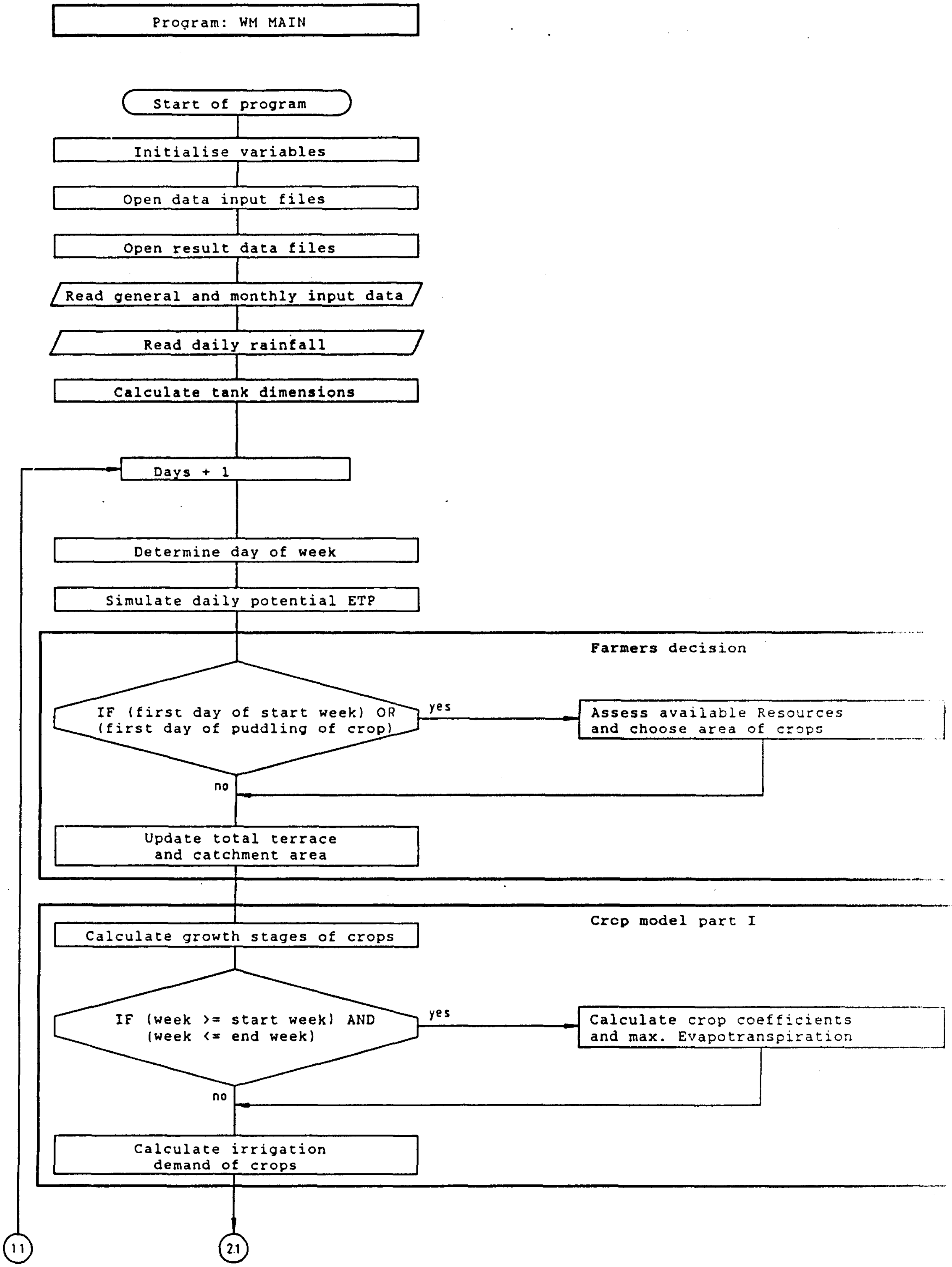
* including compensation for reduced outflow

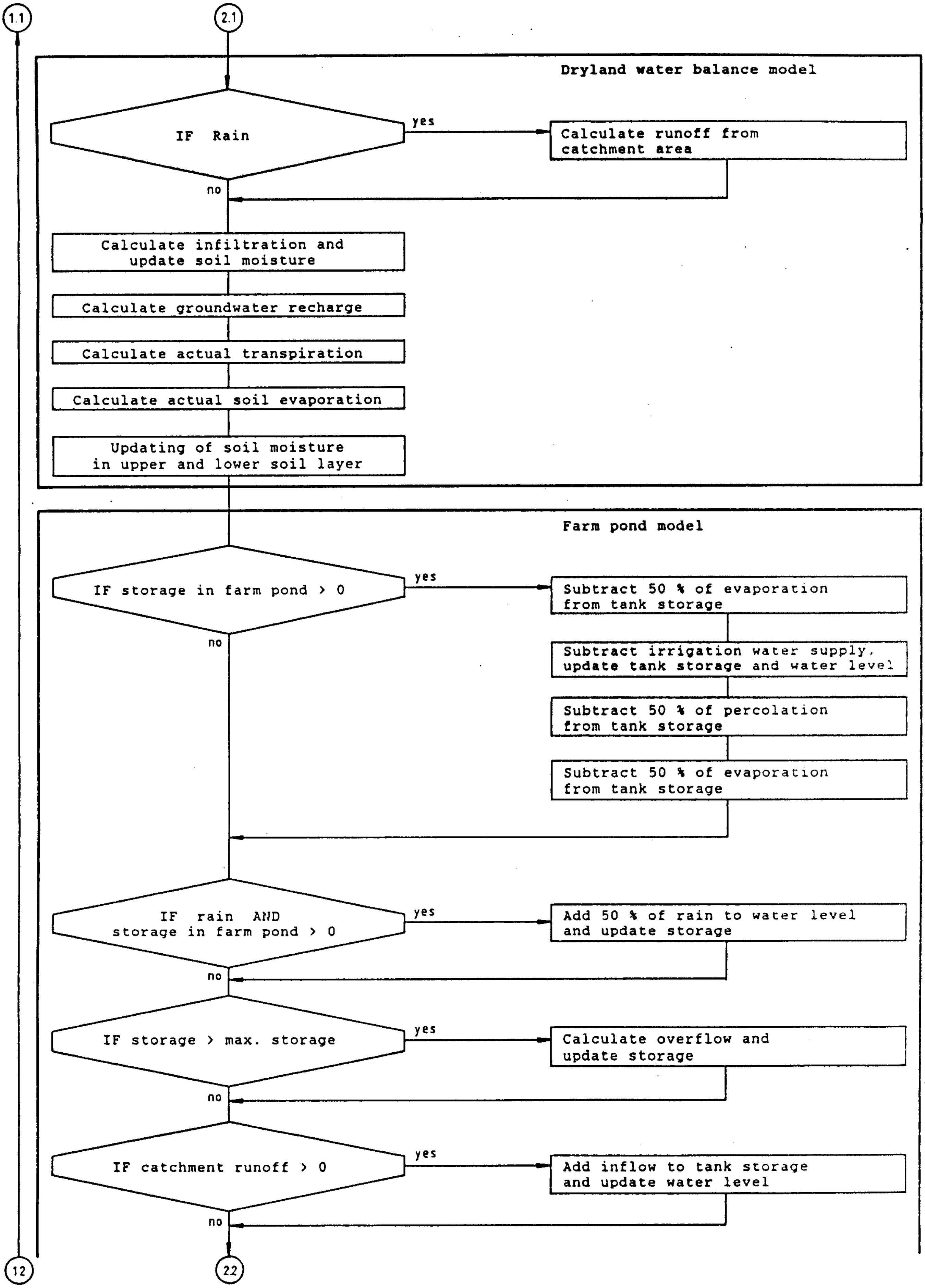
Table W.01: Results of Sensitivity Analysis

| | | | | |
|---|---|---|---|---|
| Management alternative | : | D - Terraces and farm pond | | |
| Parameter | : | Sensitivity factor of ET | | |
| Factor | - | 0.80 | 1.00 | 1.20 |
| Mean annual rainfall | $m^3$ | 95130.00 | 95130.00 | 95130.00 |
| Mean annual actual ET | $m^3$ | 74139.74 | 78904.53 | 81979.62 |
| Mean annual surf. outflow | $m^3$ | 4624.87 | 2838.28 | 2281.31 |
| Mean annual GW-discharge | $m^3$ | 15473.56 | 12614.22 | 10348.40 |
| Mean ann. storage change | $m^3$ | -1107.21 | -754.67 | -447.16 |
| Mean ann. water bal. Error | $m^3$ | -215.37 | 18.31 | 73.50 |
| Net present value | Rs | -22468.20 | -25639.81 | -31238.31 |
| Net present value * | Rs | -31475.70 | -35746.71 | -42323.66 |

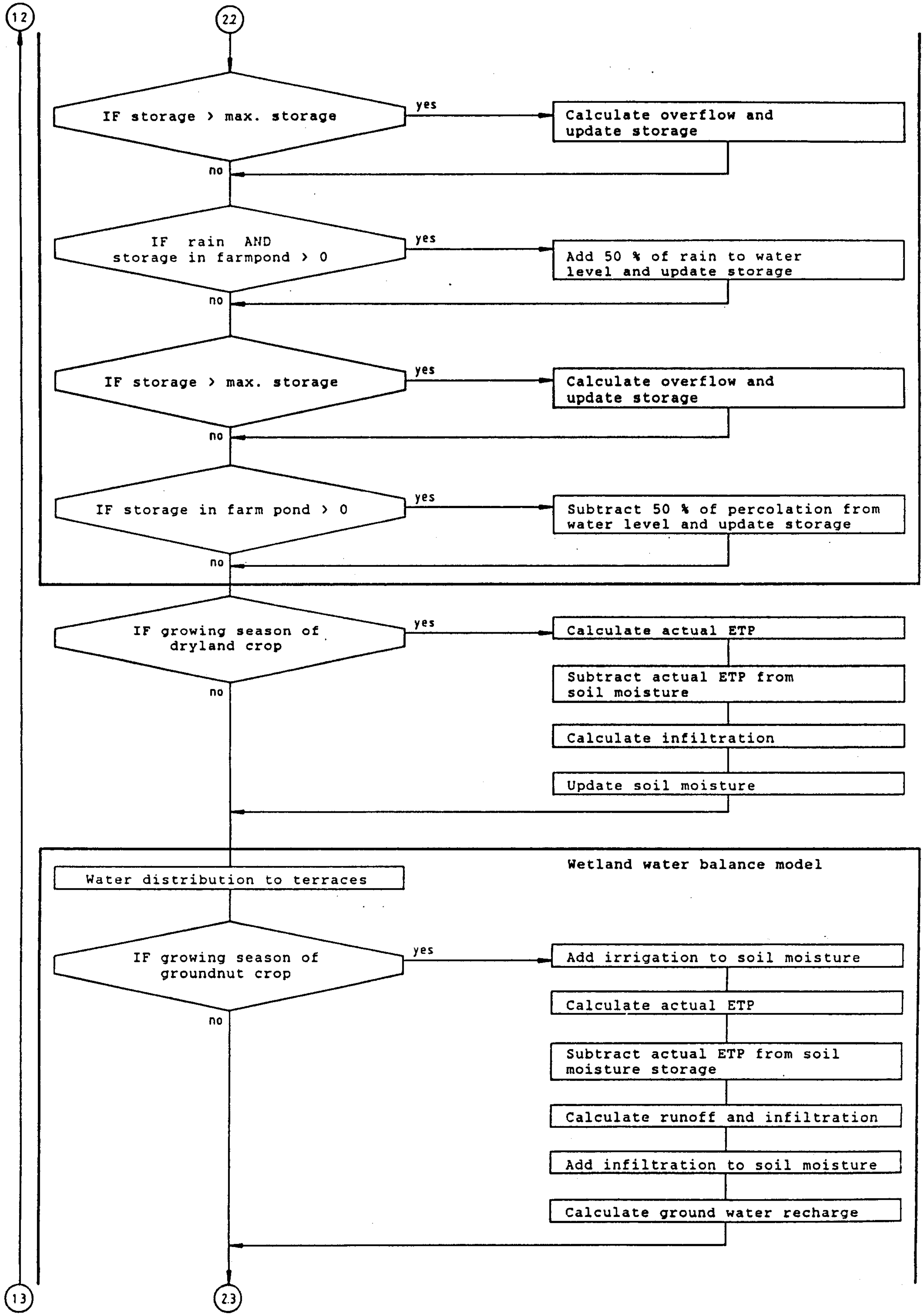
* including compensation for reduced outflow

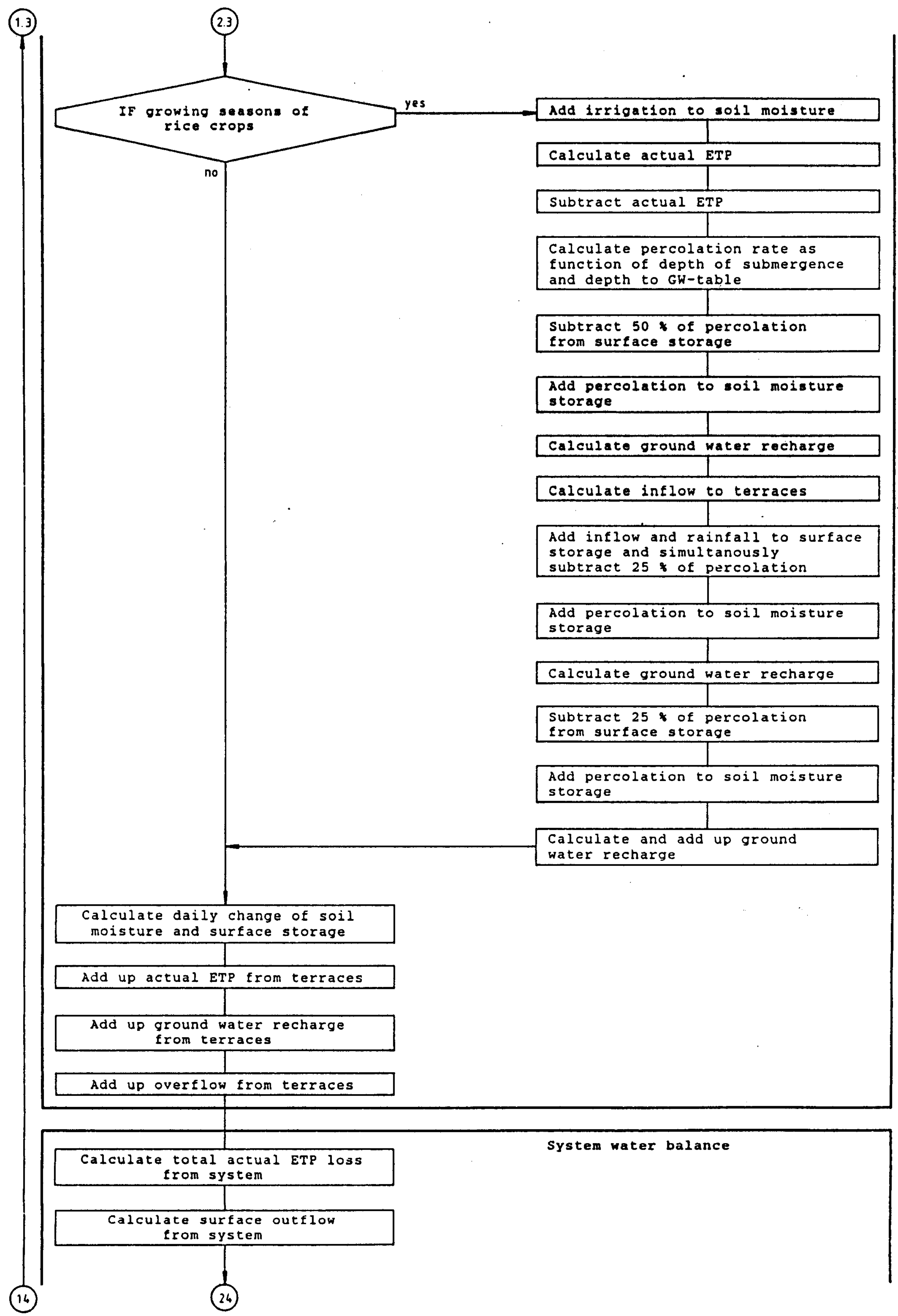
## APPENDIX X: FLOW CHART OF APPSMOD

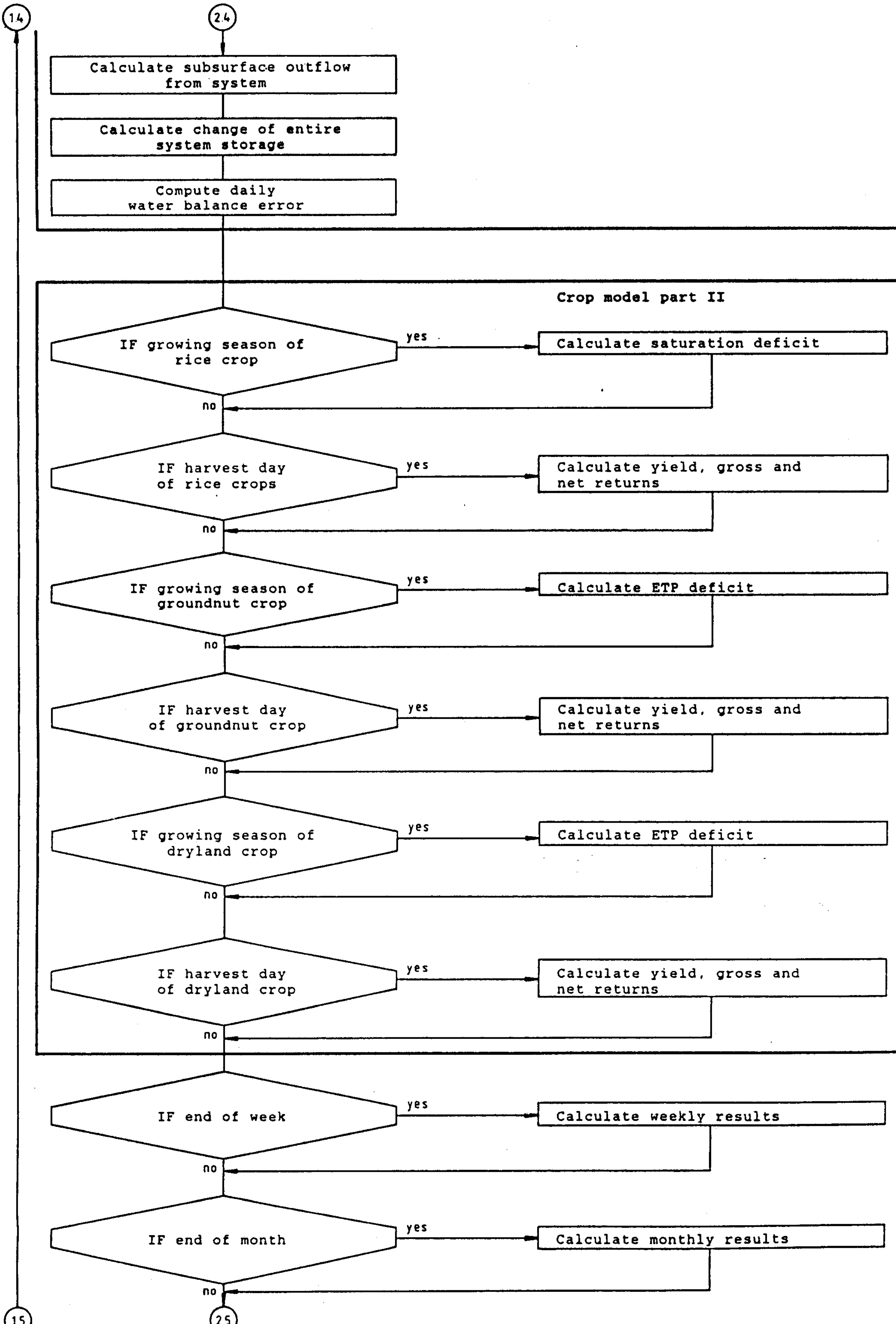

Program: WM MAIN
Start of program
Initialise variables
Open data input files
Open result data files
Read general and monthly input data
Read daily rainfall
Calculate tank dimensions
Days + 1
Determine day of week
Simulate daily potential ETP
Farmers decision
IF (first day of start week) OR (first day of puddling of crop)
yes
Assess available Resources and choose area of crops
no
Update total terrace and catchment area
Crop model part I
Calculate growth stages of crops
IF (week >= start week) AND (week <= end week)
yes
Calculate crop coefficients and max. Evapotranspiration
no
Calculate irrigation demand of crops
11
21

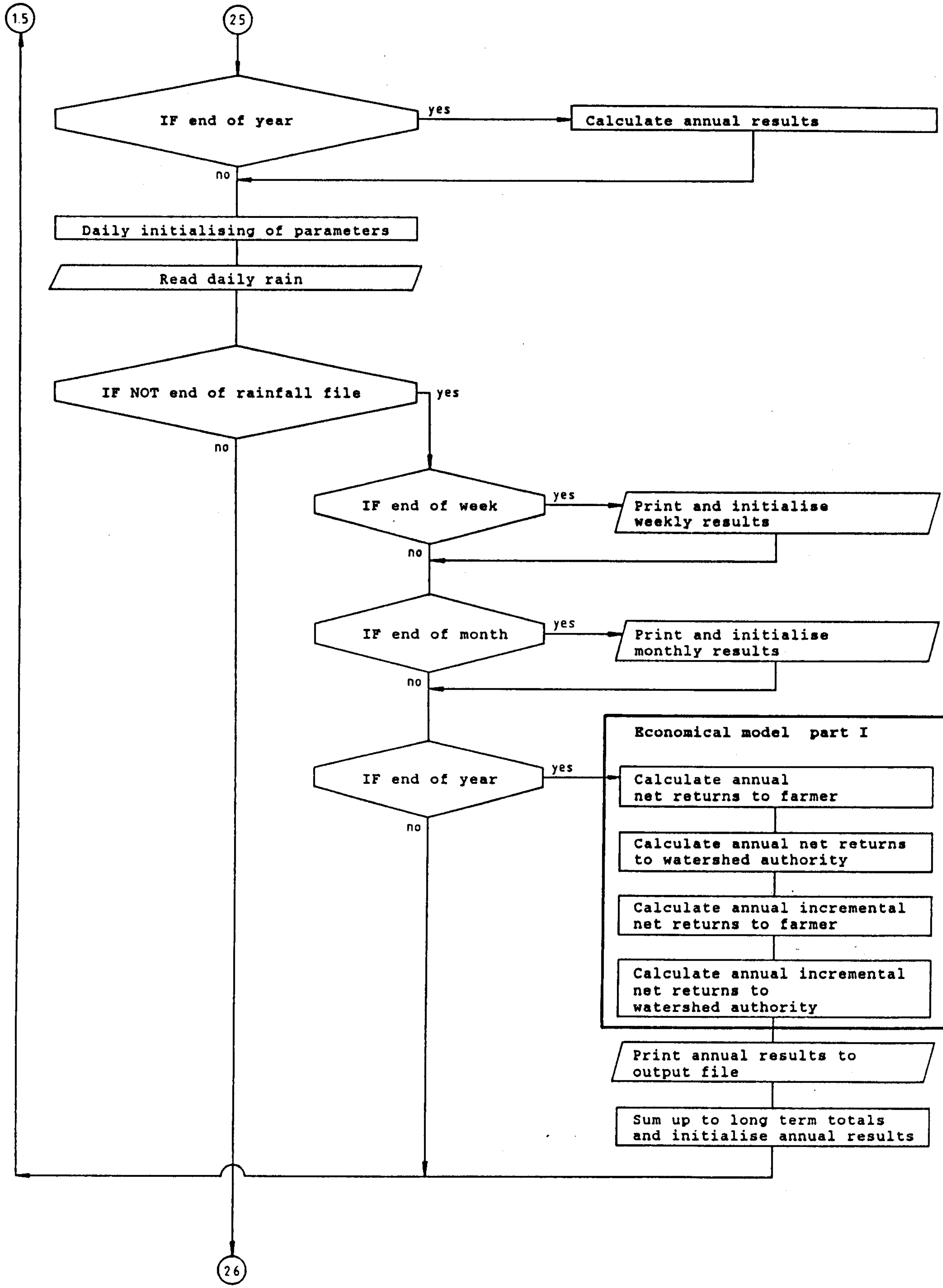


1.1
2.1
Dryland water balance model
IF Rain
yes
Calculate runoff from catchment area
no
Calculate infiltration and update soil moisture
Calculate groundwater recharge
Calculate actual transpiration
Calculate actual soil evaporation
Updating of soil moisture in upper and lower soil layer
Farm pond model
IF storage in farm pond > 0
yes
Subtract 50 % of evaporation from tank storage
no
Subtract irrigation water supply, update tank storage and water level
Subtract 50 % of percolation from tank storage
Subtract 50 % of evaporation from tank storage
IF rain AND storage in farm pond > 0
yes
Add 50 % of rain to water level and update storage
no
IF storage > max. storage
yes
Calculate overflow and update storage
no
IF catchment runoff > 0
yes
Add inflow to tank storage and update water level
no
12
22

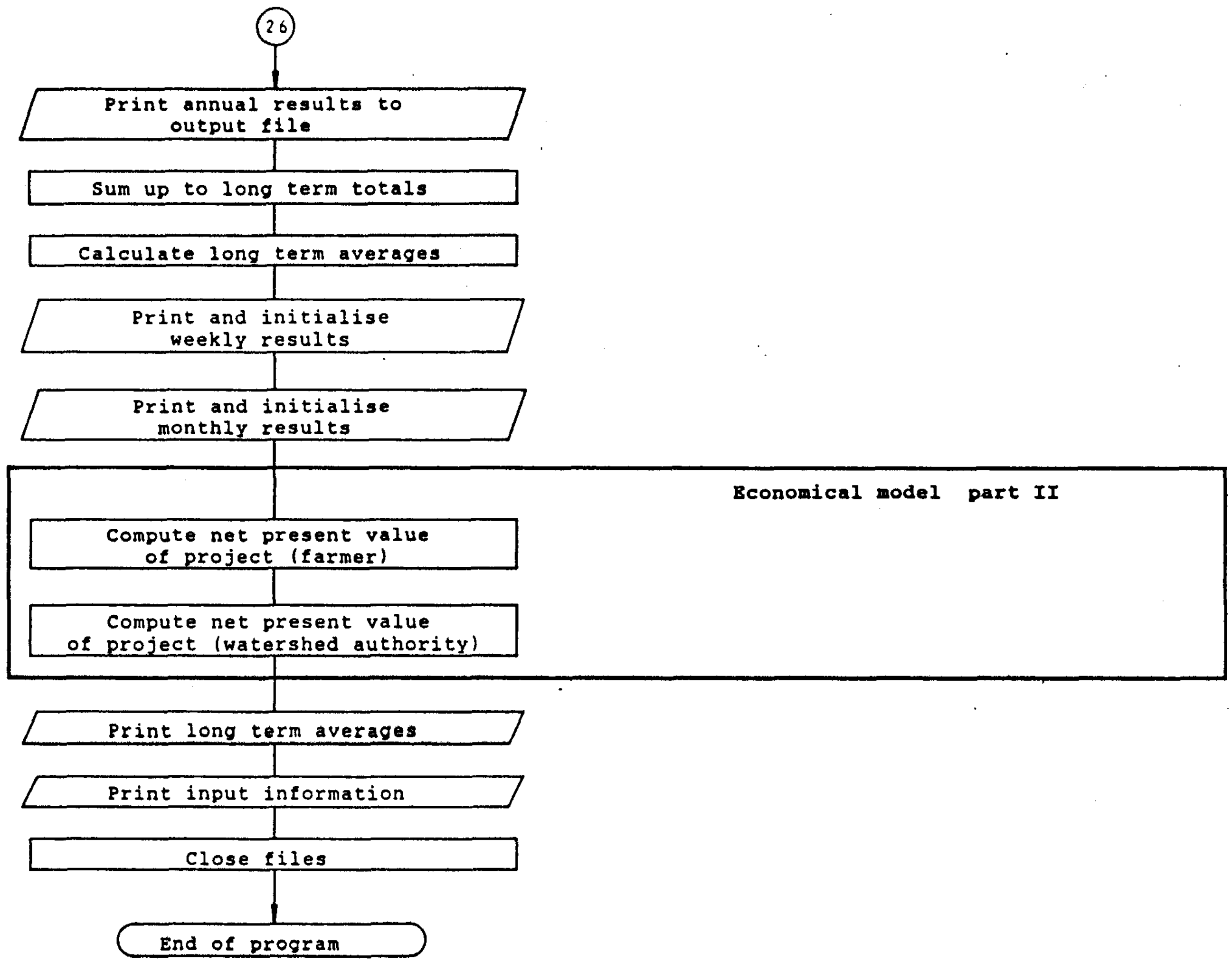

12
22
IF storage > max. storage
yes
Calculate overflow and update storage
no
IF rain AND storage in farmpond > 0
yes
Add 50 % of rain to water level and update storage
no
IF storage > max. storage
yes
Calculate overflow and update storage
no
IF storage in farm pond > 0
yes
Subtract 50 % of percolation from water level and update storage
no
IF growing season of dryland crop
yes
Calculate actual ETP
Subtract actual ETP from soil moisture
Calculate infiltration
Update soil moisture
no
Wetland water balance model
Water distribution to terraces
IF growing season of groundnut crop
yes
Add irrigation to soil moisture
Calculate actual ETP
Subtract actual ETP from soil moisture storage
Calculate runoff and infiltration
Add infiltration to soil moisture
Calculate ground water recharge
no
13
23


1.3
2.3
IF growing seasons of rice crops
yes
no
Add irrigation to soil moisture
Calculate actual ETP
Subtract actual ETP
Calculate percolation rate as function of depth of submergence and depth to GW-table
Subtract 50 % of percolation from surface storage
Add percolation to soil moisture storage
Calculate ground water recharge
Calculate inflow to terraces
Add inflow and rainfall to surface storage and simultanously subtract 25 % of percolation
Add percolation to soil moisture storage
Calculate ground water recharge
Subtract 25 % of percolation from surface storage
Add percolation to soil moisture storage
Calculate and add up ground water recharge
Calculate daily change of soil moisture and surface storage
Add up actual ETP from terraces
Add up ground water recharge from terraces
Add up overflow from terraces
System water balance
Calculate total actual ETP loss from system
Calculate surface outflow from system
14
24


1.4
2.4
Calculate subsurface outflow from system
Calculate change of entire system storage
Compute daily water balance error
Crop model part II
IF growing season of rice crop
yes
Calculate saturation deficit
no
IF harvest day of rice crops
yes
Calculate yield, gross and net returns
no
IF growing season of groundnut crop
yes
Calculate ETP deficit
no
IF harvest day of groundnut crop
yes
Calculate yield, gross and net returns
no
IF growing season of dryland crop
yes
Calculate ETP deficit
no
IF harvest day of dryland crop
yes
Calculate yield, gross and net returns
no
IF end of week
yes
Calculate weekly results
no
IF end of month
yes
Calculate monthly results
no
1.5
2.5



1.5
25
IF end of year
yes
no
Calculate annual results
Daily initialising of parameters
Read daily rain
IF NOT end of rainfall file
yes
no
IF end of week
yes
Print and initialise weekly results
no
IF end of month
yes
Print and initialise monthly results
no
Economical model part I
IF end of year
yes
no
Calculate annual net returns to farmer
Calculate annual net returns to watershed authority
Calculate annual incremental net returns to farmer
Calculate annual incremental net returns to watershed authority
Print annual results to output file
Sum up to long term totals and initialise annual results
26


26
Print annual results to output file
Sum up to long term totals
Calculate long term averages
Print and initialise weekly results
Print and initialise monthly results
Economical model part II
Compute net present value of project (farmer)
Compute net present value of project (watershed authority)
Print long term averages
Print input information
Close files
End of program

APPENDIX Y: US SOIL CONSERVATION CURVE NUMBER METHOD

Table Y.1: US SCS Curve Numbers Depending on Land Use, Treatment, Infiltration Condition and Soil Group (Soil moisture condition II, Ia = 0.2 · S)

| Land use or cover | Treatment or practice | Hydrologic Infiltration condition | Hydrologic soil group A | B | C | D |
|---|---|---|---|---|---|---|
| Fallow | SR | | 77 | 86 | 91 | 94 |
| Row crops | SR | poor | 72 | 81 | 88 | 91 |
| | SR | good | 67 | 78 | 85 | 89 |
| | C | poor | 70 | 79 | 84 | 88 |
| | C | good | 65 | 75 | 82 | 86 |
| | C&T | poor | 66 | 74 | 80 | 82 |
| | C&T | good | 62 | 71 | 78 | 81 |
| Small grain | SR | poor | 65 | 76 | 84 | 88 |
| | SR | good | 63 | 75 | 83 | 87 |
| | C | poor | 63 | 74 | 82 | 85 |
| | C | good | 61 | 73 | 81 | 84 |
| | C&T | poor | 61 | 72 | 79 | 82 |
| | C&T | good | 59 | 70 | 78 | 81 |
| Close-seeded legumes or rotation meadow | SR | poor | 66 | 77 | 85 | 89 |
| | SR | good | 58 | 72 | 81 | 85 |
| | C | poor | 64 | 75 | 83 | 85 |
| | C | good | 55 | 69 | 78 | 83 |
| | C&T | poor | 63 | 73 | 80 | 83 |
| | C&T | good | 51 | 67 | 76 | 80 |
| Pasture or range | | poor | 68 | 79 | 86 | 89 |
| | | fair | 49 | 69 | 79 | 84 |
| | | good | 39 | 61 | 74 | 80 |
| | C | poor | 47 | 67 | 81 | 88 |
| | C | fair | 25 | 59 | 75 | 83 |
| | C | good | 6 | 35 | 70 | 79 |
| Meadow (permanent) | | | 30 | 58 | 71 | 78 |
| Woods (farm woodlots) | | poor | 45 | 66 | 77 | 83 |
| | | fair | 36 | 60 | 73 | 79 |
| | | good | 25 | 55 | 70 | 77 |
| Farmsteads | | | 59 | 74 | 82 | 86 |
| Roads (dirt) | | | 72 | 82 | 87 | 89 |
| hard surface | | | 74 | 84 | 90 | 92 |

Source: [248]
SR: Straight row, C: Contoured, C&T: Contoured and terraced

Table Y.2: Definition of Hydrological Soil Groups

| Soil group | Definition |
|---|---|
| A | Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission. |
| B | Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission. |
| C | Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission. |
| D | Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission. |

Source: [36]

Table Y.3: US SCS Curve Numbers for Different Antecedent Soil Moisture Conditions (Ia = 0.2 * S)

| Antecedent soil moisture conditions | | | Range |
|---|---|---|---|
| II | I | III | III-I |
| 100 | 100 | 100 | 0 |
| 95 | 87 | 99 | 12 |
| 90 | 78 | 98 | 20 |
| 80 | 63 | 94 | 31 |
| 70 | 51 | 87 | 36 |
| 60 | 40 | 79 | 39 |
| 50 | 31 | 70 | 39 |
| 40 | 23 | 60 | 37 |
| 30 | 15 | 50 | 35 |
| 20 | 9 | 39 | 30 |
| 10 | 4 | 25 | 21 |
| 5 | 2 | 17 | 15 |
| 0 | 0 | 0 | 0 |

Source: Compiled by the author from [248]

## APPENDIX Z: FACTORS INFLUENCING SELECTION OF PAN CLASS A COEFFICIENT

**Table Z.1: Class A Pan Coefficient kpan for Different Ground Cover and Levels of Mean Relative Humidity and 24 h Wind**

| Ground cover | Pan surrounded by short green crop | | | | Pan surrounded by dry fallow land * | | | |
|---|---|---|---|---|---|---|---|---|
| RH mean (%) | | low <40 | med. 40-70 | high >70 | | low <40 | med. 40-70 | high >70 |
| Wind ** (km/d) | Upwind distance of green crop (m) | | | | Upwind distance of dry fallow (m) | | | |
| Light < 175 | 0 | 0.55 | 0.65 | 0.75 | 0 | 0.70 | 0.80 | 0.85 |
| | 10 | 0.65 | 0.75 | 0.85 | 10 | 0.60 | 0.70 | 0.80 |
| | 100 | 0.70 | 0.80 | 0.85 | 100 | 0.55 | 0.65 | 0.75 |
| | 1000 | 0.75 | 0.85 | 0.85 | 1000 | 0.50 | 0.60 | 0.70 |
| Moderate 175 - 425 | 0 | 0.50 | 0.60 | 0.65 | 0 | 0.65 | 0.75 | 0.80 |
| | 10 | 0.60 | 0.70 | 0.75 | 10 | 0.55 | 0.65 | 0.70 |
| | 100 | 0.65 | 0.75 | 0.80 | 100 | 0.50 | 0.60 | 0.65 |
| | 1000 | 0.70 | 0.80 | 0.80 | 1000 | 0.45 | 0.55 | 0.60 |
| Strong 425 - 700 | 0 | 0.45 | 0.55 | 0.60 | 0 | 0.60 | 0.65 | 0.70 |
| | 10 | 0.55 | 0.60 | 0.65 | 10 | 0.50 | 0.55 | 0.65 |
| | 100 | 0.60 | 0.65 | 0.70 | 100 | 0.45 | 0.45 | 0.60 |
| | 1000 | 0.65 | 0.70 | 0.75 | 1000 | 0.40 | 0.45 | 0.55 |
| Very strong > 700 | 0 | 0.40 | 0.45 | 0.50 | 0 | 0.50 | 0.60 | 0.65 |
| | 10 | 0.45 | 0.55 | 0.60 | 10 | 0.45 | 0.50 | 0.55 |
| | 100 | 0.50 | 0.60 | 0.65 | 100 | 0.40 | 0.45 | 0.50 |
| | 1000 | 0.55 | 0.60 | 0.65 | 1000 | 0.35 | 0.40 | 0.45 |

* For extensive areas of barefallow soils and not agricultural development, reduce kpan values by 20 % under hot windy conditions, by 5 to 10 % for moderate wind, temperature and humidity conditions.
** Total wind movement km/d.

Source: [109]

# Appendix SS: NUMERICAL SOLUTION OF GROUND WATER FLOW EQUATION

Governing partial differential equation

[245], [43], [32]

$$\frac{\delta}{\delta x}\left(T\cdot\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\left(T\cdot\frac{\delta h}{\delta y}\right)-S\frac{\delta h}{\delta t}+n=0 \qquad \text{(SS.1)}$$

where:

| | |
|---|---|
| h = Hydraulic head | [m] |
| n = Vertical GW-recharge or GW-draft | [m/s] |
| S = Storage coefficient | [-] |
| T = Transmissivity | [$m^2$/s] |
| t = Time | [s] |

Assumptions:

- The aquifer is homogeneous and isotropic
- Horizontal impermeable underlying strata
- Low gradient of groundwater table
- Small variation in saturated thickness
- Non compressible fluid

Definitions:

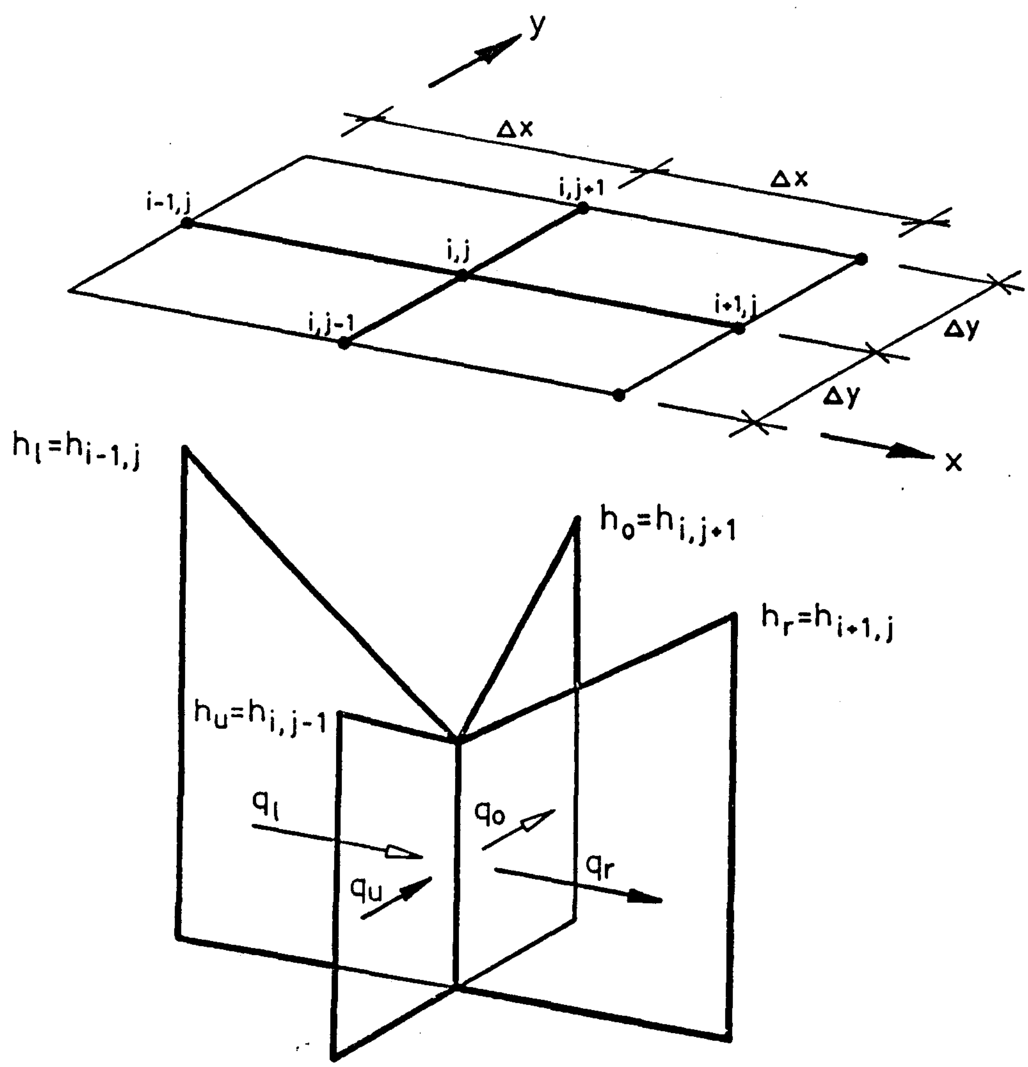



Figure SS.1: Definitions

Approximation of Partial Differential Equation into Finite Difference Form

This approach requires to replace the continuous aquifer parameters contained in the flow equation with an equivalent set of discrete elements. System parameters were discretized in the present study by a grid of 9 rows and 5 columns (Figure SS.2) resulting in 45 nodes.

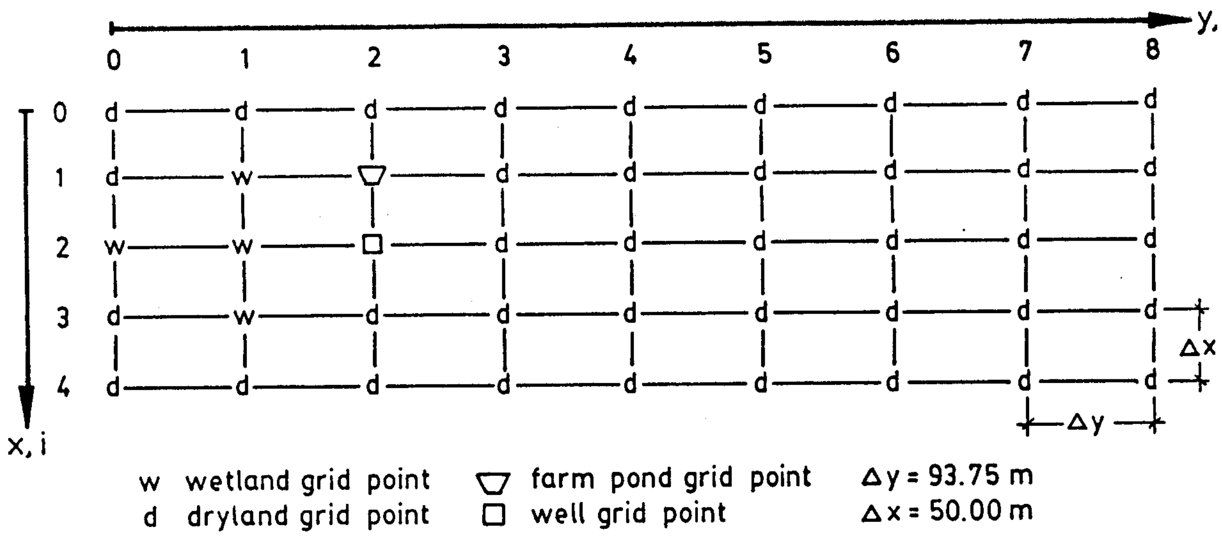



Figure SS.2: Discretized Form of Aquifer used in APPSMOD

On a dryland grid point only infiltration from drylands is considered, whereas infiltration from terraces is taken into account on wetland grid points. On the farm pond grid point all seepage from the farm pond is recharged into the aquifer. Groundwater is abstracted from the aquifer at the well grid point.

The finite difference equation to be generalized at each of these nodes were solved using a procedure developed by (Traebing 1989).

Discretized form of <u>non-steady state component</u> of equation SS.1:

$$- S \frac{\delta h}{\delta t} \approx - S \frac{h - h^{act}}{\Delta t} = - \frac{S}{\Delta t} h + \frac{S}{\Delta t} h^{act}$$

Discretized form of <u>divergence component</u> (Approximation by Laplace-molecule (Figure SS.1)).

$$f_q = \frac{\delta}{\delta x} \left( T \frac{\delta h}{\delta x} \right) + \frac{\delta}{\delta y} \left( T \frac{\delta h}{\delta y} \right)$$

$$= \frac{\delta}{\delta x} q_x + \frac{\delta}{\delta y} q_y$$

where:

$$q_r = T_r I_r = k \frac{h_r + h}{2} \cdot \frac{h_r - h}{\Delta x} = \frac{k}{2 \Delta x} \left( h_r^2 - h^2 \right)^Y$$

$$q_l = T_l I_l = k \frac{h + h_l}{2} \cdot \frac{h - h_l}{\Delta x} = \frac{k}{2x} \left( h^2 - h_l^2 \right)$$

$$q_o = T_o I_o = \frac{k}{2 \Delta y} \left( h_o^2 - h^2 \right)$$

$$q_u = T_u I_u = \frac{k}{2 \Delta y} \left( h^2 - h_u^2 \right)$$

with k = hydraulic conductivity

Boundary Conditions

$q_x\ (x = x_o) = q_x\ (x = x_{max}) = 0$
(zero flow condition at the sides of aquifer)

$q_y\ (y = y_{max}) = 0$
(zero flow conditions for upper boundary of aquifer)

$q_y\ (y = y_o) = q_u(I_o)$
(Fixed gradient at lower boundary of aquifer)

Equation to be solved at each field node

$$f_q \approx \frac{1}{\Delta x}\left(q_r - q_l\right) + \frac{1}{\Delta y}\left(q_o - q_u\right)$$

$$= \frac{k}{2}\left[\frac{1}{\Delta x^2}\left(h_r^2 - 2h^2 + h_l^2\right) + \frac{1}{\Delta y^2}\left(h_o^2 + h_u^2\right)\right]$$

$$= + h^2\ k\ \left(- \frac{1}{\Delta x^2} - \frac{1}{\Delta y^2}\right)$$

$$+ \frac{k}{2}\left(\frac{h_r^2 + h_e^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2}\right)$$

Equation to be solved at boundary nodes:

Nodes on left boundary: zero flow $\rightarrow q_l = - q_r \rightarrow h_l = h_r$

$$\rightarrow f_q \approx h^2 \cdot k \left(- \frac{1}{\Delta x^2} - \frac{1}{\Delta y^2}\right)$$

$$+ \frac{k}{2} \left(\frac{2h_r^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2}\right)$$

Nodes on right boundary:

(zero flow $\rightarrow q_r = q_l \rightarrow h_r = h_l$)

$$\rightarrow f_q \approx h^2 \cdot k \left(- \frac{1}{\Delta x^2} - \frac{1}{\Delta y^2}\right)$$

$$+ \frac{k}{2} \left(\frac{2h_l^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2}\right)$$

Nodes on upper boundary:

(zero - flow $\rightarrow q_o = - q_u \rightarrow h_o = + h_u$)

$$\rightarrow f_q \approx h^2 \cdot k \left(- \frac{1}{\Delta x^2} - \frac{1}{\Delta y^2}\right)$$

$$+ \frac{k}{2} \left( \frac{h_r^2 + h_l^2}{\Delta x^2} + \frac{2\ h_u^2}{\Delta y^2} \right)$$

Nodes on lower boundary:

($q_u$ defined by given constant gradient at lower bounday)

$$f_q \approx \frac{1}{\Delta x} \left( q_r - q_l \right) + \frac{1}{\Delta y/2} \left( q_o - q_u \right)$$

$$= \frac{k}{2\Delta x^2} \left( h_r^2 - 2h^2 + h_l^2 \right) + \frac{2}{\Delta y} \left[ \frac{k}{2\Delta y} \left( h_o^2 - h^2 \right) - q_u \right]$$

$$= h^2 \cdot k \left( - \frac{1}{\Delta x^2} - \frac{1}{\Delta y^2} \right)$$

$$+ \frac{k}{2\Delta x^2} \left( h_r^2 + h_l^2 \right) + \frac{k}{\Delta y^2}\ h_o^2 - \frac{2q_u}{\Delta y}$$

$$= h^2\ k \left( - \frac{1}{\Delta x^2} - \frac{1}{\Delta y^2} \right)$$

$$+ k\left(\frac{h_r^2\ h_l^2}{2\Delta x^2} + \frac{h_o^2}{\Delta y^2}\right) - 2\ \frac{q_u}{\Delta y}$$

The resulting equation is always of the type

$$f \approx Ah^2 + Bh + C$$

for all nodes of the net

where:

$$A = \left(-\frac{1}{\Delta x^2} - \frac{1}{\Delta y^2}\right) - k \qquad \text{(divergence component)}$$

$$B = -\frac{s}{\Delta t} \qquad \text{(non-steady state component)}$$

$$C = \qquad \text{(depending on node)}$$

Field node:

$$C = n + \frac{S}{\Delta t}\ h^{alt} + \frac{k}{2}\left(\frac{h_r^2 + h_l^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2}\right)$$

Node on left boundary:

$$C = n + \frac{S}{\Delta t} h^{alt} + \frac{k}{2} \left( \frac{2h_r^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2} \right)$$

Node on right boundary:

$$C = n + \frac{S}{\Delta t} h^{alt} + \frac{k}{2} \left( \frac{2h_l^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2} \right)$$

Node on upper boundary:

$$C = n + \frac{S}{\Delta t} h^{alt} + \frac{k}{2} \left( \frac{h_r^2 + h_l^2}{\Delta x^2} + \frac{2h_u^2}{\Delta y^2} \right)$$

Node on lower boundary:

$$C = n + \frac{S}{\Delta t} h^{alt} + \frac{k}{2} \left( \frac{h_r^2 + h_l^2}{\Delta x^2} + \frac{2h_o^2}{\Delta y^2} - 2 \frac{q_u}{\Delta y} \right)$$

Since an equation of the form $A \cdot h^2 + B \cdot h + C$ is to be solved for each node (i, j) the non-linear Gauss-Seidel-algorithm is employed.

$$h_{1/2} = -\frac{B}{2A} \pm \sqrt{\left(\frac{B}{2A}\right)^2 - \frac{C}{A}}$$

The only physically sensible solution is:

$$h = -\frac{B}{2A} + \sqrt{\left(\frac{B}{2A}\right)^2 - \frac{C}{A}}$$

when

$$\left(\frac{B}{2A}\right)^2 - \frac{C}{A} \geq 0 \qquad \text{is valid}$$

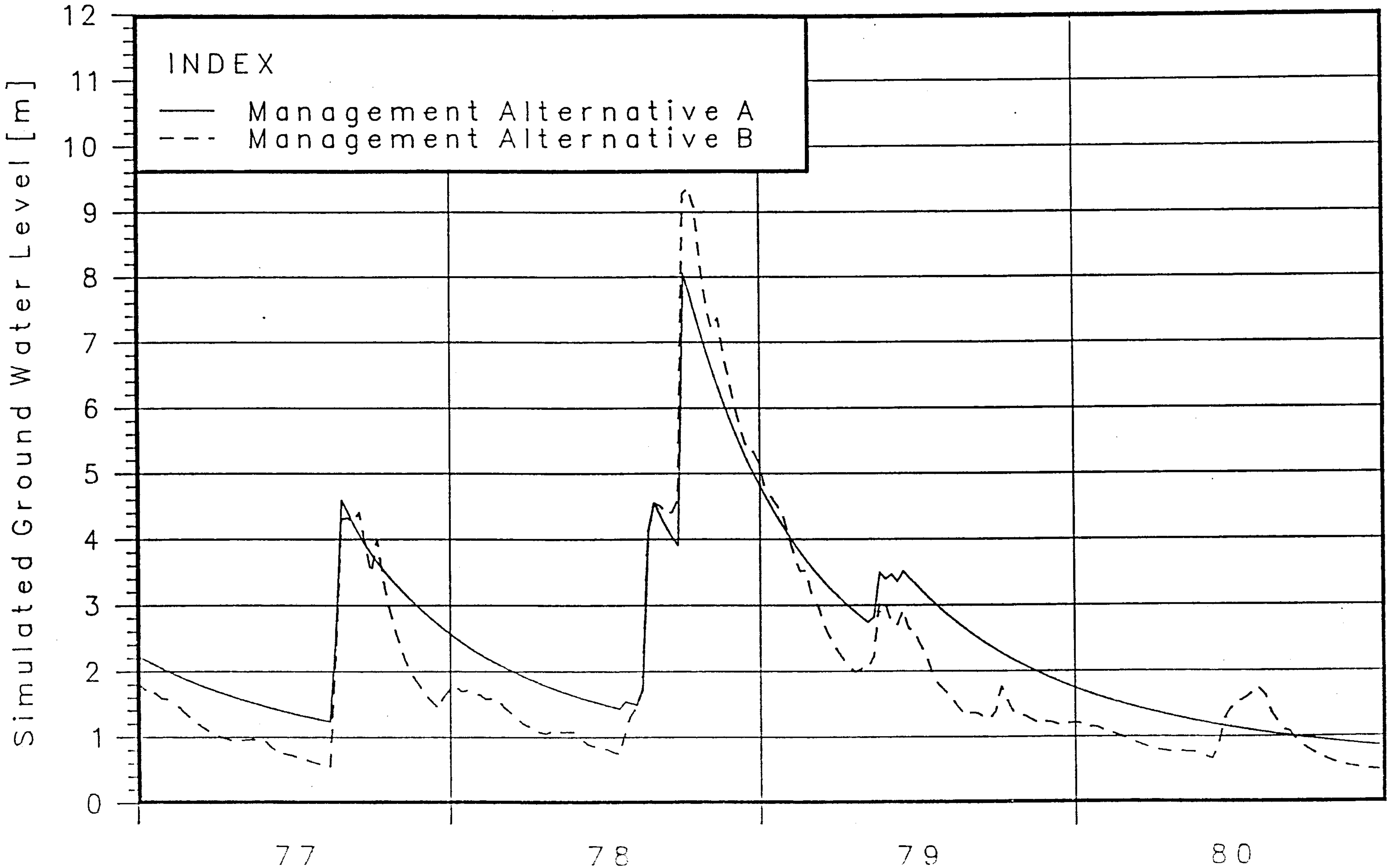
$$\rightarrow -\frac{C}{A} \geq \left(\frac{B}{2A}\right)^2$$

$$\rightarrow C \geq -\left(\frac{B}{2A}\right)^2 \cdot A \qquad \text{because } A < 0;\ C = \text{fct }(n)$$

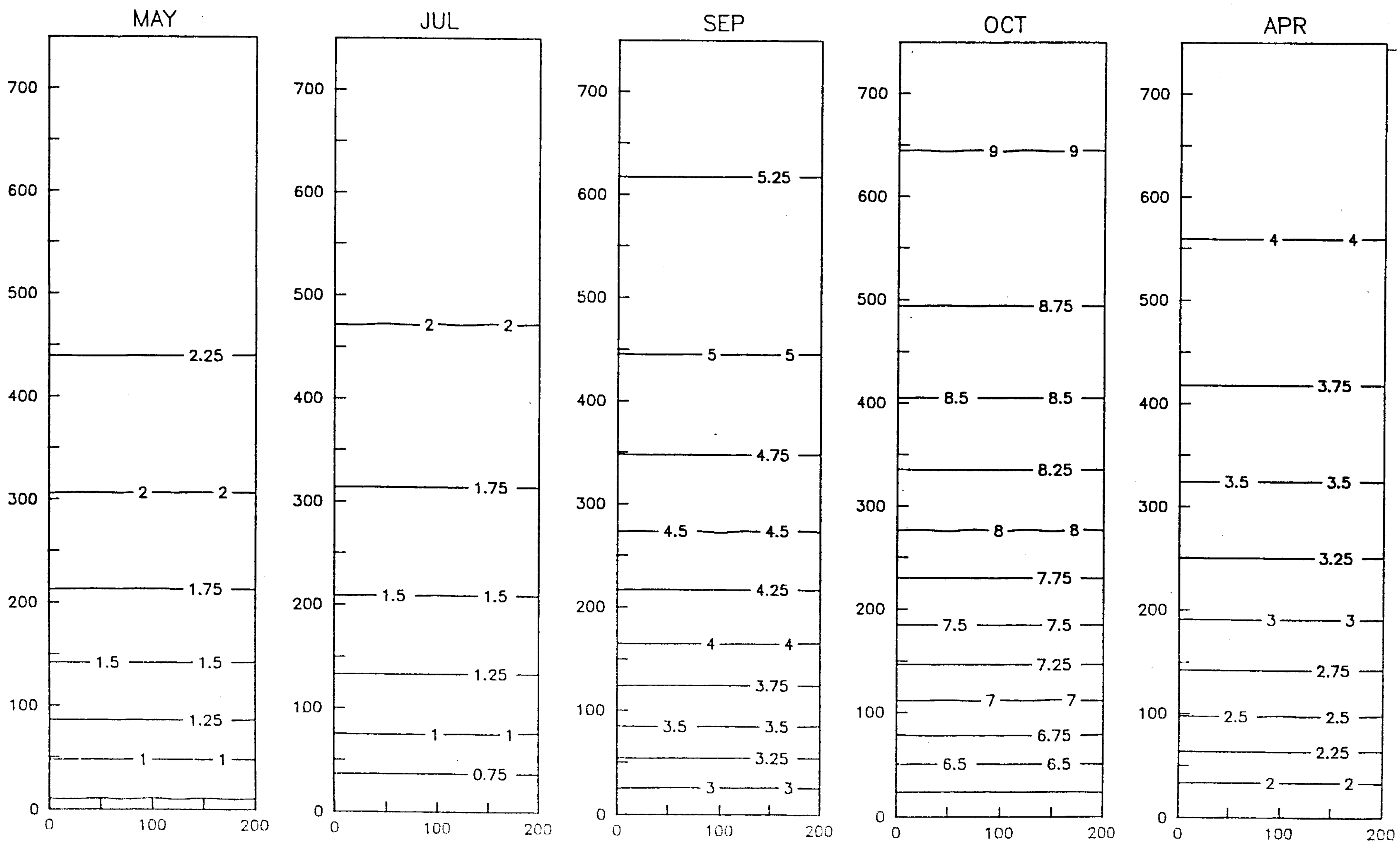
for example for a field node

$$\rightarrow n \geq -\left(\frac{B}{2A}\right)^2 - \frac{S}{\Delta t} \cdot h^{alt} - \frac{k}{2}\left(\frac{h_r^2 + h_l^2}{\Delta x^2} + \frac{h_o^2 + h_u^2}{\Delta y^2}\right)$$

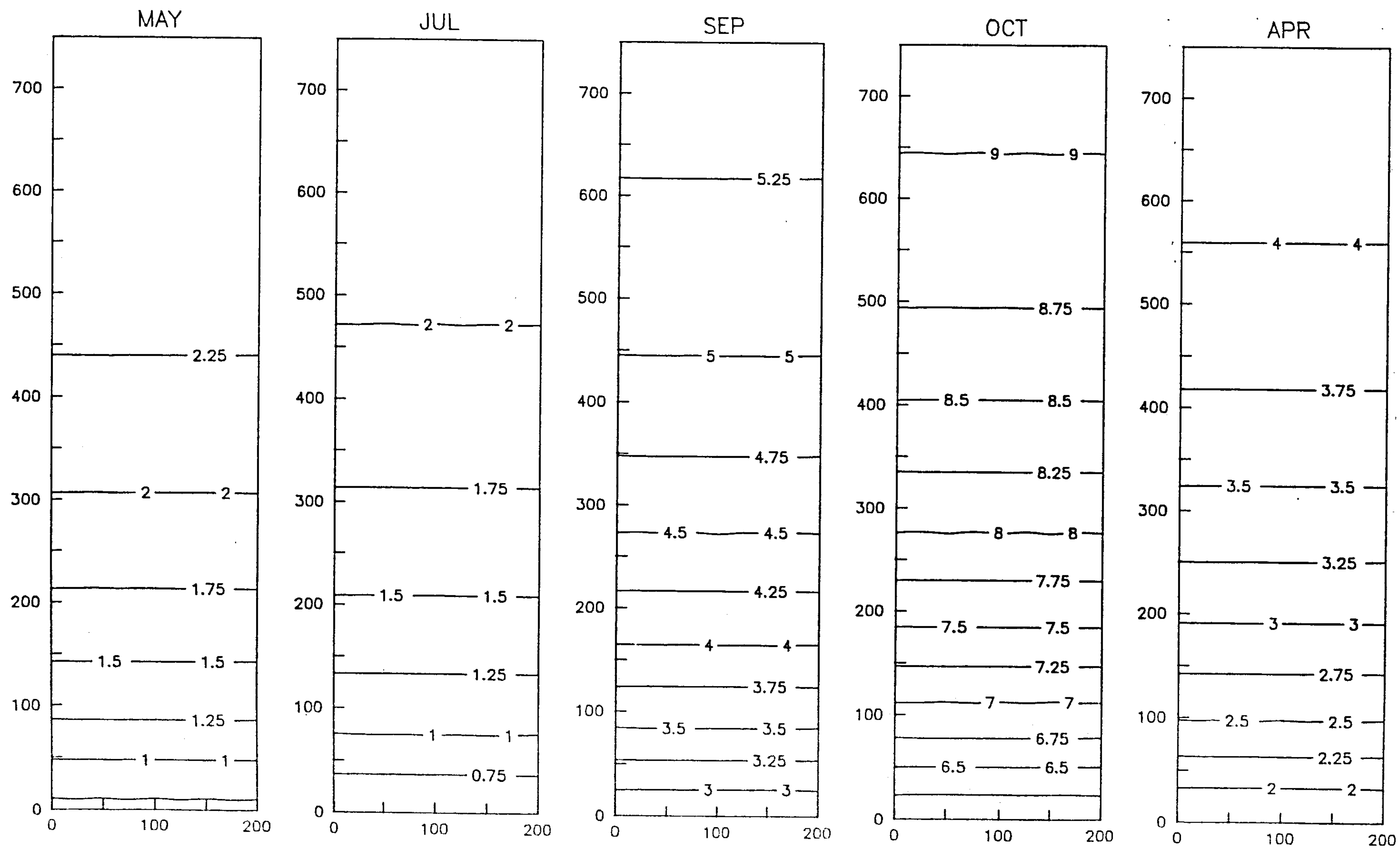
# APPENDIX TT: SIMULATED GROUND WATER CONTOURS FOR SYSTEM WITH AND WITHOUT APPT


INDEX
Management Alternative A
Management Alternative B
Simulated Ground Water Level [m]
0
1
2
3
4
5
6
7
8
9
10
11
12
77
78
79
80
TT1

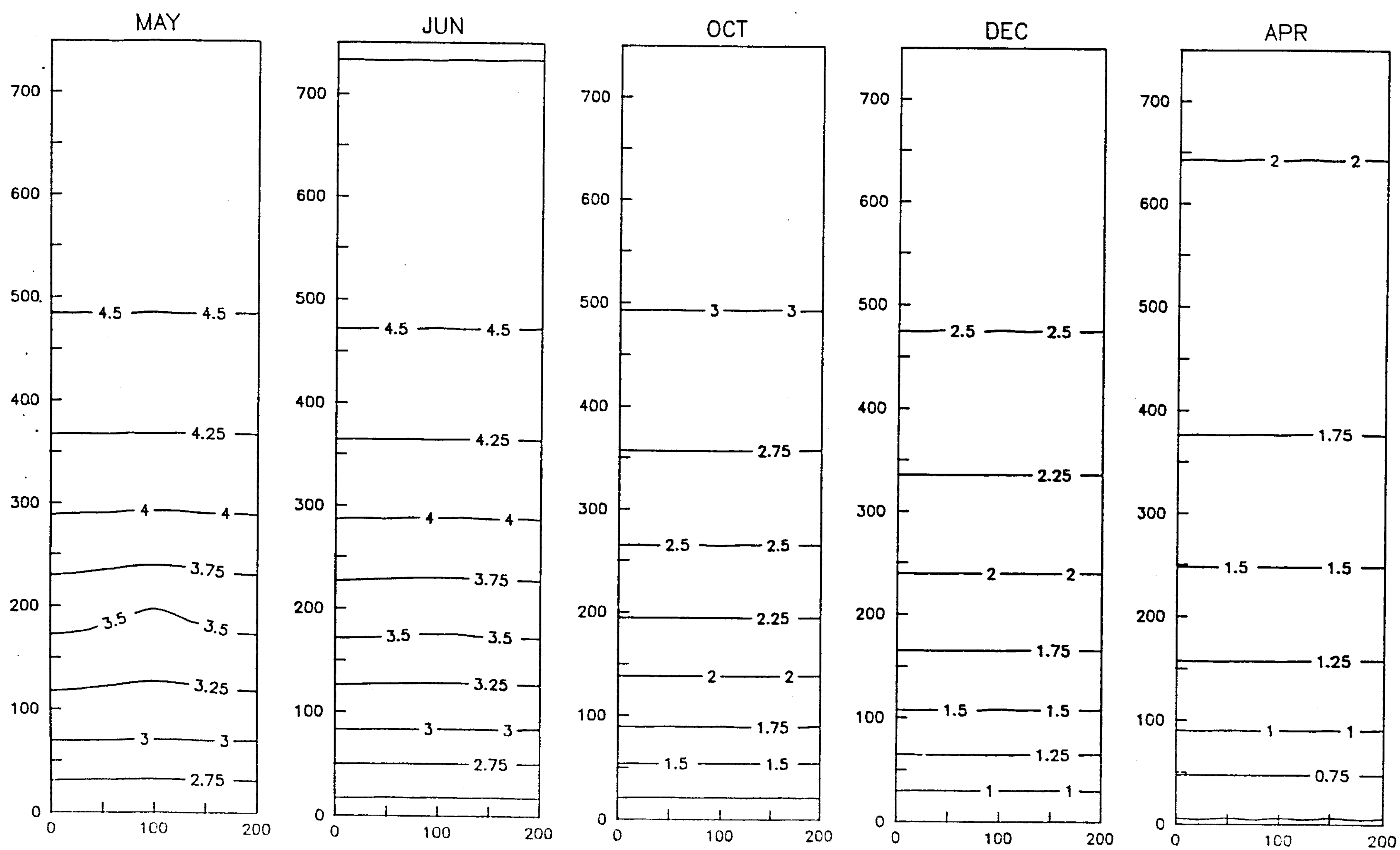
SIMULATED GW-CONTOURS (M) FOR SYSTEM WITHOUT APPT IN 1977/78



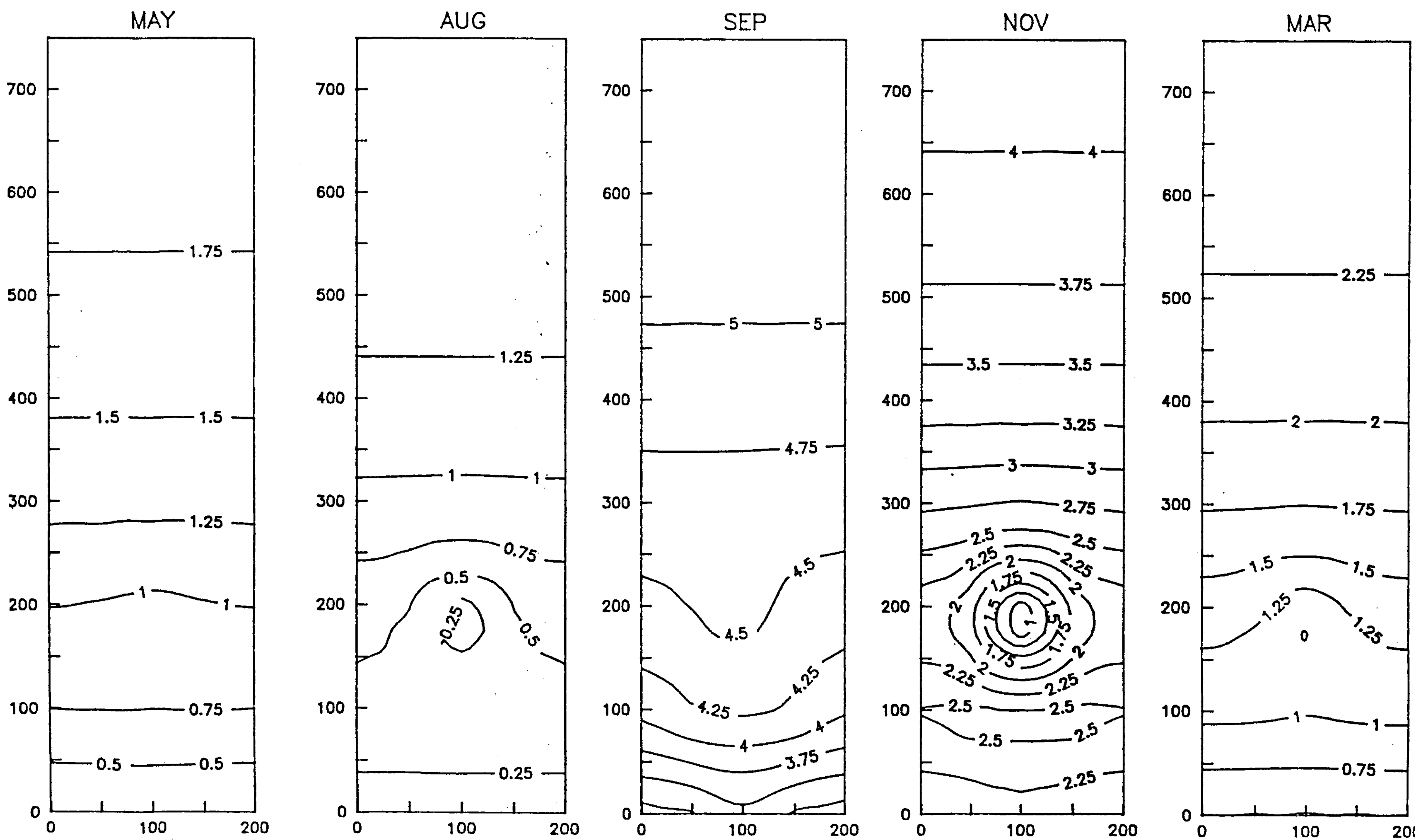
# SIMULATED GW-CONTOURS (M) FOR SYSTEM WITHOUT APPT IN 1978/79



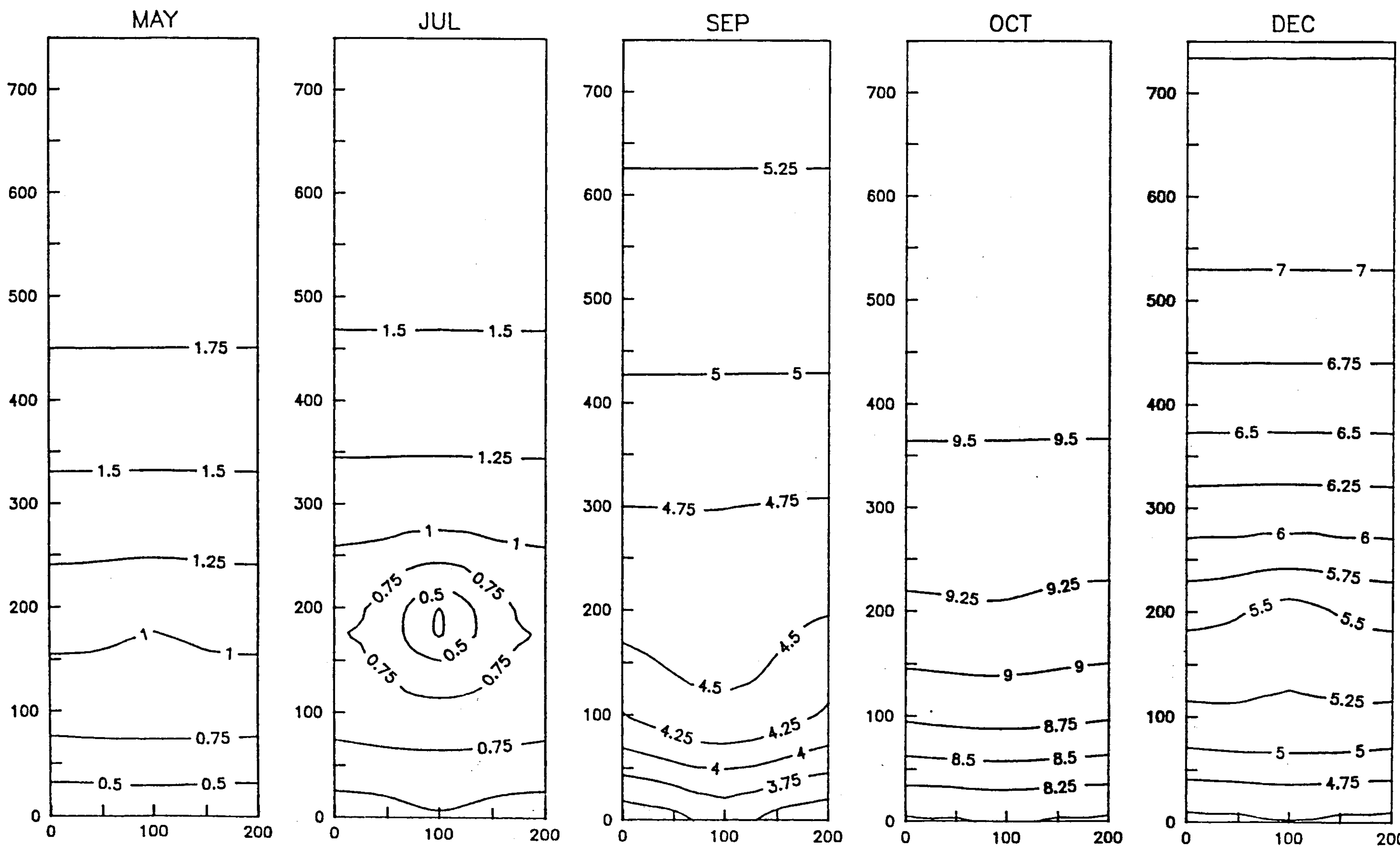
SIMULATED GW-CONTOURS (M) FOR SYSTEM WITHOUT APPT IN 1979/80



SIMULATED GW-CONTOURS (M) FOR SYSTEM WITH APPT IN 1977/78



SIMULATED GW–CONTOURS (M) FOR SYSTEM WITH APPT IN 1978/79



SIMULATED GW–CONTOURS (M) FOR SYSTEM WITH APPT IN 1979/80