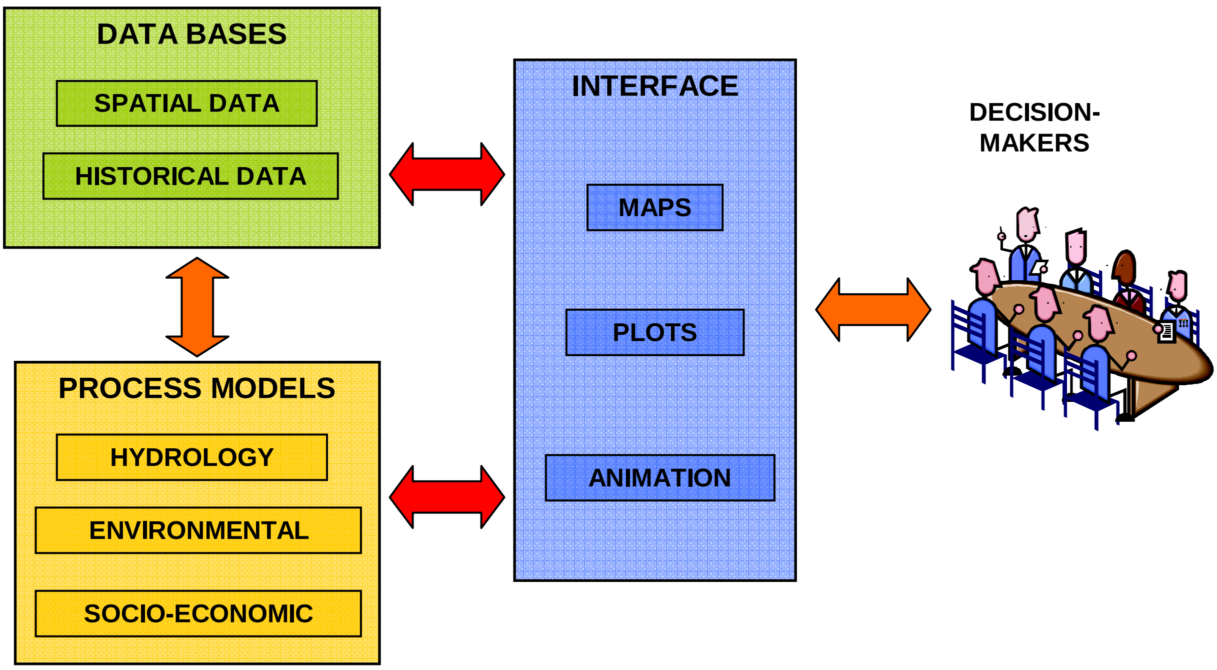
Preparation of

Ghaghra-Gomti Basin Plans
&
Development of Decision Support Systems

DRAFT FINAL REPORT
Jaunpur & Haidergarh Branch Sub-Basins
APPENDIX B
SURFACE WATER MODELS



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EXECUTIVE SUMMARY

In September 2004, SMEC International Pty Ltd entered into a contract with the Uttar Pradesh Irrigation Department for Preparation of Ghaghra-Gomti Basin Plans and Development of Decision Support Systems. The consultancy Contract is a component of the Uttar Pradesh Water Sector Restructuring Project (UPWSRP) which is being implemented with financial assistance from the World Bank.

This Draft Final Report for JBS and HBS, prepared as one of the requirements of the Contract, is intended to summarise data collection and review, to provide a detailed analysis of water management issues and options in the sub-basins, to document the system design for the DSS, to describe the different process models developed and incorporated into the DSS and to propose appropriate and efficient integrated water management strategies to improve the current irrigation system of the area.

The Draft Final Report has been structured in different separate modules, with a separate Appendix for each major component of the overall DSS. This Appendix (Appendix B – Surface Water Models: iCROP) provides a detailed description of all theoretical considerations, particularly related with hydrological processes in JBS. Although iCROP forms the core of DSS by including all components of integrated water resource management (IWRM) in JBS, this Appendix focuses mainly on its overall water balance aspect of JBS. This report should be read in conjuction with Inception and Interim Reports of JBS and GGB (SMEC 2005) submitted earlier as per contractual requirements.

BACKGROUND

The JBS and IBS areas have been delineated into micro sub-basins (MSBs) based on the gross command areas (GCAs) of the Distributary Canals. Additional MSBs have been delineated where the Distributaries bifurcate. A total of 51 MSBs have been delineated for JBS. The Distributary Gross Command Area was selected as a management unit because the boundary conditions are most easily defined and inputs/outputs measured. For the purpose of modelling the drainage and river systems, drainage basins have also been delineated. These are not considered as management units, but are used simply for modelling purposes. Within the model structure, the MSBs are further sub-divided into Homogeneous Units which lump together those areas which have similar water management requirements. This reduces the number of computations required without loss of detail.

A generic canal system model iCROP has been developed to suit the specific needs of the irrigation systems in Uttar Pradesh. This is needed because traditional irrigation models do not interface directly with GIS and do not handle conjunctive use of surface and groundwater in an efficient way. The modelling within each Homogeneous Unit is performed by a series of interlinked modules:

- Soil moisture accounting and irrigation water requirement module
- Rainfall-runoff module
- System loss module
- Groundwater system module.

The drainage and river system has been modelled by using IQQM. This is well-suited to the purpose and is widely used for such purposes in Australia. The groundwater recharge and abstraction has been modelled by Visual Modflow. This software packeage is currently used all over the world.

SOIL MOISTURE ACCOUNTING SYSTEM

Irrigation demand module is similar to the procedure included in the IQQM software. The irrigation demands are computed differently for ponded crops (i.e. rice) and non-ponded crops (all other crops eg wheat, sugarcane etc). For all crops other than rice, crop water demand is computed using the potential evapotranspiration for a reference crop (ETo) and crop factors (FAO 56). Potential evapotranspiration for the reference crop is intended to be estimated using the Penman-Montieth procedure.

During the irrigation season, the estimate is based on the actual amount of soil water (SW) and the target level of soil water (TWL) for daily average irrigation requirement over all farms. The soil moisture is updated based on actual water supply through surface or groundwater sources, once irrigation requirements are computed. The calculations for soil moisture updating and irrigation requirements are carried out on a daily basis and results presented as a cumulative total for a week, season and simulation period as a whole.

RAINFALL-RUNOFF

Runoff from all land uses except ponded crops is estimated using the USDA SCS (NRCS) Curve Number method corrected for soil moisture. The approach adopted is similar to the one used in a number of widely used models such as SWAT, EPIC, PERFECT etc. The curve number varies non-linearly with the moisture content of the soil. The curve number decreases as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. The recommended Curve Numbers have been grouped under four hydrologic soil groups based on infiltration characteristics of the soils under similar storm and cover conditions.

The SCS runoff equation is an empirical model that was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types. Since then the approach has been refined and modified. The state-of-art of this approach has been considered in the model.

SYSTEM LOSS

The seepage loss module mainly consists of:

- **Seepage from canal**

The seepage losses from canal are calculated based on discharge Vs Wetted area relationships. These relationships are developed by fitting an equation between canal discharge and wetted area using canal cross-section data. Three relationships are developed each for Seepage from Main Canal, Seepage from Distributaries and Seepage from Minors. Once the wetted area Vs Discharge relationship is obtained, canal losses are calculated based on seepage rate in cumecs per million square meter of wetted surface.

- **Seepage from field**

The seepage from fields is calculated on daily basis. Deep percolation is function of current moisture content in the root zone and saturated hydraulic conductivity (SHC), sometimes also known as saturated infiltration. In a homogeneous unit, the field channel losses are included as percentage of irrigation demands. These values have been mostly taken from standard textbooks and FAO manuals.

GROUNDWATER SYSTEM

This module simulates changes in groundwater storage due to recharge and usage. The groundwater store is treated as a two-dimensional process i.e. vertical and horizontal. The horizontal process drives the base flow component and vertical one for shallow aquifer. Impact of recharge/usage on the spatial variability of groundwater within an MSB is carried out using the DEM and results derived from sensitivity runs of the Visual MODFLOW model and iCROP.

The groundwater recharge is based on the recharge computed for each Polygon. However, groundwater storage modelling is carried out for Polygon as a whole. The groundwater storage of a Polygon is available to all homogenous units within it.

The seepage losses from a branch canal within a MSB are included in the recharge to the ground water in the MSB. The seepage from the branch canal connecting the MSBs is included spatially using the location of the canal. The sharing of seepage losses of branch canal among the adjacent MSBs is in proportion to the canal length adjoining them.

However based on spatial variability of land uses and crop mixes, information on total recharge estimated for each homogeneous unit is disaggregated into spatially varying output using the same criteria as that used for creating data for the homogeneous unit.

MODEL CALIBRATION AND VALIDATION

IQQM and Visual Modflow are directly linked with iCROP and provide the reliable tools for calibration and validation of the SMEC-developed iCROP model. The iCROP model was validated by:

- comparing IQQM-routed discharges to rivers with observed daily discharges in Sai and Gomti Rivers.
- comparing the spatial pattern of recharge to ground water and depth to groundwater calculated by both iCROP and Visual Modflow groundwater models with observed pattern of sub-surface water-logging and ground water depletion (RSAC 2002).

The model calibration runs were carried out for the period of 1997 to 2003. The validation runs were carried out from 2003 to 2006. Wherever time-series data (i.e. rainfall, evaporation, canal discharge etc) were not available, the normal sequence (1938-1947) from the 100-year data record was used. For example, rainfall after 2003 was not available.

The models were also checked for sensitivity against some important input parameters such as aquifer storage characteristics, geo-hydraulic parameters, canal seepage, agriculture inputs and so on.

The following conclusions can be drawn from the analyses in the preceding sections:

- The iCROP model simulation of all hydrological processes and historic canal operation is realistic and consistent;
- The MSBs close to main canal shows excessive water-logging due to canal seepage as well as use of canal water under the current canal operation policy;
- The MSBs at the tail ends of the canals, where canal water hardly reaches under the current canal operation, show a groundwater depleting trend because of unsustainable groundwater use;
- The model predictions can be made even more realistic by use of most up-to-date groundwater, rainfall and canal discharge data;

- More detailed site-specific investigation of input parameters such as specific yield, saturated infiltration, canal seepage, canal capacities etc is required for accurate estimation of parameters;
- The model calibration and validation must be carried out on a regular basis as more data and/or accurate data is available.

1 THEORETICAL BACKGROUND OF ICROP

1.1 INTRODUCTION

The canal system of the Jaunpur Branch Sub System is being modelled in the iCROP model by dividing the command area into 51 MSB's (Figure 1). These MSB's have been created based on the gross command areas of distributaries and areas that can be commanded by the minors and direct outlets from the Branch Canal or distributaries from which other distributaries take off. The delineation of the JBS command area in to MSB's and process adopted for delineation is discussed in detail in Appendix A-Datasets. This model is a planning model and is proposed to be used for investigating options for sustainable use of surface and groundwater and alternative options for management of the system. The following paragraphs provide detailed description of the model, data used, model testing results, its strengths and limitations and recommendations for future work.

1.2 ICROP MODEL DESCRIPTION

iCROP is a hydrologic modelling tool developed by the SMEC to suit modelling of the irrigation command areas and operation of canal systems in the Ghagra-Gomti Basin. This is a generic model and has been set up for the Jaunpur Branch System to begin with and can be implemented for other canal systems in UP. The scale of its implementation could be from a minor to branch canal depending on the issues to be addressed, data availability and hydrogeology.

This model is operated via a 32-bit Windows based, interactive menu system developed to assist running of the model and analysis of its output. Inputs to the model are made using worksheets in an EXCEL spreadsheet. The Graphic User Interface (GUI) has been developed using Microsoft Visual Basic 6.

It is a lumped-distributed parameter model with the scale at which lumping should occur is decided by the user. For the JBS System lumping was done at the distributary level while for the GG Basin it is proposed at the branch canal level. This lumping at the branch canal level is done by cumulating outcome of simulation of various processes at the homogenous unit level within a MSB. These homogenous units take into account variability due to land use, crop types, groundwater versus surface water use and soil types. The data for the model at branch level has been derived using spatially varying data available at the block level as well as data to be derived using remote sensing applications.

The decision relating to appropriate scale for the modelling is dependent on:

- Scale at which crops, water usage, land use and soils data is available ie command areas of minors, distributaries or blocks or districts,
- Time scale i.e. daily, weekly, monthly or seasonal.
- Implications of scale on the results of the questions to be addressed using the model.

The proposed structure of the canal system model and linkages of the delineated micro sub-basins is depicted in Figure 1 and processes to be modelled for each homogenous unit in the delineated micro sub-basin are shown in Figure 2.

1.2.1 Levels for Modelling

The model has been set up at three hierarchal levels. Modelling of various processes is carried out at one of these levels and then aggregated or disaggregated spatially as well as temporally to bring it to the next level up or down. The levels at which the Jaunpur basin system is modelled are:

- Irrigation System level i.e. branch canals,
- Micro Sub-Basin (MSB) level i.e. aggregated command areas consisting of minors/direct outlets taking off from the distributaries or branch canals.
- Polygon Level i.e. classification of areas within MSB having same type of soil, groundwater level, use of groundwater versus surface water and irrigated versus unirrigated area and having similar management issue like water logging or water deficit.
- Homogeneous Unit level i.e. areas within a Polygon with similar land use and crop type.

Figure 1- MSBs with canal network layer

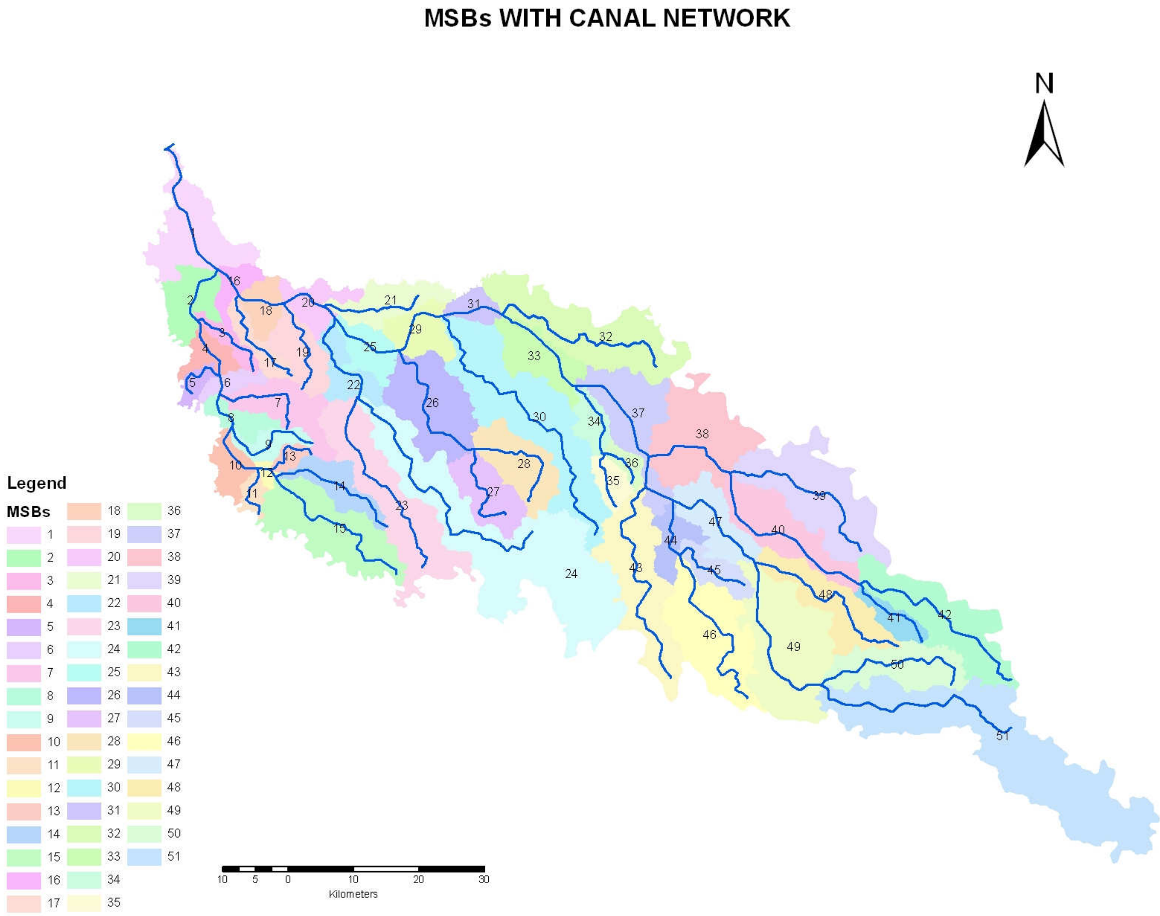
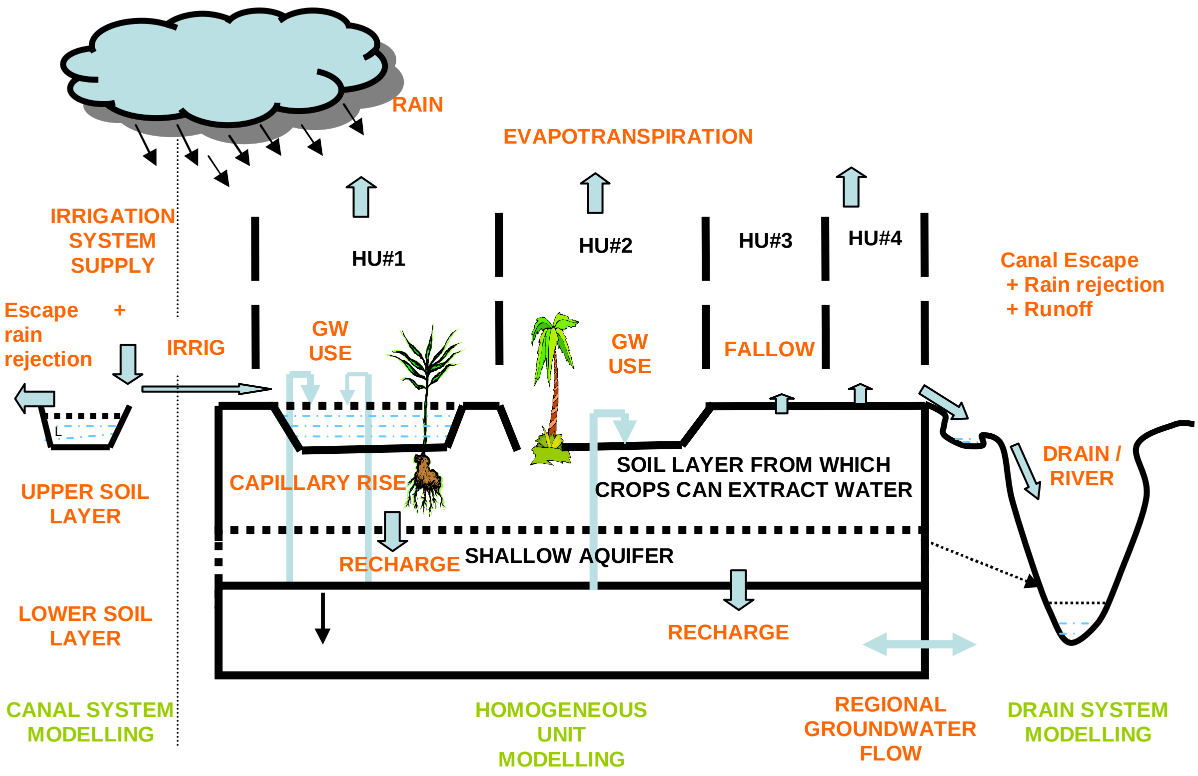


Figure 2- Processes Modelled at each Homogenous Unit Level within a MSB



1.2.2 Irrigation System Schematisation

The JBS system has been divided into 51 MSBs and each MSB is further divided into several polygons and homogeneous units. Sub-division of MSBs into polygons and homogeneous units has been done based on land use, soil types, crop types and access to canal water/groundwater or both. For details, refer to Appendix A- Datasets.

The irrigation system level defines the linkages between various MSBs. The decisions and processes at this level are made at a weekly time step which is same as the time step used in development of canal rosters. At this level the computations to be carried out are for:

- Water supply to various MSBs using rostering rules,
- Transmission and evaporation losses associated with supply of water to various MSB's,
- Estimation of rain rejection losses, and
- Water needed at the headworks versus water available.

1.2.3 Rostering System

A separate worksheet is included in the model to provide roster to be adopted for the model run. This roster to be used for the model can be one developed by the UPID or can be developed separately using an optimisation program.

1.2.4 Transmission and Evaporation Losses

System losses in the JBS consist of seepage and evaporation losses from field channels, Minors and Branch canal. The loss rates estimated by the UPID based on field observations and also used for design of the most canal networks in the Ghaghra-Gomti basin have been included in the model as default values.

In the Canal System simulation model, being included in the DSS, the losses incurred in the Branch canals, Distributaries and Minors need to be estimated as a function of the discharge on a daily time step. The losses are expected to vary depending on the amount of water available in various sections of the Branch canal as well as the MSB to which water is being supplied on the day. For the purposes of loss estimation MSBs have been grouped into two categories:

MSB-I: MSBs composed of Distributary canal and Minors and direct outlets taking off from this Distributary and

MSB-II: MSBs composed of sections of Branch canal with direct outlets and Minors taking off from the Branch Canal.

The MSB-I group consists of a Distributary canal as well as a number of Minor canals, therefore losses within it could vary depending on the rostering program for the week for the Minors within this MSB. A desk top modelling study was undertaken by SMEC team to develop a relationship between discharge at the head of the Distributary of an MSB and total losses of canal network in the MSB that may occur under best and worst case scenarios from the perspective of losses due to rostering. This study was undertaken for a number of MSBs using information on canal cross sections, design/actual discharge data, rostering data, evaporation rates and seepage rates.

For the MSB-II group, which have Minors taking directly off a Branch canal, losses are estimated as a function of sum of discharges of the Minors. To develop the relationships for these types of MSBs losses in the Minors only were taken into account. The losses in the main canal going through these MSBs are estimated as a function of discharge in the canal reach while doing water balance for the canal system network.

The canal systems used for the development of loss estimation relationships included MSBs in Deeh, Richaura, Tikri, Amethi, Aurangabad and Jais Distributary as well as MSBs having Minors taking off directly from the Jaunpur Branch Canal. The relationships developed between head discharge for the MSB and total wetted surface area and total surface area of the entire canal network in the MSB are given by Equations (1) to (4). The total wetted surface area is used to compute seepage losses while total surface area is used for computing evaporation losses.

$$WP_{msb1} = 114890\ Q \quad (R^2 = 0.86) \qquad \textbf{(1)}$$

$$WP_{msb2} = 55763\ Q \quad (R^2 = 0.91) \qquad \textbf{(2)}$$

$$TW_{msb1} = 106385\ Q \quad (R^2 = 0.86) \qquad \textbf{(3)}$$

$$TW_{msb2} = 51635\ Q \quad (R^2 = 0.91) \qquad \textbf{(4)}$$

where

WP_{msb1} = Wetted surface for MSB-I (m^2)

TW_{msb1} = Surface area for MSB-I (m^2)
WP_{msb2} = Wetted surface for MSB-II (m^2)
TW_{msb2} = Surface area for MSB-II (m^2)
Q = Head discharge for the MSB-I and sum of discharges of Minors for MSB-II (cumecs)

The losses in the canal reaches linking various MSBs are estimated based on length of canal linking the two MSBs and discharge at the head of the reach. Therefore a relationship has been developed between the head discharge for the reach and top width and wetted perimeter. The relationships developed are given by Equation (5) and (6). The loss rates per unit wetted area used to compute total losses are based on the design rates used by UPID for Kharif and Rabi seasons, while evaporation losses are computed based on daily open surface water evaporation rate and top surface area for the canal reach.

$$\mathbf{WP} = 3.8113\ Q^{0.5} \quad (R^2 = 0.99) \qquad \mathbf{(5)}$$

$$\mathbf{TW} = 3.5292\ Q^{0.5} \quad (R^2 = 0.99) \qquad \mathbf{(6)}$$

where

WP = Wetted perimeter (m)

TW = Top width (m)

Q = Head discharge for the canal reach connecting two MSBs (cumecs)

The total seepage losses are computed as total surface area multiplied by the seepage rate per unit area. For the design of the Sarda Sahayak System, including Jaunpur Branch, UPID has estimated the canal losses for the Branches and Distributaries based on a loss rate of 5 cusecs per million sq ft of wetted surface during non-monsoon period and 2.5 cusecs per million sq ft of wetted surface during monsoon period (UPID, 1985). It is mentioned in the report that these assumptions were based on actual observations however the report does not give details of locations where these observations were made. These loss rates have been adopted by SMEC for use in the Canal System Model to develop relationships between headworks discharge for an MSB and losses that would occur in the MSB.

1.2.5 Seepage from fields

The seepage from fields is calculated on daily basis. Deep percolation is function of current moisture content in the root zone and saturated hydraulic conductivity (SHC).

The function for deep percolation is,

Deep Percolation = 0 if CMC < FC
= SHC if CMC > SMC
= SHC * [(CMC – FC) / (SMC – FC)] if FC < CMC < SMC

Where,
SHC = Saturated Hydraulic Conductivity
CMC = Current Moisture Content
FC = Field Capacity
SMC = Saturation Moisture Content

The saturated hydraulic conductivity is parameter of soil type, and user can choose input distributed values if data for different soils is available. In the iCROP model, SHC is taken as 4 mm/day considering loamy soils prevailing in the area. The value of 4 mm/day is chosen after reviewing the literature for Deep percolation in Irrigated Fields. Mishra (1999) developed an equation for deep percolation in irrigated rice fields as,

$$DP = -0.164 + 0.079 * D$$

Where,

DP = deep percolation, in mm / day

D = Average depth of water stored in rice fields in mm.

Numerical calculations were made using the above equation to validate the value of 4 mm/day. For that objective, the DP was evaluated for D from 35 mm to 75 mm and average DP was calculated. Average DP obtained was 4.181 for the evaluated range. Hence, SHC of 4 mm/day is a reasonable choice. George et. al. (2004) recommended same equation in their study on Development and testing of a GIS integrated irrigation scheduling model.

1.2.6 Rain Rejection

Rain rejection flows in to drains occur when the water in the canal system is diverted from headworks but irrigation demands drop because of rainfall. Flow in excess of demands is dumped in to the drainage system through escapes on the canals. These excesses could be on Minors, Distributaries or Branch canals. This may be reduced if forecast demand cannot actually be supplied due to limitations in canal capacity, rostering or water shortage at the headworks.

1.2.7 Escape Flows

Most people who spoke to SMEC staff during the field visit stated that all drains in the system start flowing as soon as the canal system starts flowing. This is an indication that escape flows or direct outlets contribute directly to the drain flows. To date SMEC has not found any study to quantify the percentage of canal flow that ends up as escape flows.

Studies carried out to date for the JBS System show that escape flows constitute significant component of the river flows during the Rabi season. Hence, their quantification and any rules for operation of escapes/silt ejectors needs to an important element of the iCROP model. In absence of any information or data on these issues, model currently assumes any flows in excess of demands as flowing as escape flows in to drains. Further, a fraction of all water diverted in to the fields also flows into drains as escape flows. The fraction of water lost from fields to drains has been used as a calibration parameter value.

1.2.8 Micro Sub-basins

As mentioned earlier, the command area of the JBS System has been divided into a number of Micro Sub-Basins based on the source of supply. MSBs are command areas served by Branches or areas served by Minors or kulabas taking off directly from the main canal. Within an MSB there is a canal network consisting of the branch canal itself, distributaries, minors and field channels. Computations at the MSB level are based on deriving data and modelling processes at a finer scale using spatial database. The processes modelled at MSB scale include:

- Irrigation demands,
- Drinking water and industrial water requirements,
- Rainfall-Runoff,

- Transmission and evaporation losses from the canal system within the MSB, and
- Total groundwater recharge.

1.2.9 Groundwater recharge

The groundwater recharge is based on the recharge computed for each Polygon. However, groundwater storage modelling is carried out for Polygon as a whole. The groundwater storage of a Polygon is available to all homogenous units within it. The total groundwater recharge for a Polygon is computed as:

$$\text{MSB}_{\text{recharge}} = \sum_{i=1}^{n} S_L + M_{seepage} + D_{seepage} + B_{seepage} * Perc_{adj}$$

where

S_L = Seepage loss from Polygons within MSB (m^3),

$M_{seepage}$ = Seepage from all Minor canals with in an MSB (m^3),

$D_{seepage}$ = Seepage from Distributary canal in MSB (m^3),

$B_{seepage}$ = Seepage from Branch canal adjacent to the MSB (m^3), and

Per_{adj} = Percent of Branch Canal seepage losses to be included in the MSB losses.

The seepage losses from a branch canal within a MSB are included in the recharge to the ground water in the MSB. The seepage from the branch canal connecting the MSBs is included spatially using the location of the canal. The sharing of seepage losses of branch canal among the adjacent MSBs is in proportion to the canal length adjoining them.

However based on spatial variability of land uses and crop mixes, information on total recharge estimated for each homogeneous unit is disaggregated into spatially varying output using the same criteria as that used for creating data for the homogeneous unit.

Runoff from a MSB is computed as sum of runoff generated from different homogeneous units within it.

1.2.10 Drinking Water and Industrial Water Requirement

Drinking water and industrial water requirement of each MSB are estimated outside this model and included as daily values. The model has an option to assign a priority to various demands to be applied during any period of shortage. For example, the model assigns the highest priority to drinking water, the next to industrial water and the third to irrigation use. The user can assign percentage water use from canal water as compared to ground water use.

1.2.11 Homogeneous Units

Homogeneous units within an Polygon consist of areas which are similar from the point of view of crop types and land use, whereas polygons within a MSB are areas which are similar from the point of view of soil types, groundwater level, access to groundwater or surface water, and whether irrigated or unirrigated. The sub-division of each MSB into polygons is carried out using the spatial analysis of available data. The modelling of various processes within a homogeneous unit uses a daily time step. This modelling at daily time step is carried out by using daily data if available, or else by disaggregating monthly, ten-daily or weekly data into daily data. The processes modelled at a daily time step for the homogeneous units include crop water requirements, soil moisture accounting, runoff, deep seepage, and surface water/groundwater supply. The processes modelled at daily time step are shown in Figure 2.

As mentioned earlier, the DSS and models included in it are being developed in a modular manner so that various components can be upgraded or replaced with alternative algorithms in the future as more data becomes available. The approach adopted for modelling various physical processes in the current model set up are discussed in the following sub-sections.

i Soil moisture accounting and irrigation water requirement

Irrigation demand module is similar to the procedure included in the IQQM software. The irrigation demands are computed differently for ponded crops (i.e. rice) and non-ponded crops (all other crops eg wheat, sugarcane etc). For all crops other than rice, crop water demand is computed using the potential evapotranspiration for a reference crop (ETo) and crop factors (FAO 56). Potential evapotranspiration for the reference crop is intended to be estimated using the Penman-Montieth procedure.

For rice crops, the irrigation requirement (Ireq) is computed as:

If $P_{desirable} \leq P_{actual} \leq P_{max}$ then $I_{req} = 0$ **(7a)**

If $P_{actual} < P_{desirable}$ then $I_{req} = (P_{desirable} - P_{actual}) * A_{hu} * 10$ **(7b)**

where

I_{req} = Crop irrigation water requirement (m^3)

$P_{desirable}$ = Desirable ponded depth (mm)

P_{max} = Max permissible ponding depth (mm)

P_{actual} = Actual depth of ponding (mm)

$P_{actual(t)} = P_{actual\ (t-1)} + R_e - S_L - K_c * ET_o / K_e$ **(7c)**

where

R_e = Effective rainfall less Runoff
K_c = Crop factors
K_e = If method such as evaporation pans, Priestly-Taylor equation, Morton equation etc are used then this factor can be used to adjust this estimate to the Penman-Montieth ET_o.
S_L = Actual seepage from soil water store (mm)
S_{Lmax} = Maximum seepage from soil water store (mm)
SW_{t-1} = Projected soil moisture at end of time step (mm)

$$S_L = S_{L\ max} * \frac{SW_{t-1}}{SW_{max}}$$ **(7d)**

For all other crops the irrigation requirement is computed as follows:

During the irrigation season, the estimate is based on the actual amount of soil water (SW) and the target level of soil water (TWL) for daily average irrigation requirement over all farms. Within a homogeneous unit the estimated requirement is:

If $SW \geq TWL$; **then** $I_{req} = 0$ **(8a)**

If $SW < TWL$; **then** $I_{req} = (TWL - SW) * A_{hu} * 10$ **(8b)**

$$TWL = \frac{SW_{max}}{2}$$ **(8c)**

If $CW_{avail} > I_{req}$ **then**
$I_{sup} = I_{req}$ and $CW_{sup} = I_{req}$ **(9a)**

If $CW_{avail} + GW_{avail} > I_{req}$ and $CW_{avail} < I_{req}$ **then**
$I_{sup} = I_{req}$ and $CW_{sup} = CW_{avail}$ and $GW_{sup} = I_{req} - CW_{sup}$
(9b)

If $CW_{avail} + GW_{avail} < I_{req}$ and $CW_{avail} < I_{req}$ **then**
$I_{sup} = CW_{avail} + GW_{avail}$ and $CW_{sup} = CW_{avail}$ and $GW_{sup} = GW_{avail}$ and
$I_{short} = I_{req} - I_{sup}$ **(9c)**

where
I_{sup} = Irrigation water supplied to the homogeneous unit subject to surface and groundwater availability (m^3),
CW_{avail} = Water available from canal supply system taking into account capacity constraints and rostering turn (m^3),
GW_{avail} = Water available from the groundwater system (m^3),
CW_{sup} = Irrigation demands supplied from canal supply system taking into account capacity constraints and rostering turn (m^3),
GW_{sup} = Irrigation demands supplied from groundwater supply system taking into account capacity constraints and rostering turn (m^3), and
I_{short} = Shortfall in meeting irrigation demands (m^3).

The soil moisture on any given day is computed as:

For all crops (except rice during ponded days)

$$SW_t = SW_{t-1} + R_e + I_{sup} / (A_{hu} * 10) \quad \textbf{(10)}$$

$$SW_t = Max(WP, SW_t - \frac{K_C * ET_o}{K_e}) \quad \textbf{(10a)}$$

$$SW_t = Max(FC, SW_t - S_L) \quad \textbf{(10b)}$$

Where: SW_t = Projected soil moisture at end of time step (mm)
SW_{t-1} = Actual soil moisture at beginning of time step (mm)
SW_{max} = Maximum available soil water (mm)
ET_o = Reference crop potential evapotranspiration (mm)
R_e = Effective rainfall less runoff
K_c = Crop factors
K_e = If method such as evaporation pans, Priestly-Taylor equation, Morton equation etc are used then this factor can be used to adjust this estimate to the Penman-Montieth ET_o.
FC = Field capacity (mm) computed as
FC (in mm) = FC (%) * Root depth (mm) * Soil density/Water density
S_L = Actual seepage from soil water store (mm)

$$S_L = S_{L\,max} * \frac{SW_{t-1}}{SW_{max}} \quad \textbf{(10c)}$$

For rice during ponded days

$$SW_t = SW_{\max}$$

$$S_L = S_{L\,\max} \qquad \textbf{(10d)}$$

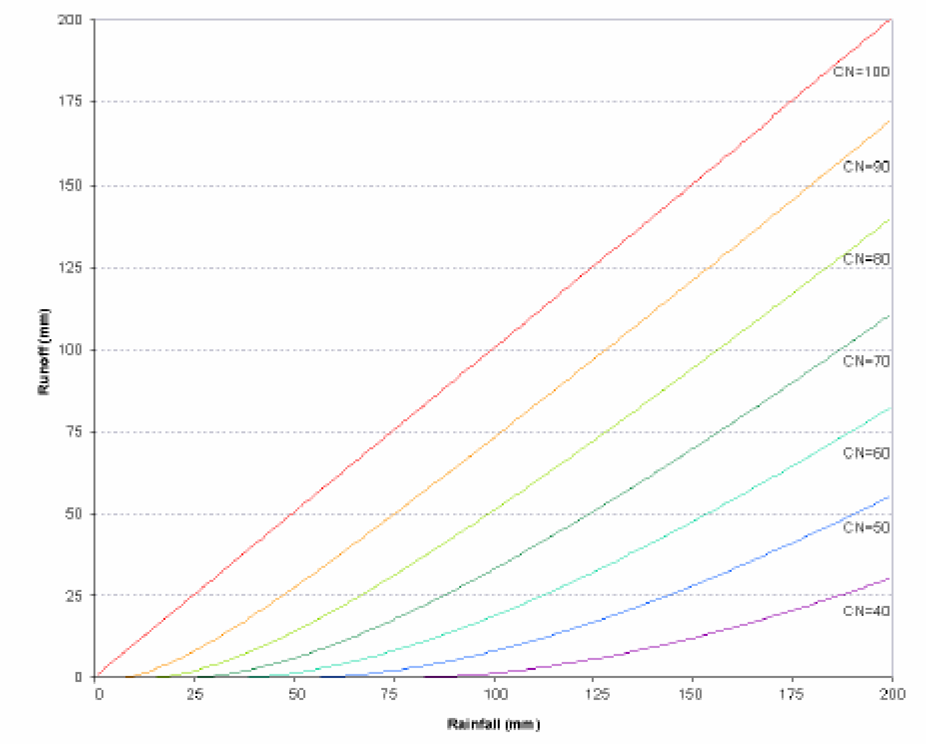
Where: S_{Lmax} = Maximum seepage from soil water store (mm)

The soil moisture is updated based on actual water supply through surface or groundwater sources, once irrigation requirements are computed. The calculations for soil moisture updating and irrigation requirements are carried out on a daily basis and results presented as a cumulative total for a week, season and simulation period as a whole.

ii Rainfall-runoff module

Runoff from all land uses except ponded crops is estimated using the USDA SCS Curve Number method corrected for soil moisture (Sharpely and Williams, 1990). The approach adopted is similar to the one used in a number of widely used models such as SWAT, EPIC, PERFECT etc. The curve number varies non-linearly with the moisture content of the soil. The curve number decreases as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation (Figure 3). This approach has also been adopted by several Indian researchers. The SCS Curve Number approach has limitations but is one of the commonly used methods for the study areas with extremely limited or no data availability.

Figure 3- Relationship of Runoff to Rainfall in SCS Curve Number Method



(Source: Neitsche et al, 2002)

The SCS runoff equation is an empirical model that came into common use in the 1950s. It was the product of more than 20 years of studies involving rainfall-runoff relationships from small rural watersheds across the USA. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1981). Since then the approach has been refined and modified.

The SCS curve number equation is (SCS, 1972):

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad \textbf{(11)}$$

Where

Q_{surf} = Runoff (mm),

R_{day} I = Rainfall for the day (mm),

I_a = Initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm), and

S = Retention parameter (mm) that varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4 * \left(\frac{1000}{\mathrm{CN}} - 10\right) \qquad \textbf{(12)}$$

where *CN* is the curve number for the day.

The initial abstraction, Ia, is commonly approximated as 0.2S and for Indian conditions a value of 0.3S has been recommended (Handbook of Hydrology, 1972). Hence

$$Q_{surf} = \frac{(R_{day} - 0.3S)^2}{(R_{day} + 0.7S)} \qquad \textbf{(13)}$$

Runoff will only occur when Rday > Ia. The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Typical curve numbers for moisture condition II and 5% slope are listed in Table 1 for various land covers and soil types (SCS, 1986).

To modify the Curve number for moisture condition II to the current soil moisture condition and slope of the catchment, corrections applied using the same procedure as that used in the SWAT model (Neitsch et al, 2002):

Correction for Slope

$$CN_{2s} = (CN_3 - CN_2) * [1 - 2*\exp(-13.86S_l)]/3 + CN_2 \qquad \textbf{(14)}$$

Where:
CN_{2s} = Handbook CN_2 value adjusted for slope,
CN_3 = Curve number for moisture condition 3 (wet), and
S_l = Average slope of the catchment.

Correction for Soil Moisture Condition

The fluctuation in soil moisture content changes the retention parameter and retention parameter corresponding to a given soil moisture condition is computed as:

$$s = s_1 * \{1 - \frac{SW}{SW + \exp[w_1 - w_2 * SW]}\} \qquad \textbf{(15)}$$

Where:
s1 = Retention parameter corresponding to dry condition soil moisture i.e. CN_1 Curve Number,
w_1 and w_2 = Shape parameters, and
SW = Current soil moisture content.

CN_1 and CN_3 i.e. curve numbers for dry moisture condition and saturated moisture condition is computed as:

$$CN_1 = CN_2 - \frac{20(100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)]} \qquad \textbf{(16)}$$

$$CN_3 = CN_2 \exp[0.00673(100 - CN_2)] \qquad \textbf{(17)}$$

Values for w_1 and w_2 are obtained by solving Equation 15 assuming that:

- Retention parameter for moisture condition I curve number corresponds to wilting point,
- Retention parameter for moisture condition III curve number corresponds to field capacity, and
- Soil has a curve number of 99 (S = 2.54) when completely saturated.

$$w_1 = \ln\left\{\frac{FC}{1 - S_3/S_1} - FC\right\} + w_2 * FC \qquad \textbf{(18)}$$

$$w_2 = \frac{\ln\left\{\frac{FC}{1 - S_3/S_1} - FC\right\} + \ln\left\{\frac{SAT}{1 - 2.54/S_1} - SAT\right\}}{(SAT - FC)} \quad \textbf{(19)}$$

where:

w_1 = First shape coefficient,

w_2 = Second shape coefficient,

FC = Amount of water in the soil profile at field capacity (mm),

S_3 = Retention parameter for the moisture condition III curve number,

S_{max} = Retention parameter for the moisture condition I curve number,

SAT = Amount of water in the soil profile when completely saturated (mm), and

2.54 = Retention parameter value for a curve number of 99.

The recommended Curve Numbers have been grouped under four hydrologic soil groups based on infiltration characteristics of the soils under similar storm and cover conditions. The four soil groups are:

A: The soils have a high infiltration rate (i.e. low runoff potential) even when thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.

B: The soils have a moderate infiltration rate when thoroughly wetted. They chiefly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.

C: The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.

D: (High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have high swelling potential, soils that have a permanent water table, soils that have a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow rate of water transmission.

The approach for modelling of surface runoff versus infiltration described above is one of the most commonly used under conditions of limited or no data availability. However, if in future more data becomes available to cover the hydrologic and spatial variability, then some alternative approaches can also be recommended.

Table 1- Runoff Curve Numbers for Cultivated Agricultural Lands

Cover			Hydrologic Soil Group			
Land Use	**Treatment or practice**	**Hydrologic condition**	**A**	**B**	**C**	**D**
Fallow	Bare soil	-	77	86	91	94
	Crop residue Cover	Poor	76	85	90	93
		Good	74	83	88	90
Row Crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row w/residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured w/residue	Poor	69		83	87
		Good	64	74	81	85
	Contoured & terraced	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured & terraced/residue	Poor	65	73	79	81
		Good	61	70	77	80
Small Grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row w/residue	Poor	64	75	83	86

Source: SCS 1986

Runoff computed using the above steps is modified to take in to account the bunding around the farms built by farmers to capture runoff on the farm itself. The depth of bunding is an input parameter and runoff equal to bunding depth is retained on the farm to increase the infiltration and meet crop water requirements. However, if soil is saturated then this retention of some runoff on the farm is not done.

For ponded crops runoff is estimated (refer Equation **7c** for details) as:

$$\text{If } P_{actual(t)} > P_{max} \text{ then } Q_{surf} = P_{max} - P_{actual(t)} \text{ else } Q_{surf} = 0.$$

1.2.12 Groundwater system module

This module simulates changes in groundwater storage due to recharge and usage. The groundwater store is treated as a two-dimensional process i.e. vertical and horizontal. The horizontal process drives the base flow component and vertical one for shallow aquifer. Impact of recharge/usage on the spatial variability of groundwater within an MSB is carried out using the DEM and results derived from sensitivity runs of the Visual

Modflow model for JBS and iCROP. The variation in groundwater storage/levels in the current model set up is computed according to:

$$GW_i - GW_{i-1} = MSB_{recharge} - GW_{use} - Baseflow \quad \textbf{(20)}$$

$$GL_{inc} = (GW_i - GW_{i-1})/(A_{hu}*10*S_y) \quad \textbf{(21)}$$

where:

GW_i = Groundwater storage under each MSB for time step I (m^3),

GL_{inc} = Incremental change in groundwater level since previous time step (mm),

S_y = Specific yield of the aquifer (%) and

Baseflow = Baseflow to drainage system (m^3)

1.2.13 Water Balance and Water Requirement Calculations

This is the main module of the model which manages calls to other modules and also aggregates water requirements of various MSBs, water required at the headworks, rostering decisions and supply of water among MSBs. The module operates in two modes i.e.:

- Bottom up to cumulate orders of all MSBs including losses in the canal reaches linking MSBs subject to canal capacity constraints,
- Top down starting from available water at headworks and then supplying water to various MSBs also taking into account losses in canal reaches linking MSBs.

Demand Computations (Bottom-Up): During bottom-up computations water demands calculations are started from most downstream MSB and are continued to next upstream MSB by adding transmission and evaporation losses in the canal reach connecting the two MSBs. This process is continued till all MSBs and canal reaches up to headworks are completed. The total demand in any canal reach is limited to the canal capacity. Irrigation demands within each MSB are computed by selecting a specified percentile rainfall (eg 75%ile rainfall) depending on the risk that UPID is prepared to take on having a shortfall in water supply if rainfall is less than the percentile value used and assuming no groundwater use. In case of a Distributary (with its own network of MSBs) taking off from a branch canal/distributary with its own network of MSBs, the branching distributary calculations are completed before proceeding further up the main branch canal/distributary.

Demand Allocation Computations (Top Down): Top down calculations are based on diversion of water into the canal system from headworks based on either the historical data or based on demands computed during the bottom up calculations limited by the water available in the river or main canal for diversion into the system. The water supply to each MSB is governed by the water available in the branch canal and rostering. Losses in canal reaches connecting various MSBs are subtracted to compute water available for the MSB downstream of a location.

Irrigation demands for a MSB are computed as the sum of irrigation demands for all homogeneous units within it.

1.2.14 Model Inputs

The inputs to the model are:

i Climatic:

- Daily rainfall,
- Daily Pan Evaporation,
- Reference Crop Evapotranspiration,

ii Flow data

- Daily canal flow at headworks
- Daily flows in drains

iii Infrastructure data

- Canal capacities at various locations,
- Cross-section information,
- Lined versus unlined sections, and
- Location and capacity of escape structures.

iv Cropping information

- Crops planted and area under them during Kharif, Rabi and Jaayad,
- Monthly crop factors for crops planted,
- Irrigation efficiency including field channel losses,
- Crop calendars showing planting and harvesting dates, and
- Rice ponding requirements during its various stages of growth as desirable ponding depth and maximum permissible ponding depth, number of days before harvesting when irrigation is stopped.

v Losses

- Seepage losses from the canals built in different soil conditions under lined/unlined conditions,
- Estimate of escape loss for typical field channels, and
- Estimate of escape losses from Minors/Distributaries/Branch canal.

vi Water usage

- Groundwater pumping capacity from aquifer, and
- Drainage water use and locations.

vii Land use, soils and topography

- Average slope in various homogeneous units of MSBs,
- Land use in MSBs,
- Soil types in MSBs,
- Soil properties i.e. field capacity, wilting point, saturation moisture content, and

- Specific yield of shallow and deep aquifers.

1.2.15 Model Outputs

The model outputs are designed for different types of users eg Technical Users, stakeholders and decision makers. The kind of output of interest to each group varies, generally stakeholders are interested in the summary results plus the relativities between various stakeholders. The information for stakeholders should be presented in a manner such that a person with no technical knowledge or detailed understanding of the system should also be able to understand it. The other extreme are the technical persons who like to understand how the various models are working, interactions between various processes included in the model and computed values of various components on daily, weekly or monthly basis. The information needs of decision makers are somewhere between the needs of Technical persons and stakeholders. However, information targeted for decision makers too should be in a non-technical language and easy to understand. The default outputs targeted towards these three different audiences are discussed in following paragraphs.

Technical users: To be able to investigate the model and interactions between various processes, the model provides options for printing out detailed outputs on a daily basis for a large number of parameters for the selected period. These outputs can be analysed by using graphs and statistical capabilities of the EXCEL. The outputs that can be analysed by a Technical User are:

- Runoff from each MSB,
- Surface and groundwater usage,
- Crop Demands,
- Total recharge to the shallow and deep aquifers,
- Transmission and Evaporation losses from canals,
- Imbalance between groundwater usage and recharge,
- Frequency of shortfall and magnitude of shortfalls in meeting demands,
- Time series of shortfalls in canal water supplies to meet the demands, and
- Water balance annual as well as for the total simulation period.

Decision makers: Model provides number of summary tables and standard graphs with emphasis on triple bottom line i.e. economic, environmental and social implications (equity) of the policy measure/management option being considered. The design of these outputs has been undertaken in consultation with client. A standard report summarising results of option being studied and time series plots of water availability versus demand are prepared as part of each model run.

Stakeholders: The standard plots and information prepared for the stakeholders from each model runs are:

- Fraction of water demand of each MSB met through surface and groundwater,
- Shortfalls in meeting demands and frequency of shortfalls for both surface and groundwater,
- Reasons for shortfalls i.e. canal capacity constraints, inadequate water at headworks, and

- Statistics of and plots of water availability to each MSB, variability in water availability over 100 years of climatic conditions.

1.2.16 Model Limitations

As mentioned earlier, modelling approach adopted is the one that was considered most suitable for the data available now and that is likely to be available in near future. Thus modelling approaches for number of processes are based on the widely used methods for which model parameter values could be used from other studies. The lack of data and choice of models introduces some limitations and it is recommended that UPID initiate a data collection program to reduce the limitations resulting from data inadequacy. These limitations result in uncertainty in the modelling outcomes. The major limitations of the model in terms of modelling approach and parameter values used are:

- Lack of local data to derive or regionalise parameter values for the rainfall-runoff modelling. Hence, number of textbook/information from published literature has been used and choice of algorithms has been for the tested and commonly used algorithms so as to have reasonable confidence on the model predictions.
- Drain flows are not being monitored by the UPID. Hence this limits the capacity to calibrate the model for runoff/escape flows.
- Modelling approach is designed to address issues at Macro scale i.e. MSBs and to get a perspective of water balance for the system and therefore results may have larger error bounds at field scale. However, with data availability at the field scale, the error bounds associated with model outcomes can be reduced. From the modelling approach adopted, it is expected that relativities between different land uses or crop mixes or recharges etc would be much more accurate than the absolute values.
- Model is designed as a planning model and some components could be upgraded in future for usage as an operational tool.

1.2.17 Model Strengths

The strengths of the modelling approach adopted are that:

- It provides system wide water balance in terms of inputs and outputs targeted towards both a layman as well as technical user and can also provide details of how sustainable or otherwise current practices are. Sensitivity analysis can be used to further assess the robustness of the modelling outcomes.
- Use of tested and commonly used modelling approaches and level of complexity commensurate with the data available and likely to be available in near future. Minimal number of parameters required for setting up of model with default values provided for most of the parameter values.
- Flexibility to upgrade or make changes/substitution to various modules in the future as more/better monitoring data becomes available.
- Quick turn around time for carrying out what-if scenarios.
- Use of Excel for inputs and outputs interface and Visual Basic Programming language for the modelling algorithms. Excel is one of the most commonly used spreadsheet software and requires minimal learning effort. Most of the Engineers are conversant with use of Excel spreadsheet. Further, Visual Basic is not only used for writing Macros but is also one of the commonly used languages for

software development. It is therefore very easy to find people with skills in Visual Basic programming. Hence any future upgrades would be easier to manage in a cost effective manner.

- It can serve as a powerful educational tool to understand the interactions in the system and to drive the monitoring system needs and design.
- Designed to study impact of policy and water management options under range of hydrological conditions experienced in the catchments.

1.3 MODEL SCHEMATIC

The geographical locations of various 51 MSB's and their linkages with the canal system and draingage are shown in Figure 4. Some MSB details are given in Table 2.

Figure 4- Geographical locations of various MSB's and their linkages

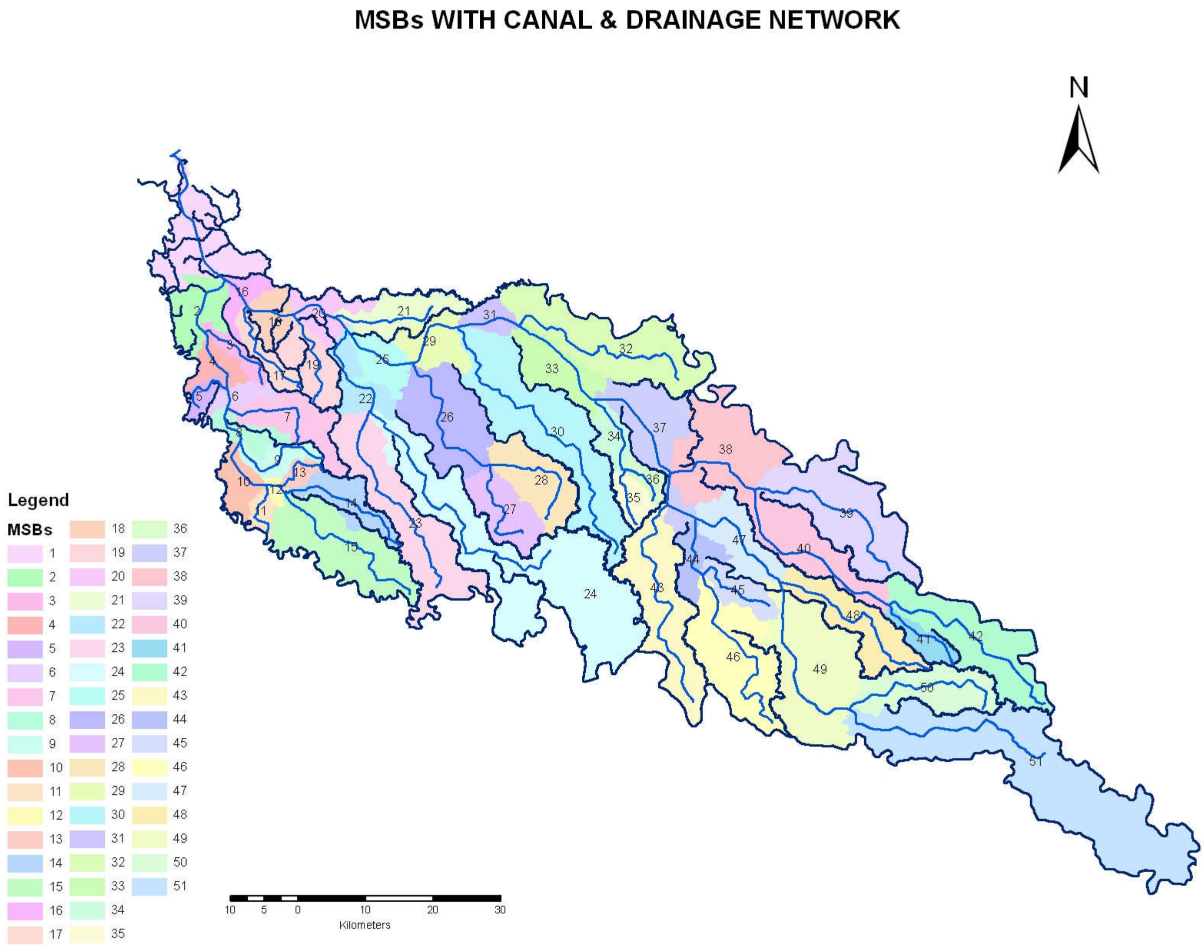


Table 2- MSB's of the JBS System and their salient features

MSB_ID	MSB_Description	MSB Area (ha)	Current LU and %age area
1	JB Head-Deeh	14084	57
2	Deeh Head - Dautra	7183	63
3	Dautara Dy	2717	65
4	Deeh Dautra-Tejpur	3719	70
5	Tajpur Dy	2007	70
6	Deeh Tejpur-Nasiarabad	2708	72
7	Nasiarabad Dy	9025	72
8	Deeh Nasiarabad-Mau	3675	68
9	Mau Dy	3693	64
10	Deeh Mau-Sirsi	4396	63
11	Sirsi Dy	2004	62
12	Deeh Sirsi-Gopalpur	887	63
13	Gopalpur Dy	1698	65
14	Udaipur Dy	6706	69
15	Deeh Udaipur-Tail	17750	67
16	JB Deeh-Daultapur	3376	62
17	Daulatapur Dy	3950	67
18	JB Daulatapur-Shahmau	4371	63
19	Shahmau Dy	7196	66
20	JB Shahmau-Richaura	5289	65
21	Richaura Dy	7542	77
22	Jais Head-Ateha	5877	72
23	Ateha Dy	21728	69
24	Jais Ateha-Tail	44531	70
25	JB Jais-Amethi	5634	76
26	Amethi Head-Bhaironagar	15730	69
27	Bhaironagar Dy	8521	70
28	Amethi Bhaironagar-Tail	10232	69
29	JB Amethi-Tikri	6521	76
30	Tikri Dy	29209	65
31	JB Tikri-Aurangabad	3181	66
32	Aurangabad Dy	21370	67
33	JB Aurangabad-Gopalpur	8890	68
34	Gopalpur Head - Kalyanpur	3882	65
35	Kalyanpur Dy	3348	60
36	Gopalpur Kalyanpur - Tail	2156	61
37	JB Gopalpur-Ramganj	13705	66
38	Ramganj Head-Chanda	18040	68
39	Chanda Dy	21885	71
40	Ramganj Chanda-Singramau	13151	73
41	Singramau Dy	3679	79
42	Ramganj Singramau-Tail	17631	78
43	Chilbila Dy	19281	75
44	Nagapur Head-Madafarpur	4752	71
45	Madafarpur Dy	4779	76
46	Nagapur Madafarpur-Tail	18758	78
47	JB Nagapur-Dharauli	9029	72
48	Dhaurali Dy	12106	75
49	JB Dhaurali-Bhimapur	23642	76
50	Bhimapur Dy	11947	78
51	JB Bhimapur-Tail	45423	79

The major processes to be modelled by the iCROP model set up for the JBS system are:

- Crop water requirements,
- Runoff from various land uses,
- Recharge to groundwater and groundwater availability from shallow aquifer,
- Soil moisture accounting,
- Water balance for the canal system,
- Losses in the canals and field channels and
- Diversions for irrigation, domestic and industrial use.

1.4 DATA USED

The data used for setting up of iCROP model for the JBS System is discussed in following sections:

1.4.1 Rainfall

The rainfall data available for the JBS is discussed in Appendix A- Datasets. The procedure adopted for deriving representative rainfall for various MSB's was:

- Compute average rainfall over each MSB using isohyet method. Development of isohyets and computation of average rainfall was done using GIS set up for the system.
- Based on Thiessen polygons identify rainfall stations influencing rainfall over a MSB and relative weights (Figure 5 and Table 3)
- Use a maximum of two rainfall stations for any MSB to minimise the averaging effect of using too many rainfall stations. Use of more stations lead to increase in number of rain days and reduction in peak rainfall.
- To convert weighted rainfall of the stations chosen for each MSB to the average rainfall of the MSB computed from isohyets method, compute multiplication factor.

Figure 5- GIS map of Thiessen polygon for JBS ad HBS

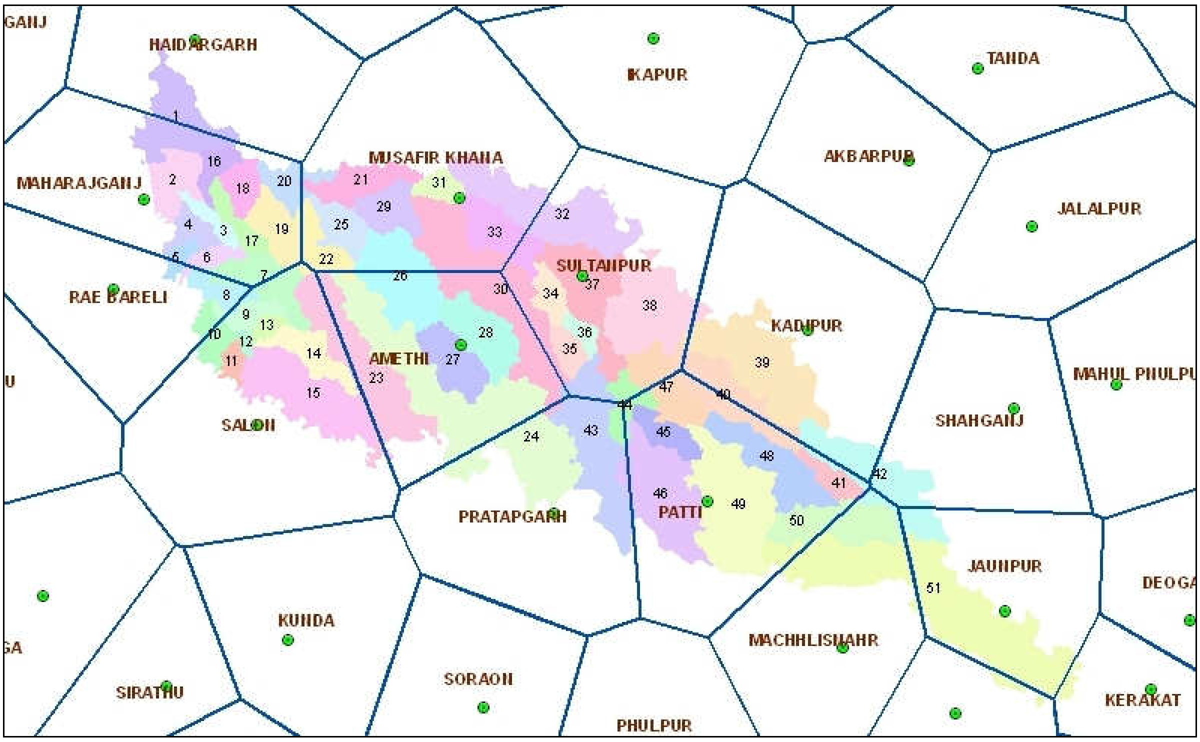


Table 3- Rainfall stations influencing each MSB, Thiessen weights

MSB_ID	MSB_Name	Station Name	% MSB area	Average Annual Rainfall 1901-2003 (mm)
1	Jaunpur_1	Haidergarh	52.60	942
		Maharajganj	47.40	
2	Deeh_1	Maharajganj	100.00	865
3	Dautra	Maharajganj	100.00	865
4	Deeh_2	Maharajganj	100.00	865
5	Tajpur	Maharajganj	71.10	880
		Rae Bareli	28.90	
6	Deeh_3	Maharajganj	88.84	880
		Rae Bareli	11.16	
7	Nasirabad	Maharajganj	52.56	896
		Rae Bareli	3.01	
		Salon	44.44	
8	Deeh_4	Maharajganj	3.38	896
		Rae Bareli	82.10	
		Salon	14.52	
9	Mau	Rae Bareli	12.99	900
		Salon	87.01	
10	Deeh_5	Rae Bareli	37.47	899
		Salon	62.53	
11	Sirsi	Salon	100.00	900
12	Deeh_6	Salon	100.00	900
13	Gopalpur_Deeh	Salon	100.00	900
14	Udaipur	Amethi	0.03	
		Salon	99.97	900
15	Deeh_7	Amethi	0.13	
		Salon	99.87	900
16	Jaunpur_2	Maharajganj	100.00	865
17	Daulatpur	Maharajganj	100.00	865
18	Jaunpur_3	Maharajganj	100.00	865
19	Shahmau	Musafir Khana	1.43	896
		Maharajganj	98.23	
		Salon	0.34	
20	Jaunpur_4	Musafir Khana	22.21	865
		Maharajganj	77.79	
21	Richaura	Musafir Khana	99.30	952
		Maharajganj	0.70	
22	Jais_1	Musafir Khana	79.92	952
		Maharajganj	6.90	
		Amethi	8.47	
		Salon	4.72	
23	Ateha	Musafir Khana	0.01	984
		Amethi	72.18	
		Salon	27.82	
24	Jais_2	Amethi	63.90	982
		Pratapgarh	36.10	
25	Jaunpur_5	Musafir Khana	100.00	952
26	Amethi_1	Musafir Khana	38.53	958
		Amethi	61.47	
27	Bhairopur	Amethi	100.00	984

28	Amethi_2	Amethi	100.00	984
29	Jaunpur_6	Musafir Khana	100.00	984
30	Tikri	Musafir Khana	38.10	984
		Sultanpur	0.00	
		Amethi	60.78	
		Pratapgarh	1.12	
31	Jaunpur_7	Musafir Khana	100.00	952
32	Aurangabad	Musafir Khana	52.28	976
		Sultanpur	47.72	
33	Jaunpur_8	Musafir Khana	93.66	952
		Sultanpur	5.25	
		Amethi	1.08	
34	Gopalpur_1	Sultanpur	83.55	998
		Amethi	16.45	
35	Kalyanpur	Sultanpur	54.38	
		Amethi	45.62	
36	Gopalpur_2	Sultanpur	100.00	998
37	Jaunpur_9	Musafir Khana	0.04	998
		Sultanpur	99.96	
38	Ramganj_1	Sultanpur	100.00	998
39	Chanda	Sultanpur	7.33	1104
		Kadipur	92.67	
40	Ramganj_2	Sultanpur	13.39	1052
		Kadipur	50.67	
		Patti	35.93	
41	Singaramau	Patti	99.54	999
		Machhlisnahr	0.46	
42	Ramganj_3	Kadipur	36.56	1028
		Shahganj	35.99	
		Patti	6.21	
		Machhlisnahr	9.95	
		Jaunpur	11.29	
43	Chilbila	Sultanpur	10.97	980
		Amethi	4.41	
		Patti	1.31	
		Pratapgarh	83.31	
44	Nagapur_1	Sultanpur	37.28	1002
		Patti	29.51	
		Pratapgarh	33.21	
45	Nagapur_2	Patti	85.62	999
		Pratapgarh	14.38	
46	Madafarpur	Patti	100.00	999
47	Jaunpur_10	Sultanpur	52.66	998
		Patti	47.34	
48	Dharauli	Patti	100.00	999
49	Jaunpur_11	Patti	100.00	999
50	Bhimpur	Patti	47.16	975
		Machhlisnahr	52.84	
51	Jaunpur_12	Patti	5.16	981
		Machhlisnahr	32.65	
		Mariahu	0.11	
		Jaunpur	60.96	
		Kerakat	1.12	

The 10-year driest, wettest and average climatic periods were identified from the 103-year rainfall data for 12 rainfall stations having influence on the JBS System for the development of different management scenarios. The three periods are:

- Driest 10 year sequence – 1987 to 1996 with average rainfall as 795 mm.
- Wettest 10 year sequence – 1977 to 1986 with average rainfall as 1103 mm.
- Average 10 year sequence – 1938 to 1947 with average rainfall as 968 mm.

1.4.2 Flow

The Sai and Gomti Rivers are tributaries of the Ganges River and all streamflow data for the Ganges River and its tributaries is classified and was therefore not provided to the SMEC. The 10-daily average discharge data for four CWC sites on the Gomti River and two CWC sites on the Sai River were made accessible to the SMEC for necessary analyses on the SWaRA computer in the SWaRA confidential data centre. The sites for which flow data are available are:

- Sai River at Rae Bareli,
- Sai River at Jalalpur,
- Gomti River at Lucknow,
- Gomti River at Maighat,
- Gomti River at Sultanpur, and
- Gomti River at Jaunpur.

The iCROP model verification is carried out based on these flow data from the above six CWC sites. With 10-daily average, the peaks of discharge flows will not be as sharp as they happen to be in instantaneous discharge hydrographs. However, the lean flow hydrograph will still be largely unaffected, providing an opportunity to compare the model simulated runoff to the observed flow at the gauging site.

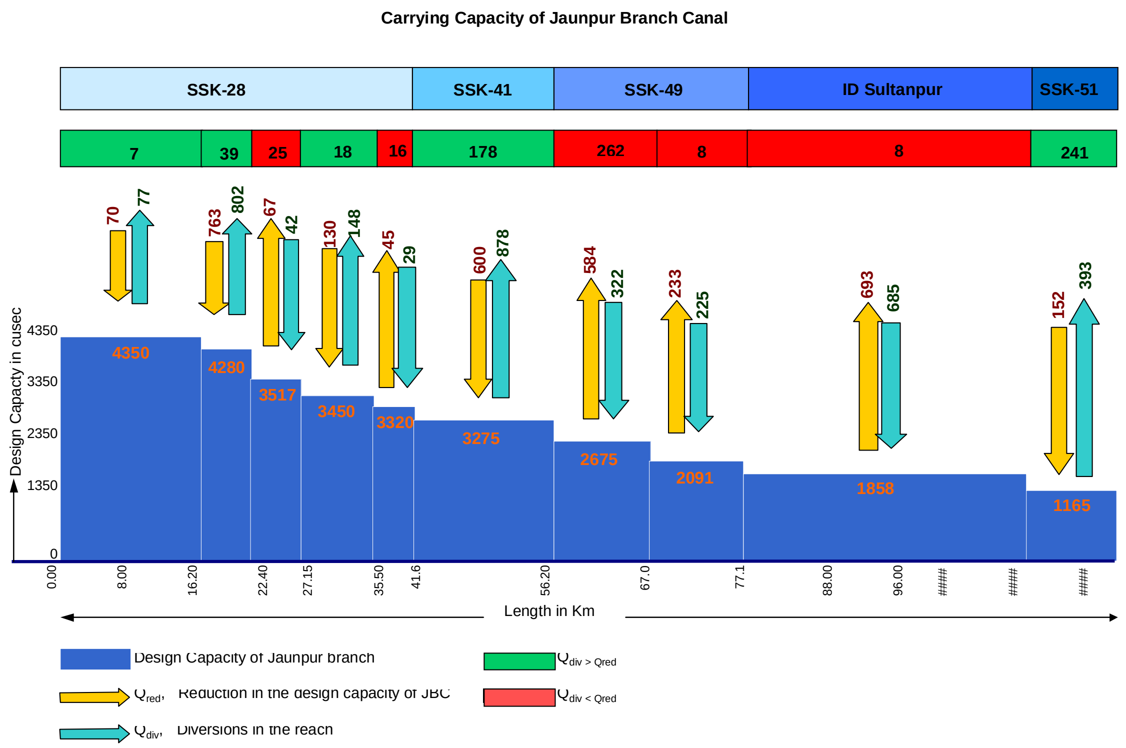
1.4.3 Crop Water Requirements

Crop water requirements have been computed using Penman Montieth method and is summarised in Appendix A- Datasets. The daily requirements were computed for each individual crop and to account for planting to occur over a period of 2-3 weeks, daily requirements based on staggered planting were computed and average demand per unit area with staggered planting was computed. In iCROP model, only reference evapotranspiration and crop coefficient data are used.

1.4.4 Canal System

One of the important input data to the model is information on canal system. This includes canal capacities, rosters, minimum flow in canals when they are being used, and rules for sharing of shortages between canals. This data was collated by SMEC from the Divisional Offices of the UPID. The canal capacities collated from UPID Divisions are summarised at Appendix A-Datasets.On processing of this collated information it was found that for number of reaches of the Jaunpur Branch, reduction in Jaunpur Branch capacity was higher than sum of all minors and direct outlets in the reach (Figure 6). The reason for this discrepancy is postulated to be either lack of or incompleteness of data on direct outlets. The canal system data needs to be checked and modified in the model, if needed. In the current model setup, capacities of minors/direct outlets in reaches with such discrepancies, have been increased in the model, to match the reduction in capacity of the branch canal.

Figure 6- Carrying capacity of Jaunpur Branch Canal



2 ICROP CALIBRATION AND VALIDATION

2.1 INTRODUCTION

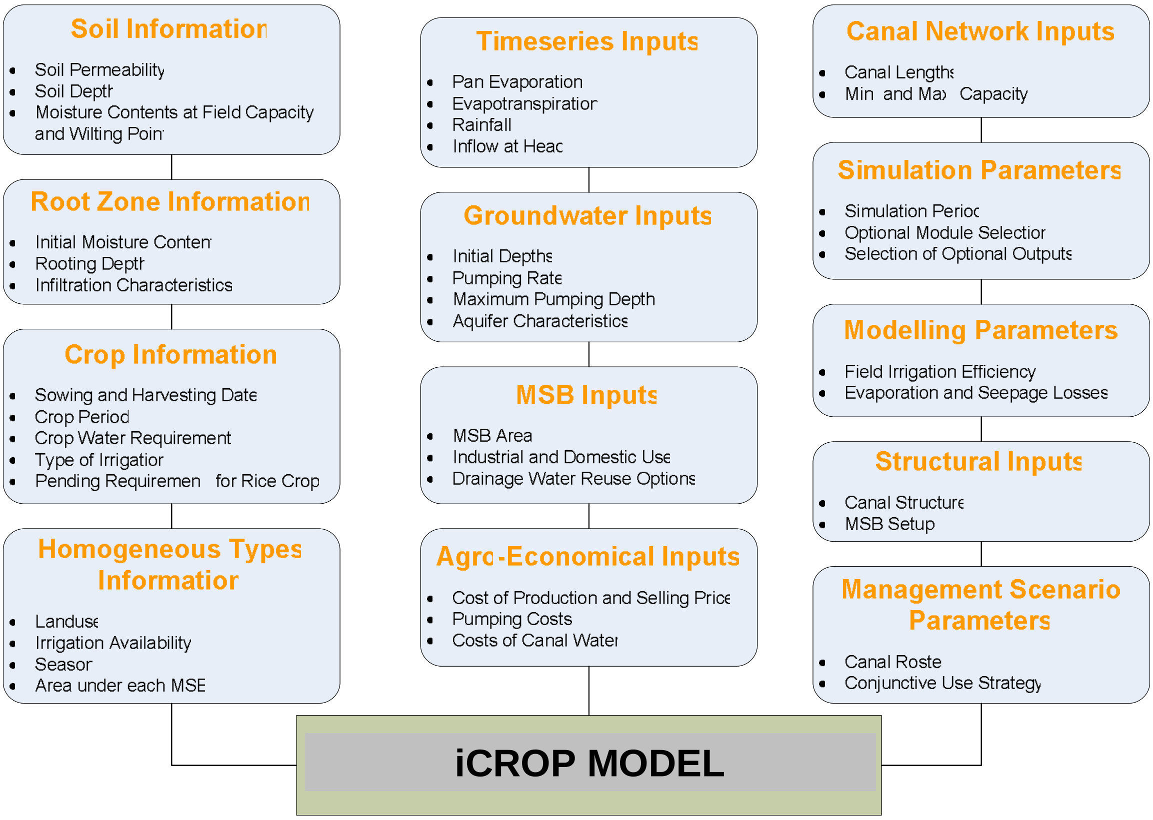
The core model in the DSS is the iCROP model. This is a water balance model that covers hydrological processes on the soil surface, in the root zone and in shallow ground water.

The calibration and validation of the iCROP model was performed in two stages. First, the iCROP model was calibrated and validated by adjusting key parameters to match, to the extent possible, the observed ground water depths. During this process, the model outputs were checked for "reasonableness". For example, the percentage of canal discharge that is lost to seepage was compared with expected rates, and the rainfall-runoff percentages were also checked. Second, the runoff and drainage was compared with observed river discharges. The IQQM model was used in this process to aggregate the iCROP outflows based on drainage catchments, and then to rout these discharges to the gauging stations.

2.2 ICROP MODEL INPUTS

There are numerous inputs in the iCROP model as illustrated in Figure 7. These are information related to soils, crops and other land use, hydrology and climate, physical constraints of canal system, canal operation roster and available discharge and many others. Many of them are fixed parameters which generally describe the physical infrastructures such as canal length, capacity, command area etc. They can usually be measured with a greater accuracy. However, some important hydro-geological and other hydro-climatic parameters that describe the surface and subsurface hydrological processes of the JBS and to which the model exhibits a higher sensitivity are discussed below.

Figure 7- Inputs to iCROP Model



Apart from input parameters, there are hundreds of other parameters in the model. These have been included in the input file in the model and discussed with UPID technical experts on several occasions during formal and informal presentations and meetings.

2.2.1 Specific Yield

Considering the geo-morphological characteristics of unconfined shallow aquifer of the JBS, the specific yield may vary from 5 to 12%. Specific yield in the model is considered to be varying from 8 to 10 % with an average value of approximately 9%. However, the analysis of the past UPID ground water data from 1997 to 2003 (piezometer levels time series) was carried out in greater detail. Few MSBs exhibit somewhat larger fluctuation in the ground water level, which can be justified only with smaller values of specific yield. The MSBs showing a larger seasonal fluctuation in the ground water levels over the years have been assigned a specific yield of 5%.

2.2.2 Reference Evapotranspiration

Reference crop evapotranspiration is calculated using Penman-Monteith crop water requirement calculation procedure (FAO 1997). This is done externally and input in the model as a time-series covering the period from 1901 to 2003.

2.2.3 Pump Capacity

Installed pump capacity in each polygon is calculated assuming that on an average, a typical shallow tubewell is operated approximately 4 to 8 hours at the discharge capacity of 40 to 60 m3/day. The state-operated deep tubewells extract ground water from deeper levels of the shallow unconfined aquifer. The records (Minor Irrigation Department, Census 2001) show that the contribution of deep tubewells is marginal compared to that of shallow tubewells i.e. less than 5% of the total ground water irrigation. For this reason, the installed pump capacity includes the deep tubewell contribution, assuming that such approximation is admissible without affecting accuracy of the model.

2.2.4 Runoff Curve Number

The rainfall-runoff process is modelled using the US-SCS curve number method. The curve number simulating the runoff characteristics of a specific catchment area depends on various catchment characteristics, particularly antecedent soil moisture and land use of the catchment. In the model, the curve number 60 is considered for cropped/vegetated area and a higher curve number 76 for the fallow and barren area.

2.2.5 Canal Seepage Loss

Different studies show slightly different amount of seepage losses from canals. The revised project report for Sarda Sahayak Pariyojna (UPID 1985, page 75) reports that losses for Branches, Distributaries and Minors were taken of 2.5 cusecs per million sq ft wetted area during monsoon months and 5 cusecs per million sq ft during non-monsoon months. This was stated to be based on "actual observations". These values have been used in the model, and sensitivity of model results to these values was assessed.

2.2.6 Canal Roster and Discharge

Based on the study of canal discharge data over recent period covering 1992 to 2005 at different distributary intakes, actual roster of past canal operation was produced. Actual historic time series of canal discharge at the head of Jaunpur Branch is used in conjunction with the actual roster to allocate the canal water in different distributaries of the system. Under the current canal operation, the canal water is given preference over ground water use irrespective of the level of ground water and type of crops.

2.2.7 Initial GW Levels

The model requires the initial ground water levels at the polygon level. As simulation starts from pre-monsoon period of any year, ground water level data of 93 UPID wells was used for this. A surface was fitted to the ground water table data for JBS using GIS tools, and ground water levels for each polygon were extracted.

2.2.8 Saturated Infiltration/Deep Percolation

Considering the type of soil in the JBS which is mostly dominated by loamy soils over fine loamy soils, the saturated infiltration (ie. deep percolation) is taken as 4 mm/day in the model.

2.3 CALIBRATION AND VALIDATION AGAINST GW DEPTHS

All relevant hydrological procedures simulating the hydrological processes in the JBS are coded into iCROP. iCROP is a comprehensive stand-alone object-oriented computer program in Visual Basic, where all relevant input parameters are assigned the appropriate values either through the model interface or in the input worksheets in a very user-friendly environment. Similarly, all relevant output parameters can be seen and further analysed in the forms of tables, graphs and GIS-based map objects in accordance with the users' convenience and preference.

There are several options available in the model to check its accuracy and consistency. Two important checks are the simulation of ground water surface over the JBS and that of runoff from the JBS. Firstly, the model prediction of the ground water surface can be compared with the observed ground water surface recorded in the past. The analysis of the ground water processes in the JBS has been carried out using the Visual MODFLOW software package. The iCROP model assumes that each MSB operates as a "bucket", with no transfers between buckets. Drainage from the buckets to the drainage systems is modelled. It is shown later in this section that such approximation is admissible in the model without any appreciable compromise with model accuracy. Consequently, iCROP prediction of ground water level is considered adequate for all practical purposes, thereby obviating the need for use of the Visual MODFLOW package for subsequent analyses.

Secondly, the model prediction of runoff from the field can be routed through the existing drainage network of the JBS i.e. Gomti and Sai drainage network and compared with the observed time series of flow at various gauge stations in the Gomti and Sai basin. The well-known Integrated Quantity and Quality Modelling (IQQM) hydrological software package has been used for this purpose. The iCROP model calibration and validation using two above-mentioned procedures are described in the subsequent sections.

2.3.1 Model Calibration using GW Depth as indicator

The iCROP model was set up and the base case scenario run was carried out for 1997-2003 simulation period. The iCROP SIU-level output values of net recharge to ground water are subsequently used as input to the Visual MODFLOW model. Visual MODFLOW produces a map of ground water surface levels which is converted to a map of ground water depths using the GIS facility. The GIS-based maps of the model prediction of ground water depths and observed ground water depth prepared based on RSAC post-monsoon 2002 ground water data are given in Figure 8 and Figure 9 respectively. The model prediction is in good agreement with the actual field observations and consistent over the space. The areas of four eco-zones (i.e. 0 - 3 m bgl, 3 - 5 m bgl, 5 - 8 m bgl and >8 mbgl) in the model prediction and the field observations are also quite comparable, as shown in Table 4. There is a difference of 4% in the 5 – 8 mbgl eco-zone.

Figure 8- Map of Depth to Groundwater from model prediction

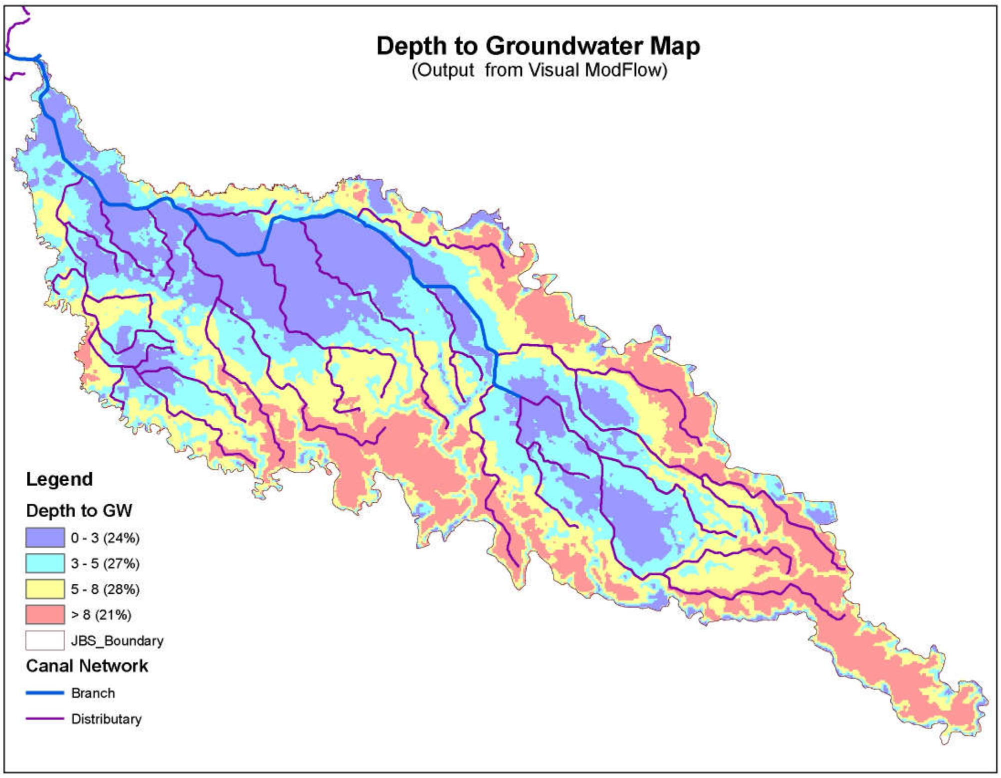


Figure 9- Map of Depth to Groundwater from RSAC data (Post-monsoon 2002)

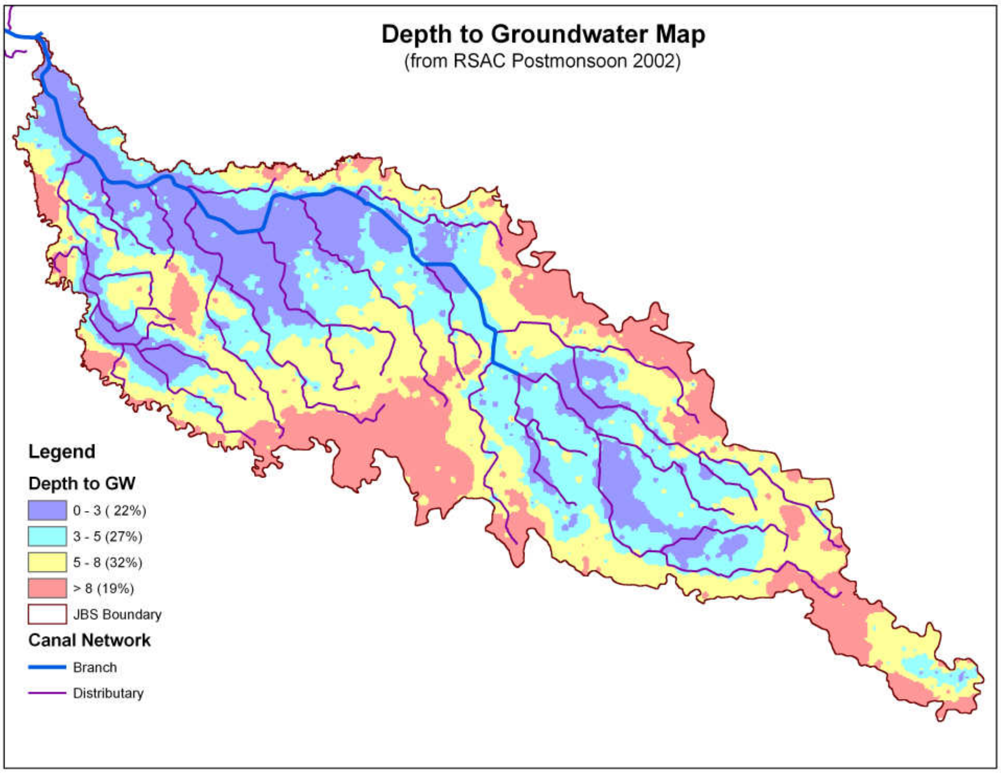


Table 4- Predicted & observed areas in different GW Depth zones in JBS

GW Depth Zone (mbgl)	Predicted Area (%) MODFLOW	Observed Area (%) RSAC (2002)
0 - 3	24	22
3 - 5	27	27
5 - 8	28	32
> 8	21	19

Figure 10 to

Figure 12 show the comparison between the model prediction and UPID observation of ground water depths in some selected MSBs in head, middle and tail reaches over the simulation period. With a few exceptions, most MSBs show a reasonable agreement with the observed pattern.

The predicted levels tend to show a declining trend in ground water levels at the Tail of the system (Figure 31) compared to observed levels that have a flat trend (neither rising nor falling). The reason for this discrepancy is likely to be the assumption in the model that irrigators will pump ground water to meet the full crop requirements. In reality, the irrigators are likely to under-irrigate the crops where the ground water is deep and they are paying the full cost of ground water pumping. The largest discrepancy is at the extreme tail of the system (MSB 51) where the model predicts that the ground water would be about 3 m lower than the observed level after approximately 5.5 years. This represents less than 0.5 m per year, which translates to a difference of only 4 cm of recharge (assuming 8% specific yield). The rainfall in this area is around 100 cm per year, so the discrepancy is only 4% of rainfall, well within the range of possible measurement errors.

The model predictions also show the predicted amplitude of variation from season to season is flatter in some MSBs than the observed amplitude. There are several possible explanations for this difference, but the most likely is that the assumed value of specific yield in the model is larger than the actual value. A more comprehensive study focussing on specific yield covering most of JBS may result in an improved model.

Some discrepancy between modelled and predicted is likely due to limited number of UPID observation wells (i.e. about 90) over JBS which have been used to calculate the initial polygon-wise ground water depth and the ground water depth in each MSB for pre- and post-monsoon over the modelling period. A comparison of RSAC data from over 2700 points (post-monsoon 2002) with UPID data using only about 90 points (used in the model calibration) show considerable differences (Figure 13).

Figure 10- Observed (red) and predicted (blue) GW Depths in Head Reach

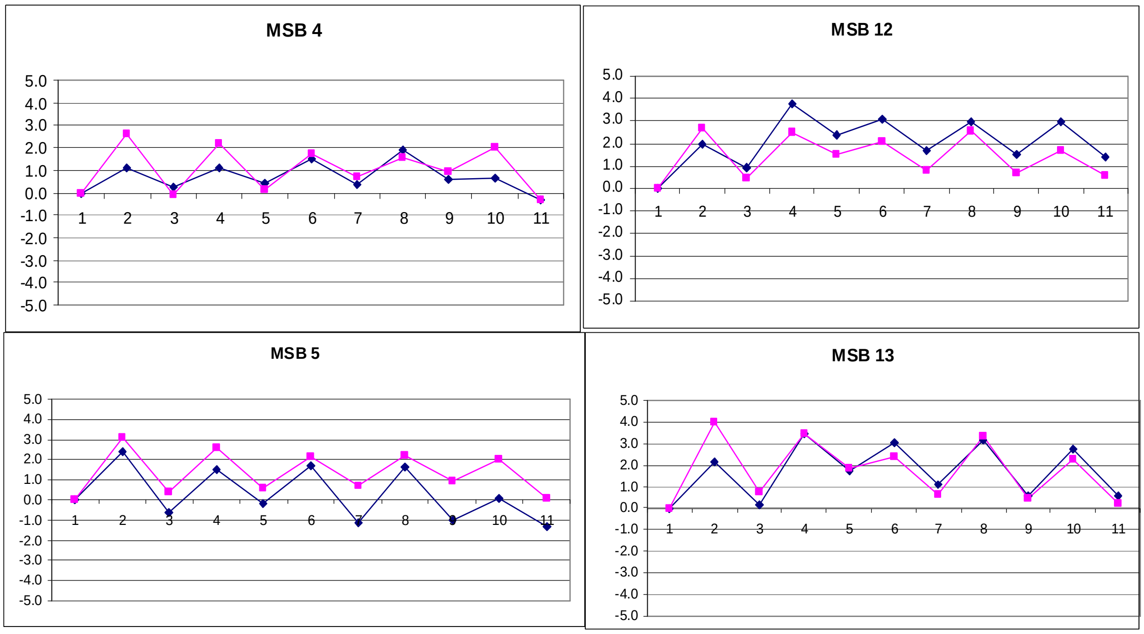


Figure 11- Observed (red) and predicted (blue) GW Depths in Middle Reach

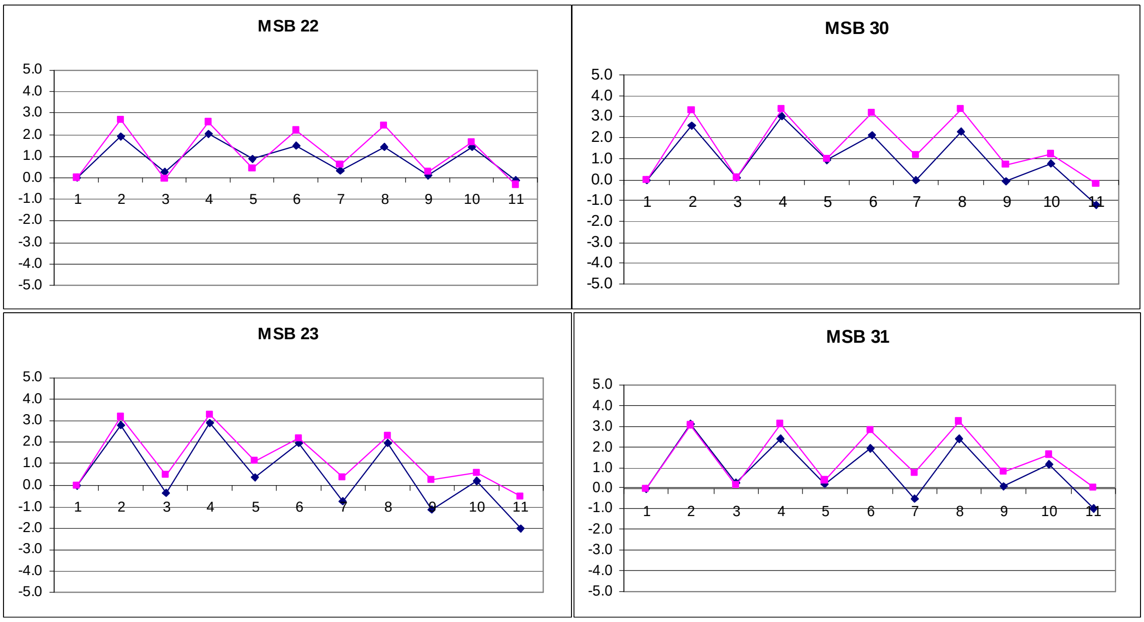
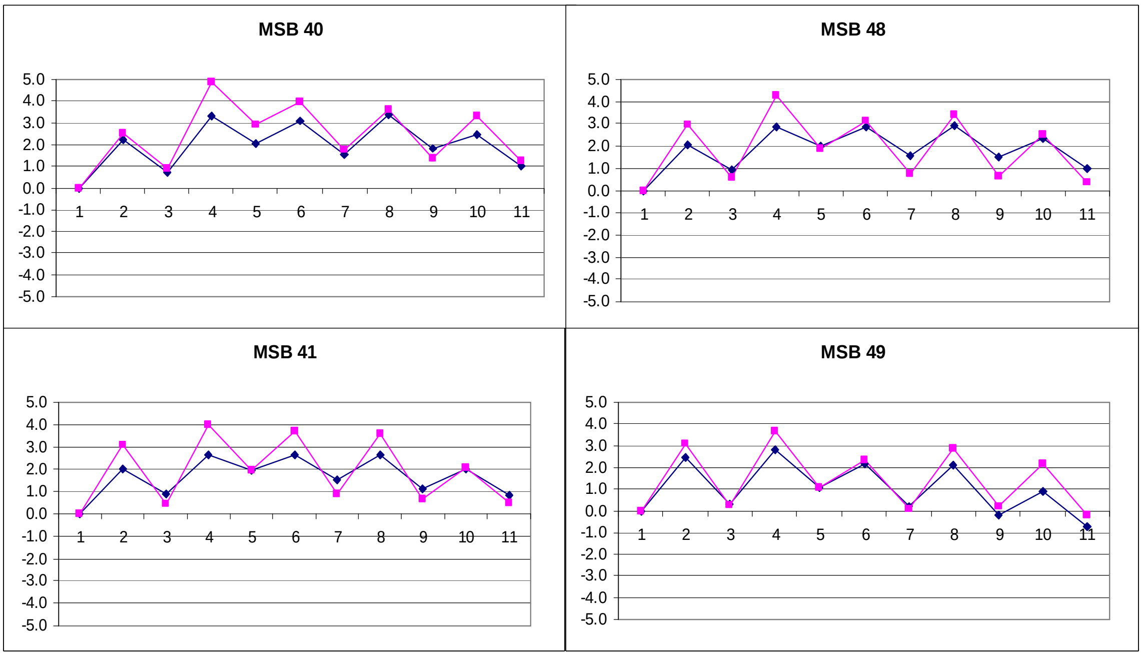


Figure 12- Observed (red) and predicted (blue) GW Depths in Tail Reach

(a)



(b)

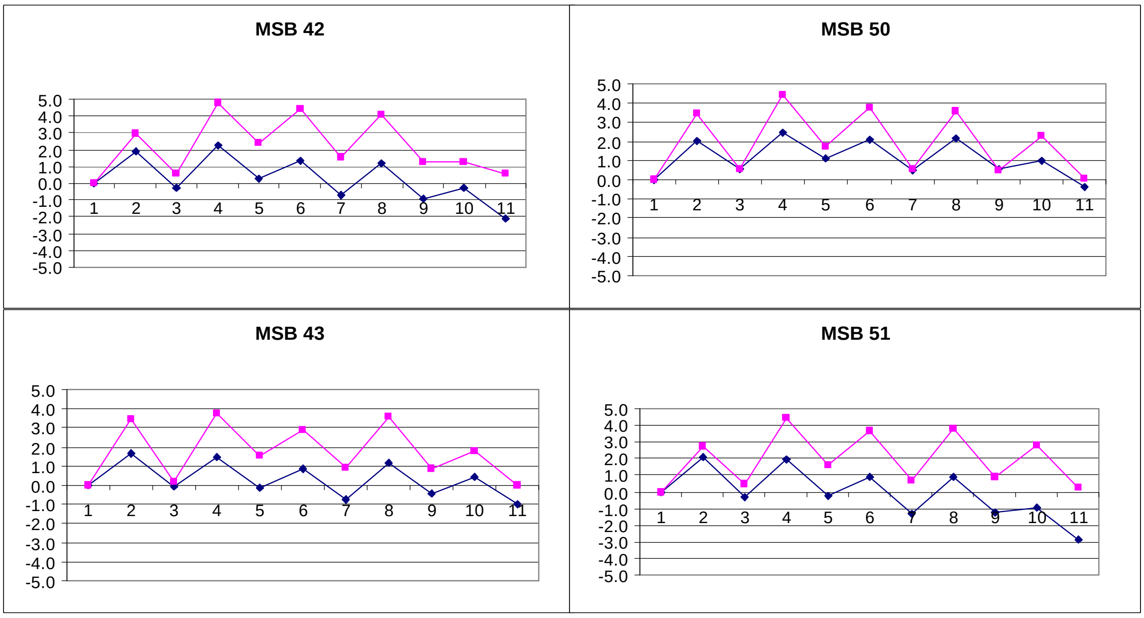
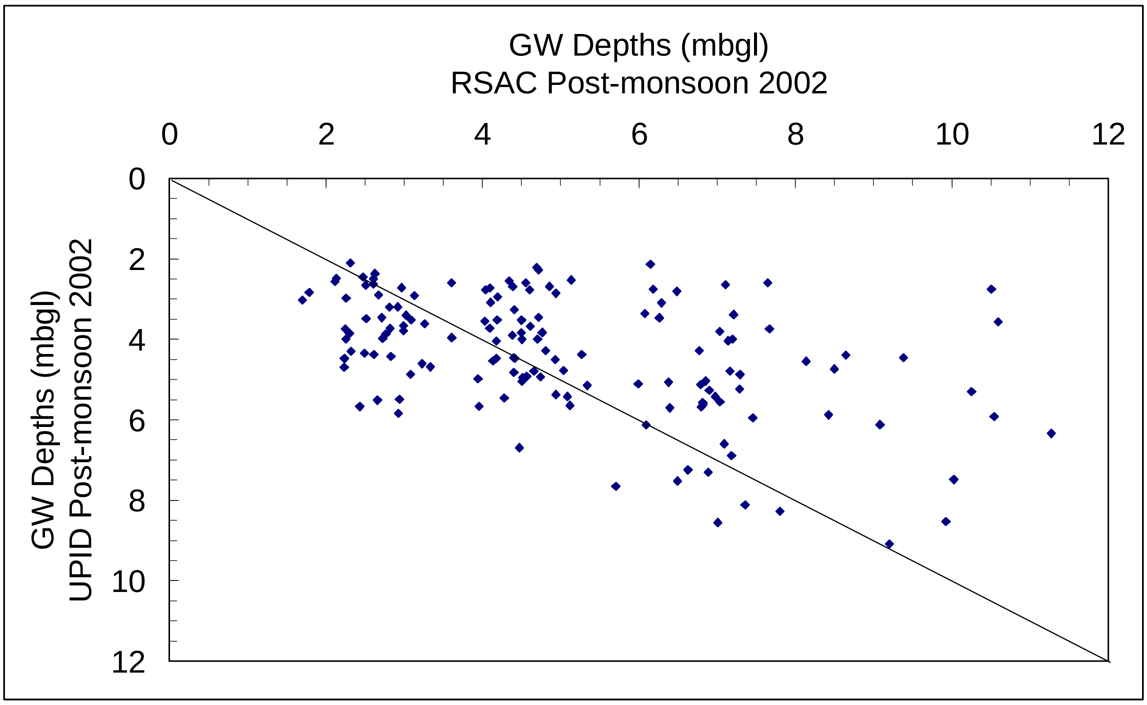


Figure 13- GW Depth observations of RSAC and UPID in post-monsoon 2002



Thus, all results and assessments presented above verify that the iCROP model is a reasonable representation of the hydrological processes occurring in the JBS area and simulates the whole water balance involving canal, rainfall and ground water in a realistic manner. However, marginal discrepancies exist at some places due to various reasons. Apart from the above, some other causes for discrepancies are discussed below:

- The ground water use varies from place to place depending on whether a particular command area is in head reach of canal or tail reach; it is inside the command area or outside. The use varies from season to season, year to year, across the development stages of crops and crop to crop. To incorporate this variability in a more realistic extent, a detailed study of ground water use in the JBS is required. All seasonal abstractions from each individual pump in the JBS must be recorded to make the model more realistic.
- Most canals have been silted over the years resulting in reduced discharge capacities. Records of gauge heights are available on distributaries level, however, stage-discharge curves have not been updated accordingly and some discrepancy in discharges is likely to occur due to this reason. A more accurate measurement of canal discharges at various locations must be maintained to improve the model performance.
- There have been illegal abstractions at various places, particularly in head reach of the canals.
- Canal discharges do not always follow the rosters, and there is no documentation available giving the reasons for variations from the rosters. Therefore, it is not possible to model future canal discharges reliably because variations from the roster cannot be included in the models because there is no basis on which to make these variations. Documentation of any variations from the roster should be kept and the variations and basis of the variations should be included in the model in the future.
- More site-specific investigations of geo-hydrological parameters such as specific yield, saturated hydraulic conductivity of soil etc will improve the model performance.

Finally, Figure 14 and Figure 15 show the ground water depths in post-monsoon 2002 predicted by the model and observed by RSAC respectively. These figures, plotted to the same scale, are output by the iCROP model using polygon-wise average values. Clearly, the model prediction is consistent and a good fit to the observed GW pattern. Furthermore, Figure 16 provides a similar comparison between observed and predicted ground water levels in a graphical form. The comparison clearly illustrates a reasonable correlation between the model predictions and field observations. In short, these comparisons clearly demonstrate that iCROP model prediction of ground water level can be considered to be adequately accurate for all practical assessments. For this reason, only iCROP is used hereafter for all analyses involving ground water level computations.

Figure 14- Predicted GW depth in polygons for post-monsoon 2002

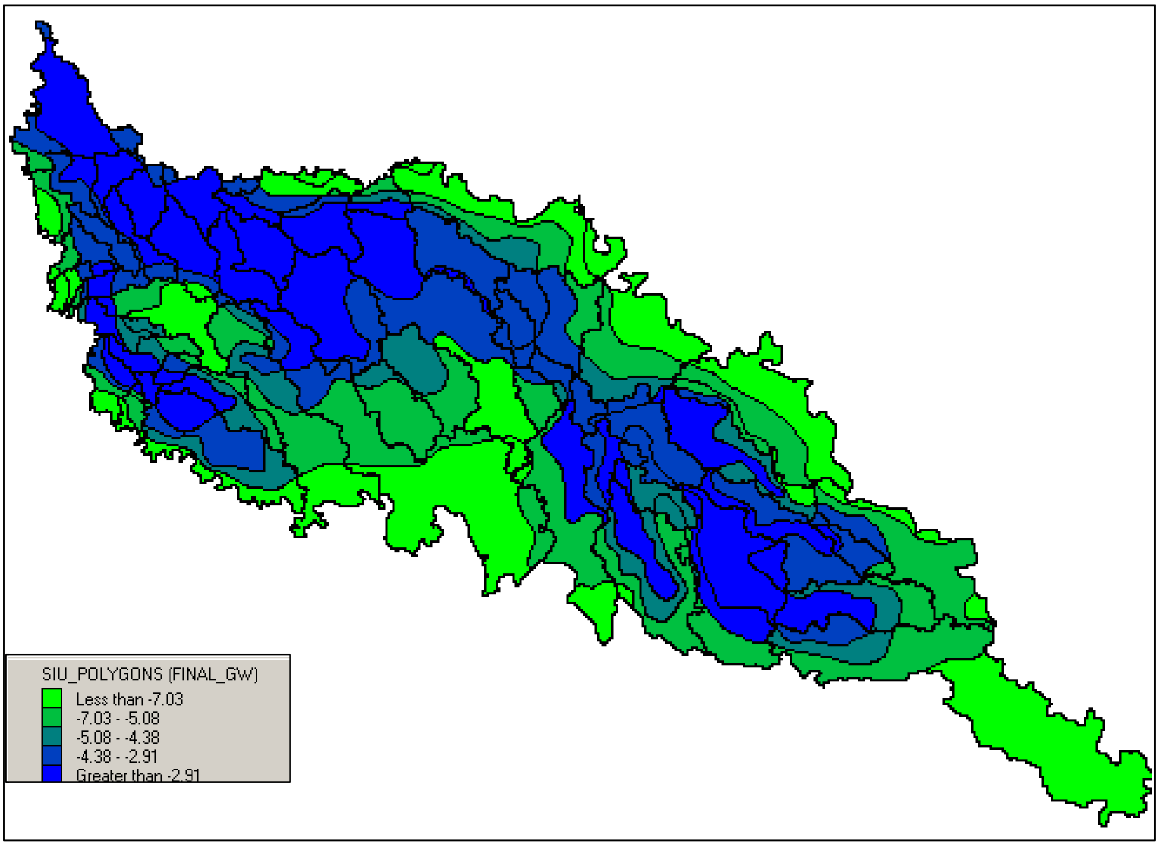


Figure 15- Observed (RSAC) GW depth in polygons for post-monsoon 2002

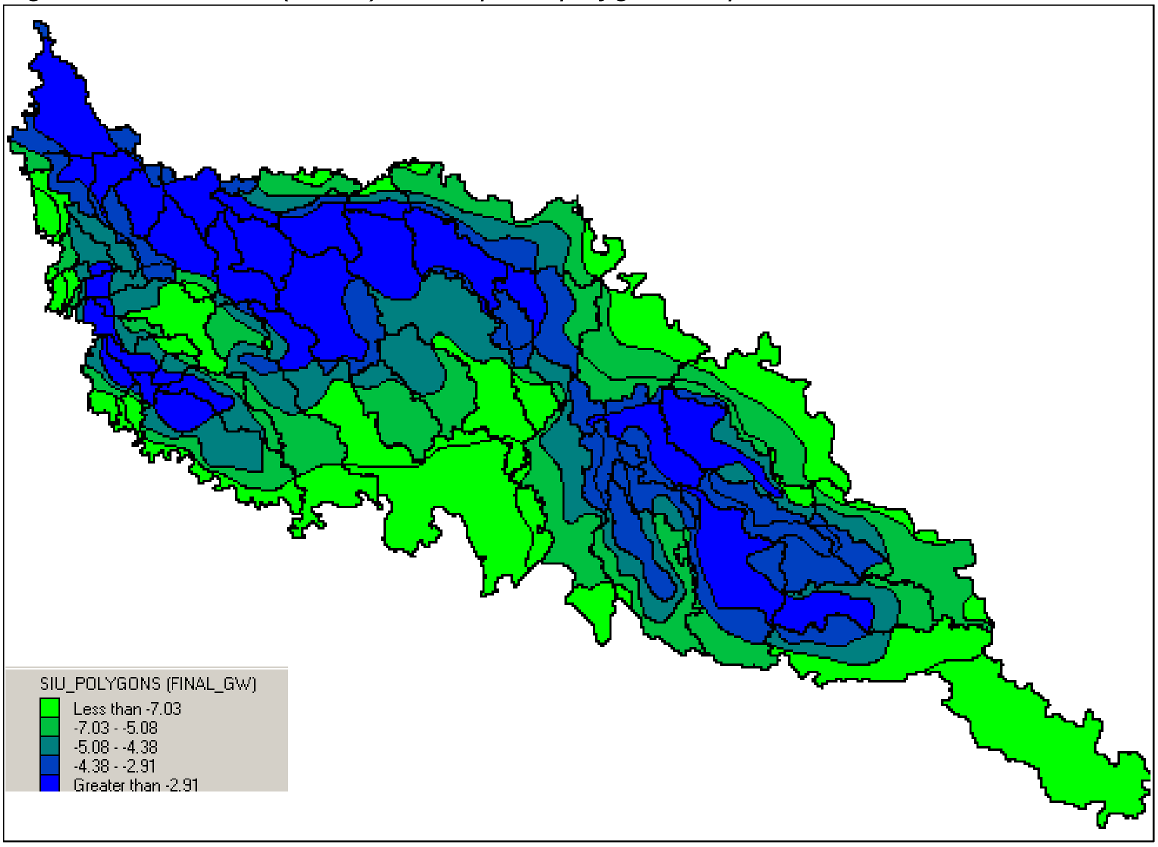
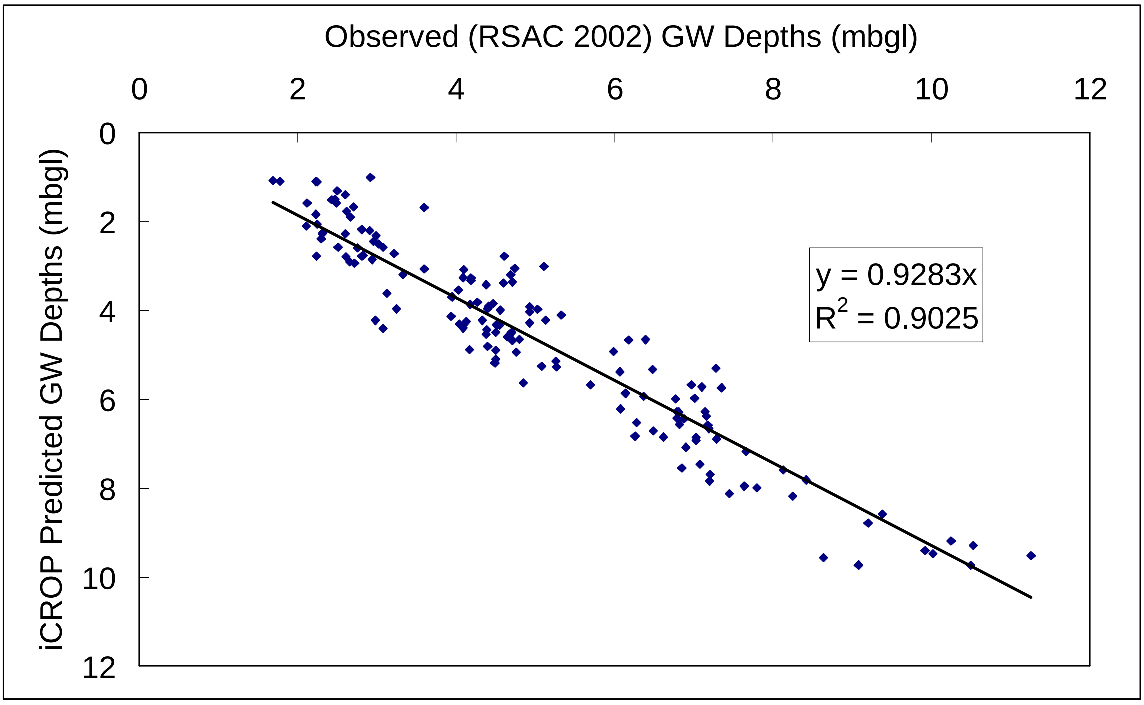


Figure 16- Predicted vs Observed GW depths by Polygon (Post-monsoon 2002)



2.3.2 Discussion of Base Case

The base case represents the actual canal operation in the recent past and exhibits the manner the system behaved over the period of simulation. As mentioned earlier, the historic simulation period covers from 1997 to 2003. The detailed system water balance of 6 year-simulation is shown in Table 5. Some of important model observations are discussed below:

- The system water balance shows that in JBS, the average rainfall and canal water contributions to the total JBS water resources are approximately 80% (5174 MCM or 954mm) and 20% (1285 MCM) respectively. As most rainfall occur during the Kharif season, the water balance as shown in Figure 17 clearly demonstrates the excessive escape due to rain rejection during this season.This also demonstrates the behaviour of a typical run-off-river canal system.
- The annual average effective rainfall is about 3533 MCM (651mm) which is about 68% of the total rainfall, resulting in about 32% surface runoff.
- The base flow component is about 6.7 % of the total system water resource.
- The largest canal escape occurs during the Kharif season whereas it is the lowest in the Rabi season (i.e. 8%). The escape during the Jayad season is more because the canal runs during this period at times without having much water requirement. This may however not the case in the recent years as the Jayad crops in the recent years have increased due to introduction of Mentha and other similar cash crops.
- The average annual groundwater extraction in JBS is about 1301 MCM. It is interesting to see that although the annual canal water available and the groundwater extraction are almost the same, the area irrigated by canal is much less compared to that irrigated by groundwater. This is because the canal water efficiency is much less than that of groundwater and as discussed earlier, a substantial part of canal water is lost through escape due to rain rejection.

Table 5- System Water Balance – iCROP computations

System Water Balance

All Units are in Million Meter Cube

Component	Kharif		Rabi		Jaayad		Total	
	Average	Percent	Average	Percent	Average	Percent	Average	Percent
Inputs								
Rainfall	4617.0	87.6	211.5	33.1	345.4	63.1	5173.8	80.1
Canal supply	655.4	12.4	427.7	66.9	201.8	36.9	1284.9	19.9
Total	**5272.3**	**100.0**	**639.2**	**100.0**	**547.1**	**100.0**	**6458.6**	**100.0**
Outputs								
ET (Plants use)	1761.5	40.6	1248.4	82.9	441.0	66.8	3450.9	53.1
Domestic & Industrial use	45.2	1.0	43.7	2.9	30.0	4.5	118.9	1.8
Canal net evaporation	-1.1	0.0	1.6	0.1	1.2	0.2	1.7	0.0
Runoff	2097.8	48.4	78.1	5.2	35.9	5.4	2211.8	34.0
Escape flow (Net of reuse)	259.2	6.0	-38.9	-2.6	64.8	9.8	285.0	4.4
Base flow	173.0	4.0	172.2	11.4	87.6	13.3	432.7	6.7
Total	**4335.6**	**100.0**	**1505.1**	**100.0**	**660.4**	**100.0**	**6501.1**	**100.0**
Increase in subsurface storage	**936.8**		**-865.9**		**-113.3**		**-42.4**	

Canal Water Balance

All Units are in Million Meter Cube

Component	Kharif		Rabi		Jaayad		Total	
	Average	Percent	Average	Percent	Average	Percent	Average	Percent
Inputs								
Canal supply	**655.4**		**427.7**		**201.8**		**1284.9**	
Outputs								
Evaporation losses	-1.1	-0.2	1.6	0.4	1.2	0.6	1.7	0.1
Seepage losses	58.4	8.9	90.9	21.3	36.5	18.1	185.8	14.5
Escape flow	259.2	39.5	-38.9	-9.1	64.8	32.1	285.0	22.2
Water supplied to farms	339.0	51.7	374.1	87.5	99.3	49.2	812.3	63.2
Total	**655.4**	**100.0**	**427.7**	**100.0**	**201.8**	**100.0**	**1284.9**	**100.0**

Field Water Balance

All Units are in Million Meter Cube

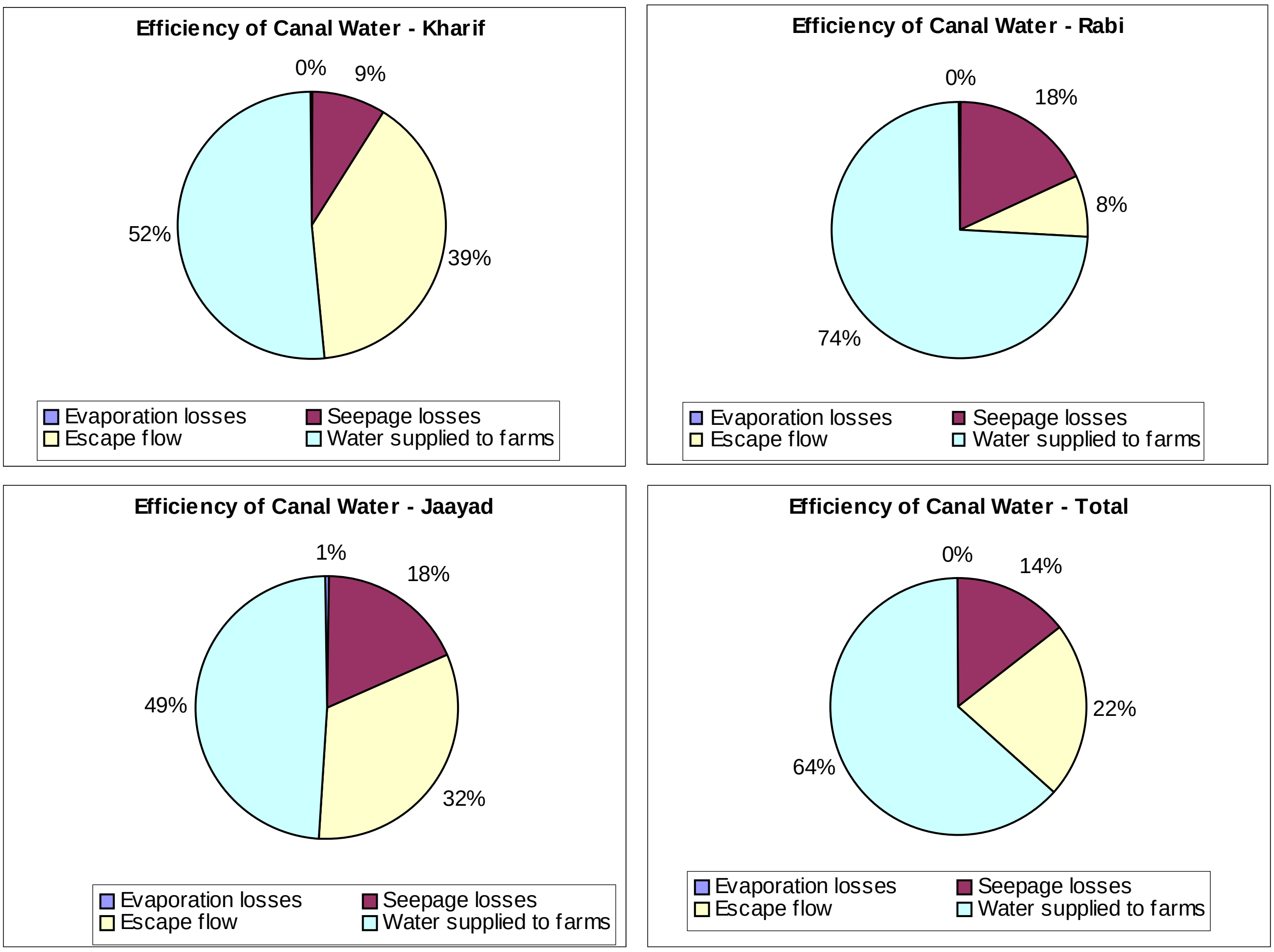
Component	Kharif		Rabi		Jaayad		Total	
	Average	Percent	Average	Percent	Average	Percent	Average	Percent
Inputs								
Rainfall	2995.4	87.2	207.8	18.7	329.4	59.8	3532.6	69.3
Ground water supply	104.5	3.0	531.5	47.9	123.7	22.5	759.7	14.9
Canal supply and drainage water use	334.0	9.7	370.8	33.4	97.4	17.7	802.2	15.7
Total	**3433.8**	**100.0**	**1110.1**	**100.0**	**550.5**	**100.0**	**5094.4**	**100.0**
Outputs								
Evapotranspiration	1761.5	54.4	1248.4	84.9	441.0	88.4	3450.9	66.2
Seepage	1002.4	30.9	148.1	10.1	38.1	7.6	1188.6	22.8
Runoff	476.3	14.7	74.5	5.1	19.9	4.0	570.6	11.0
Total	**3240.2**	**100.0**	**1471.0**	**100.0**	**499.0**	**100.0**	**5210.1**	**100.0**
Increase in subsurface store	***193.7***		***-360.9***		***51.5***		***-115.7***	

Ground Water Balance

All Units are in Million Meter Cube

Component	Kharif		Rabi		Jaayad		Total	
	Average	Percent	Average	Percent	Average	Percent	Average	Percent
Inputs								
Seepage from canals	58.4	5.5	90.9	38.0	36.5	48.9	185.8	13.5
Seepage from field	1002.4	94.5	148.1	62.0	38.1	51.1	1188.6	86.5
Total	**1060.7**	**100.0**	**239.1**	**100.0**	**74.6**	**100.0**	**1374.4**	**100.0**
Extractions								
For agriculture	104.5	32.9	531.5	71.4	123.7	51.7	759.7	58.4
For domestic and industrial use	40.2	12.7	40.4	5.4	28.1	11.8	108.8	8.4
Flow to drains/river	173.0	54.5	172.2	23.1	87.6	36.6	432.7	33.3
Total	**317.7**	**100.0**	**744.1**	**100.0**	**239.4**	**100.0**	**1301.2**	**100.0**
Increase in subsurface storage	**743.1**		**-505.0**		**-164.8**		**73.3**	

Figure 17- iCROP simulation-Canal water efficiency in JBS



2.3.3 Model Validation using ground water depth as indicator

Because of lack of ground water level data for pre-monsoon 2003, the model could not be run for 2003 onwards for model validation purpose. For this, the model validation run up to 2006 was carried out with the same pre-monsoon 1997 ground water levels as initial values for ground water levels. Rainfall and evaporation data are also not available for 2003 onwards so a normal rainfall sequence of 10 years from 1939 to 1948 was adopted and the same period was chosen for evaporation. The model prediction of the post-monsoon 2002 ground water table is shown in Figure 18. The observed ground water depth during the same period obtained from 250 piezometer data records (Figure 19) shows a reasonable agreement with the model prediction. Some discrepancies exist, particularly in the tail end of the JBS. This is likely due to lack of piezometer data. For example, in the large polygon # 51-4 there is no piezometer. This is clearly seen in Figure 20. The model predicts slightly higher values of water-logged area. This may be due to increased groundwater extraction in this area in the recent years. In the model, the extraction is assumed to be constant over the period of calibration and validation. However, in practice, groundwater extraction has increased over the years.

Figure 21 shows the comparison of predicted GW depths in post-monsoon 2002 and 2005. This clearly shows that the ground water in most polygons with shallower ground water table have risen up whereas the ground water in most polygons with deeper ground water table have gone deeper. This is an expected trend under the current canal operation. This validates that the performance of the iCROP model is consistent and simulates the canal operation and all hydrological processes in a reasonable manner.

Figure 18- Predicted GW Depths polygon-wise (post-monsoon 2005)

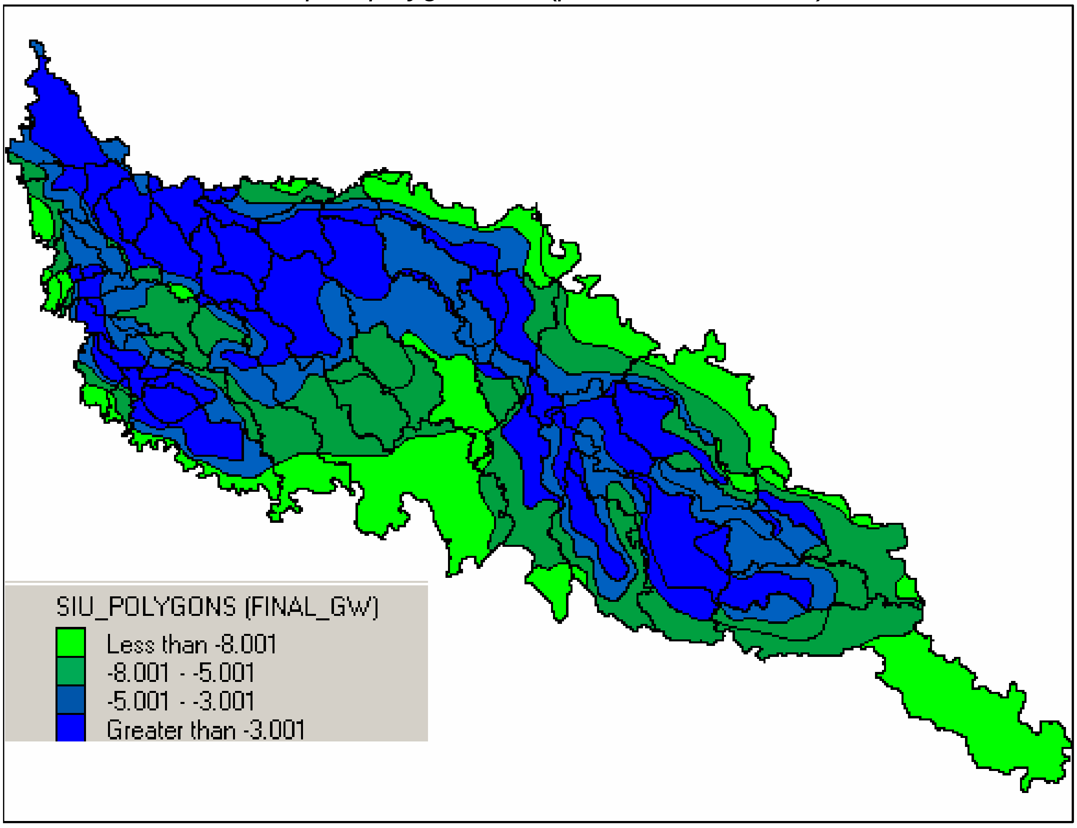


Figure 19- Observed GW Depths polygon-wise (post-monsoon 2002)

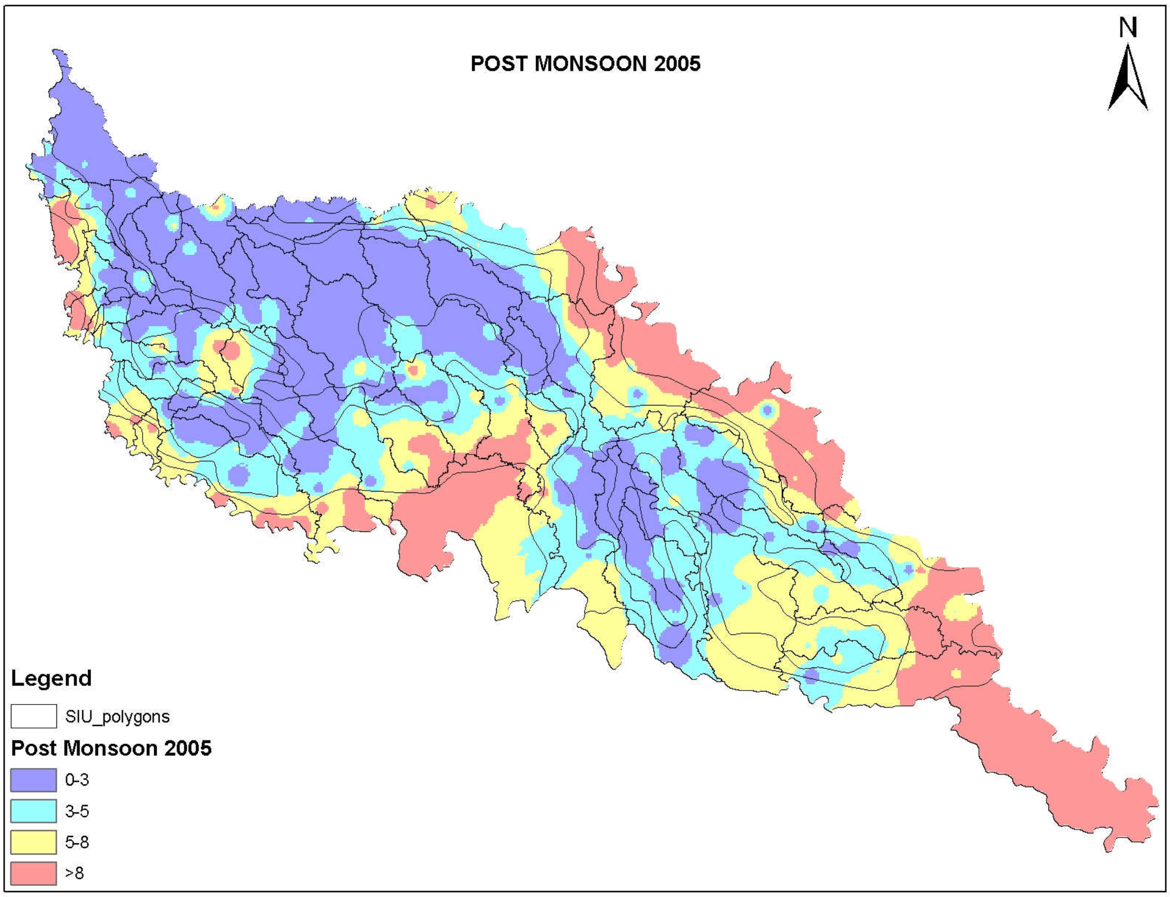


Figure 20- Piezometer locations in JBS (note low density in tail reaches)

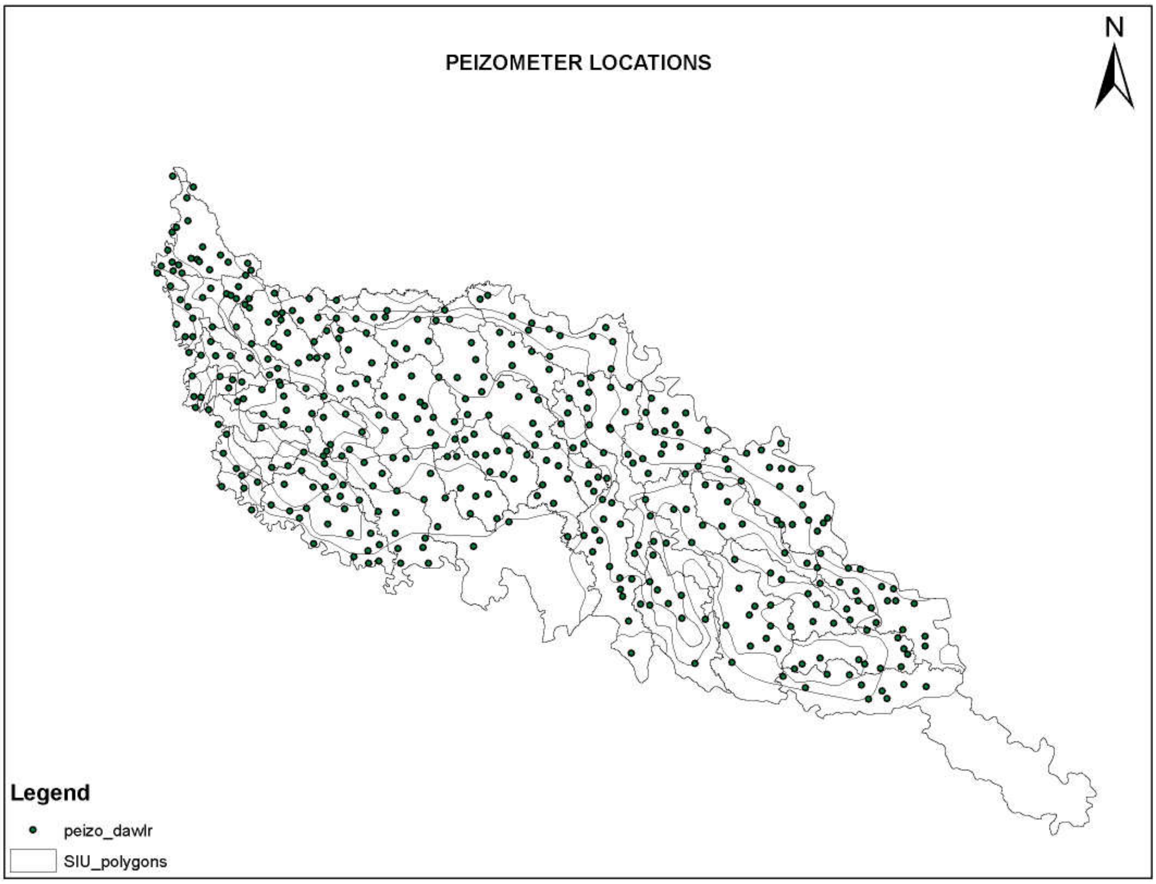
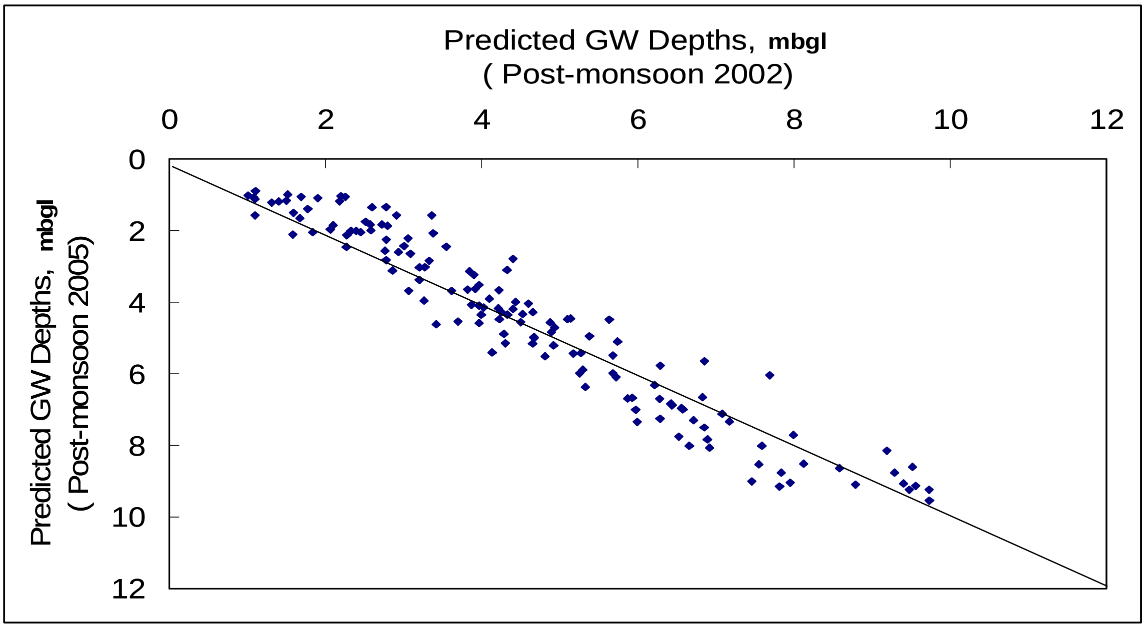


Figure 21- Scatter plot of Predicted GW Depths (post-monsoon 2002 and 2005)



2.4 CALIBRATION & VALIDATION AGAINST RIVER DISCHARGES

2.4.1 Drainage Network in IQQM

Figure 22 shows the Gomti-Sai drainage network of JBS-HBS and surrounding area. Altogether, there are 46 major drainage catchments contributing to the Sai and Gomti rivers. Runoff contribution of MSBs contributing to these drains is calculated based on the proportion of MSB areas draining into them. Apart from this, some parts of few MSBs drain directly to the Sai and Gomti rivers. Runoff contribution of drains outside the JBS is also calculated in a similar manner, assuming that these external catchments exhibit runoff trend similar to that of nearby MSBs.

Figure 22- Drainage network in JBS and surrounding area

Figure 23 represents the IQQM schematic and Figure 24 represents the IQQM model network of the same drainage system. The IQQM simulates runoff on hourly, daily or monthly time step. The daily time step is considered appropriate for the JBS runoff simulation. At each stream junction, some runoff is added to the river system. The model routs the flow between the junctions using the non-linear Muskinghum routing procedure. Among the major input parameters are length of stream between junctions, width of stream, Muskinghum routing parameters, headwater inflow time series for the uppermost gauge stations, stream rainfall and evaporation etc. Average width of 100 m is adopted for the Sai and Gomti rivers whereas width of 20m is adopted for most drains.

Figure 23- IQQM Schematic of drainage network of JBS-HBS and surrounding area

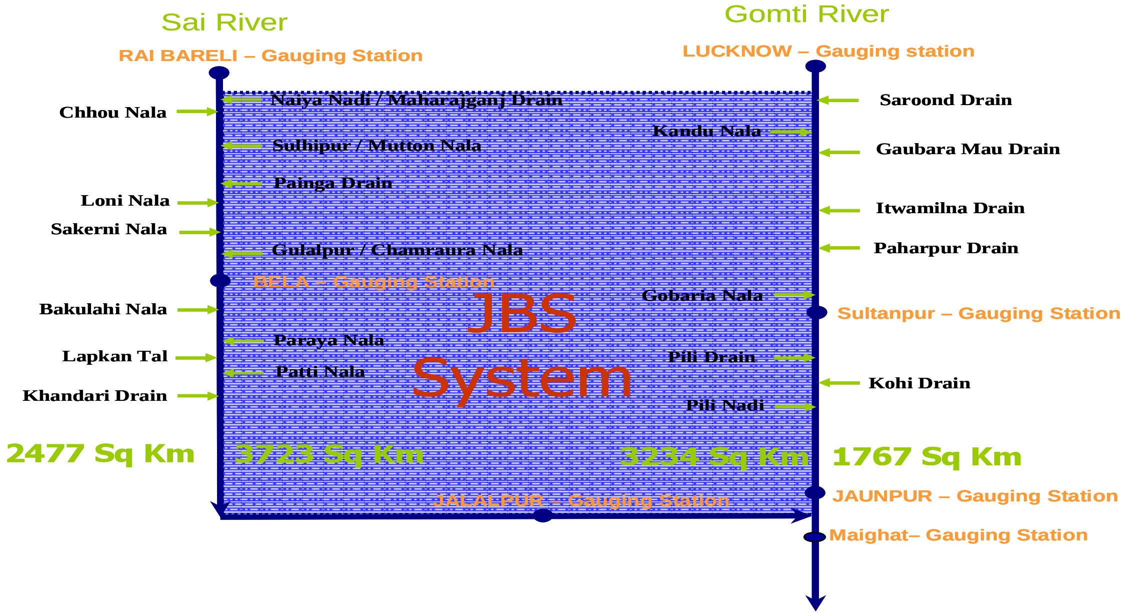
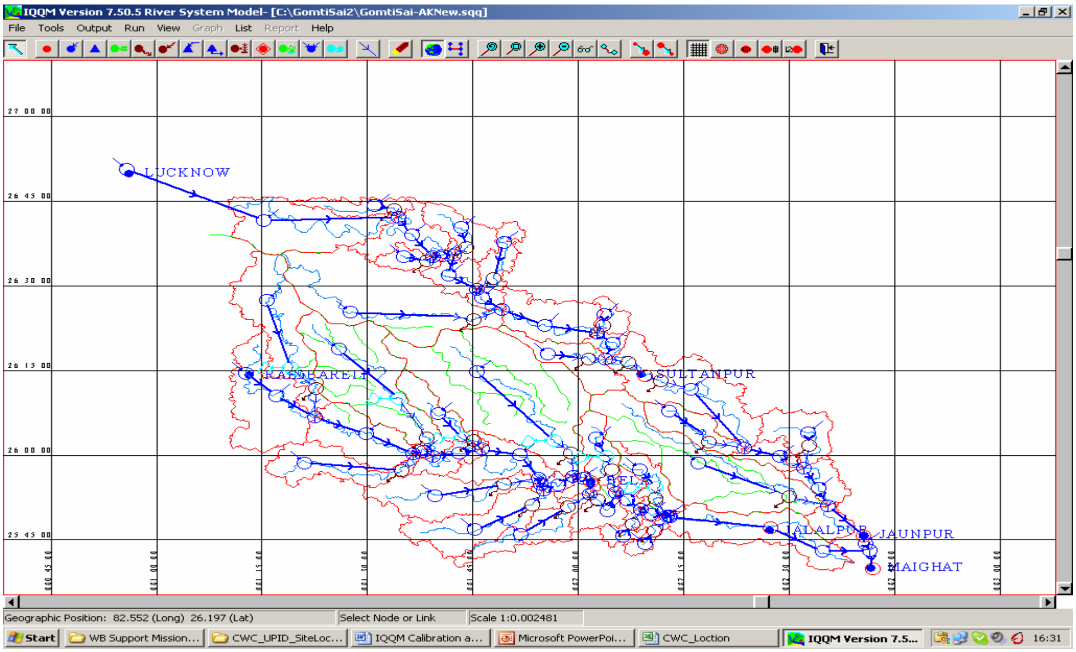


Figure 24- IQQM model drainage networks of JBS-HBS and surrounding area



2.4.2 River Discharge Data

The 10-daily river discharge data for the Gomti and Sai rivers for six CWC gauge stations were made available for calibration and validation of IQQM model. The data covered the period of 10 years from 1991 to 2000. The daily data could not be made available because of restriction on sharing of daily discharges in these rivers. As IQQM model uses a daily time step, 10-daily average CWC data for all six gauge stations was converted to daily format assuming that the flow remains the same over the ten days. These daily discharge time series were subsequently converted to IQQM daily discharge time series.

Although the assumption of uniform discharge over 10 days can produce some discrepancies between the predicted and the observed values, particularly during high flow periods, the result will be comparable during low flow period. Therefore, more attention was given to assessing the low flow periods.

2.4.3 IQQM Model Calibration

IQQM is a complex model capable of modelling rainfall-runoff processes, baseflows, river routing, reservoir operations and irrigation operations. In this project, however, IQQM is used in a very limited way. IQQM is used simply to route the iCROP drainage discharges down the rivers to the gauging stations, and to compare the observed and modelled discharges at the gauging station sites. Therefore, the only IQQM parameters that are relevant to this modelling process are the routing coefficients. The volume of discharge to the rivers from the JBS-HBS areas is computed by iCROP, and is input into IQQM.

The iCROP model was run from 1997 to 2003 for calibration. Unfortunately, the river discharge data provided by CWC covered the period 1991-2000 only. Therefore, the only concurrent period is June 1997 to December 2000. IQQM was run for only 3.5 years period from June 1997 to December 2000, and the river discharges modelled by IQQM were compared with CWC data.

The IQQM routing coefficients were estimated based on channel properties. Routing effects are greatest when there is a very rapid increase or decrease in river discharge. Therefore, the routing coefficients have a very small effect during the non-monsoon period, because the river discharge does not vary much from day-to-day.

After the model was run, the river discharges were extracted at the Maighat gauge station which is located just downstream of the confluence of the Gomti and Sai rivers. The predicted versus observed flows were plotted on the same time scale graph using the IQQM in-built graphic facility. The model simulation of runoff was considered to be quite consistent and reasonable. It was concluded that the routing coefficients were appropriate, and these were not changed.

As expected, non-monsoon month discharges have been simulated reasonably well, but there is some discrepancy between the modelled and observed discharges in monsoon months. The comparison plot is not given here because of restriction on sharing discharge data for these rivers.

It was concluded that the iCROP model is a reasonable representation of the whole water balance on the JBS study area and consequently it simulates the management operation of the JBS adequately.

2.4.4 Model Sensitivity

The model sensitivity analyses have been carried out for the input parameters which are likely to be less accurate due to inadequate data or difficulty in measuring them. In this regard, the parameters chosen for the sensitivity analyses are canal discharge at head of system, canal losses within system, specific yield of shallow aquifer, saturated hydraulic conductivity of soil in active zone (top 1 m) and shallow tubewell pumping capacity.

i Specific Yield

The storage of the unconfined aquifer (specific yield Sy) has been estimated by comparing the estimated annual recharge (20% of monsoon rainfall by tritium studies) and the fluctuation of groundwater level in the general range of 0.5 to 3 metres (with exceptions up to 5 metres). Based on this simple assumption Sy should be in the range of 5% to 30%. Considering that the soils of the shallow aquifer of JBS are dominated by loam on fine loam with some clay, kanker and silt-sand lenses, the specific yield may vary from 5% to 15%. The base case scenario was run using specific yield, Sy, in order of 8-10%. To assess model sensitivity to specific yield, specific yield for the entire basin was varied to 5% and also to 15%.

Figure 25 shows the ground water table with all parameters and inputs as for the base case, except that specific yield is set to 5%. Figure 26 shows a scatter plot of ground water depths polygon-wise for the base case and for the case with specific yield set to 5%. This plot shows that depths increase in the deeper ground water zones, and reduce in the shallower ground water zones. The result also suggests that the result with 5% specific yield is significantly different from calibration results illustrated in earlier section, illustrating the model sensitivity to specific yield significant. Consequently, it is necessary that such parameter is estimated more accurately through extensive geotechnical investigation.

Figure 25- Predicted GW Depths at 5% Specific Yield

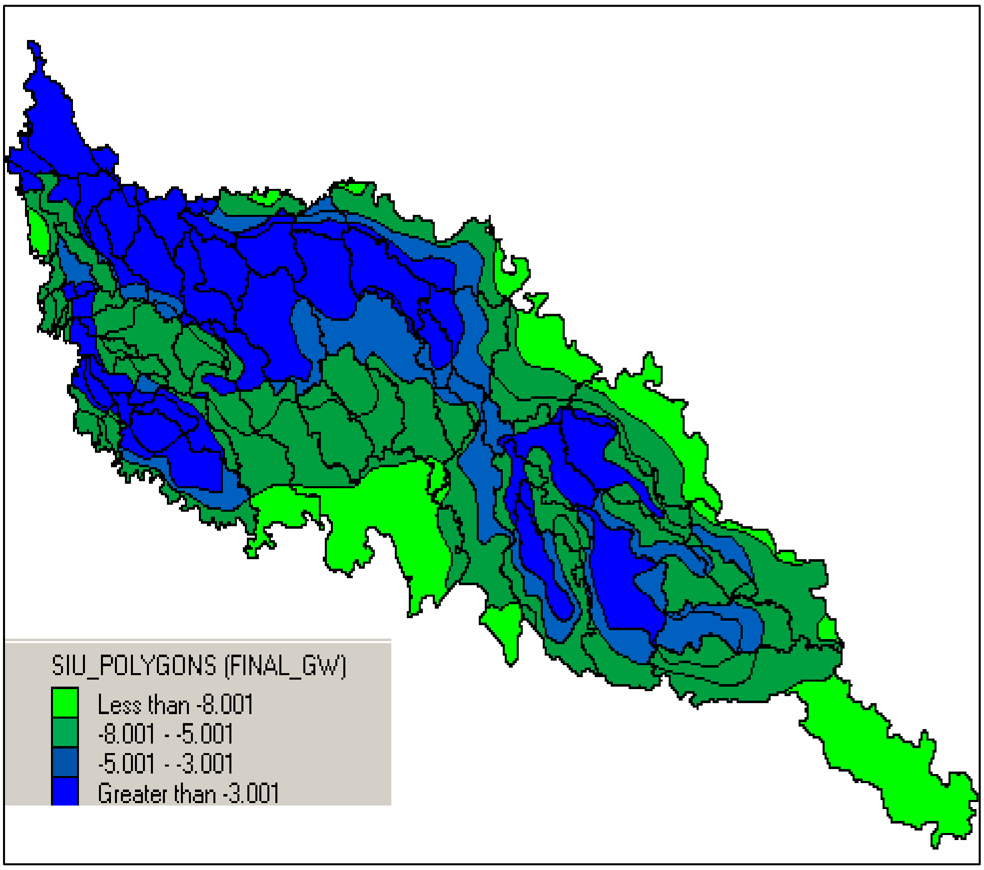
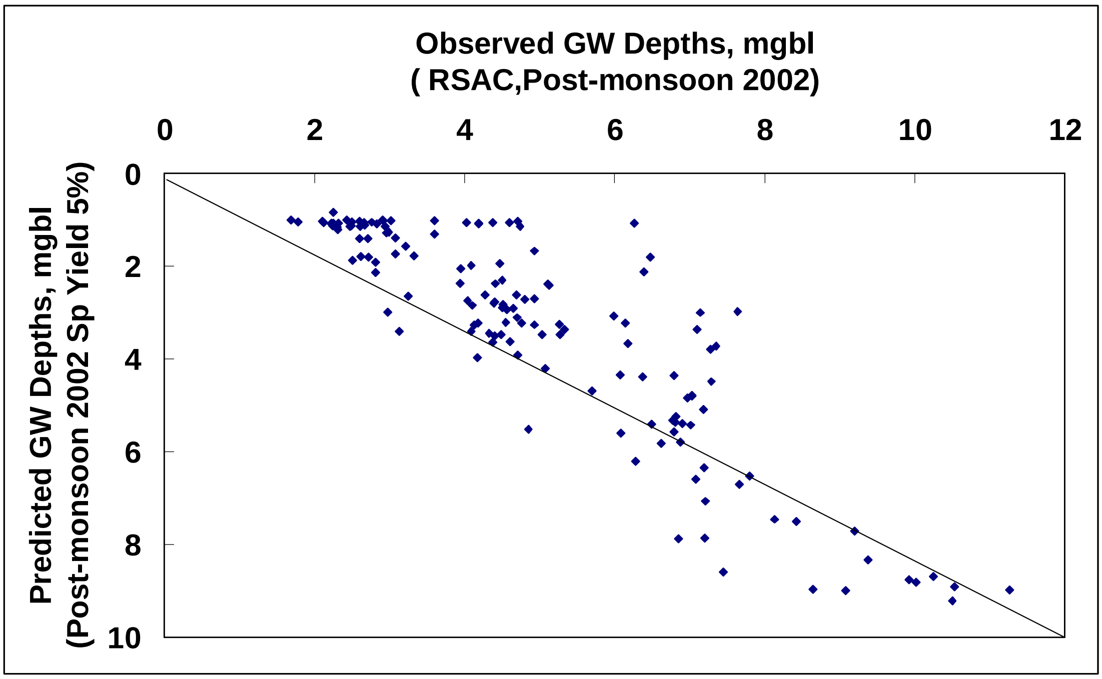


Figure 26- Scatter plot of GW Depths for Base Case and 5% Specific Yield



Similarly, Figure 27 shows the predicted groundwater table for the specific yield of 15% and Figure 28 the comparison of final groundwater depths with the RSAC observations in post-monsoon 2002. Figure 29 presents the groundwater depth fluctuations in MSBs in head reach where predicted amplitude of fluctuation is much flatter as expected. Thus, the results are once again consistent and expected, suggesting that the predicted groundwater depths are deeper than those in the calibration case. The model predictions are significantly skewed in relation to the base case results discussed earlier.

These results thus demonstrate that the model is sensitive to the choice of specific yield. A detailed geotechnical investigation may be desirable to determine its spatial variability over the JBS to further enhance the model accuracy.

Figure 27- Predicted GW depths for base case and 15% specific yield

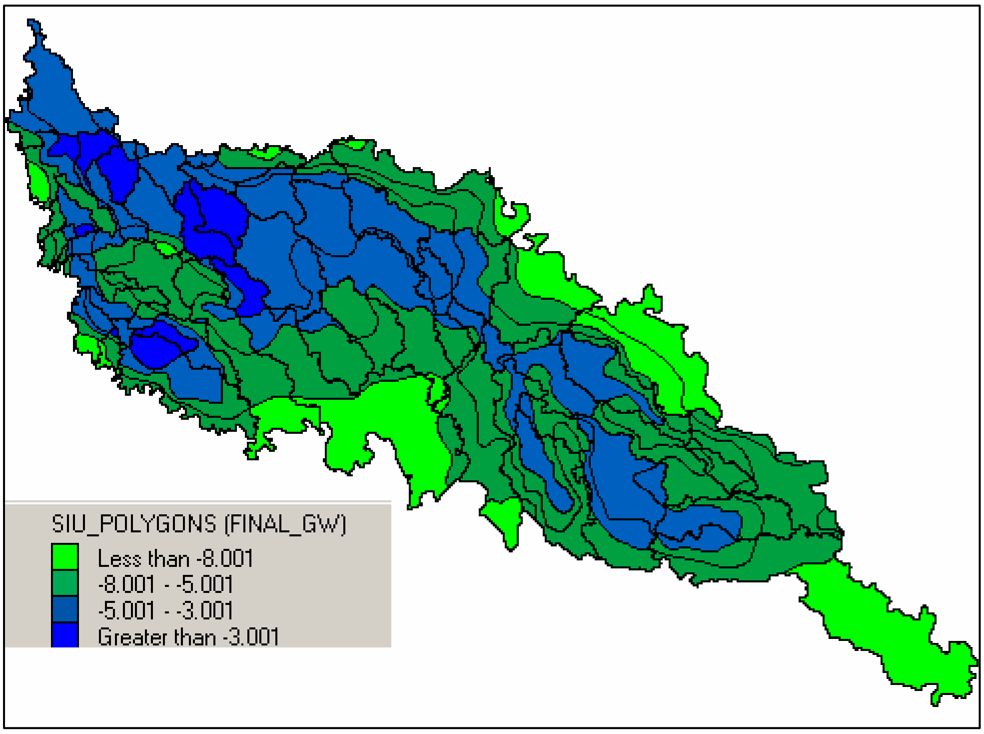


Figure 28- Scatter plot of GW Depths for Base Case and 15% Specific Yield

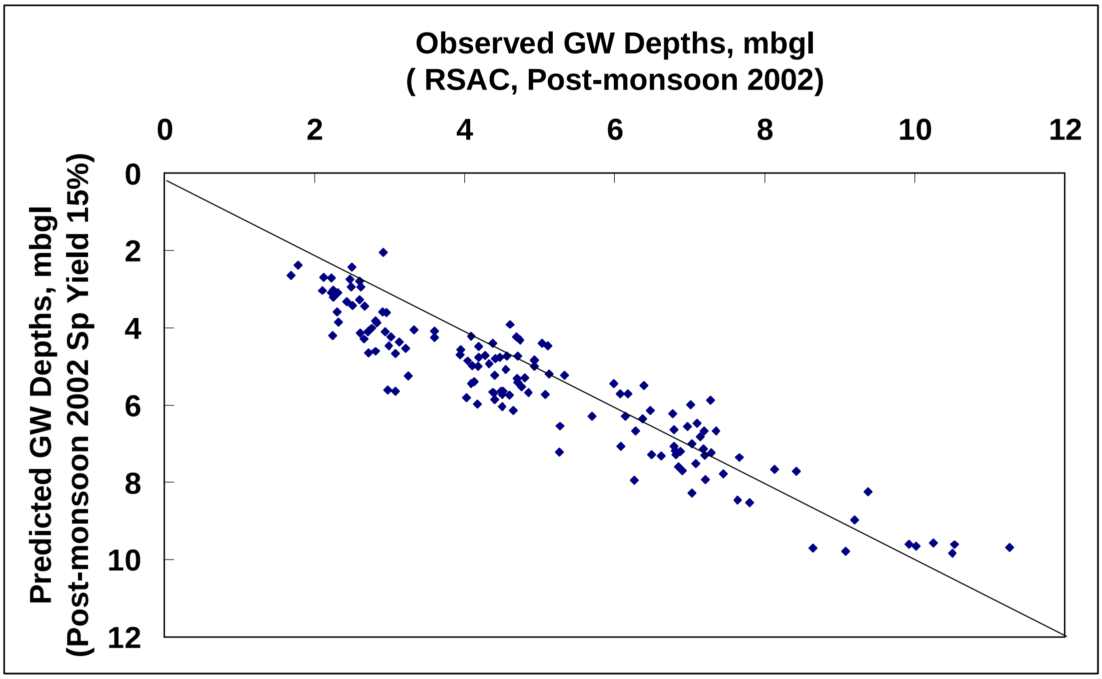
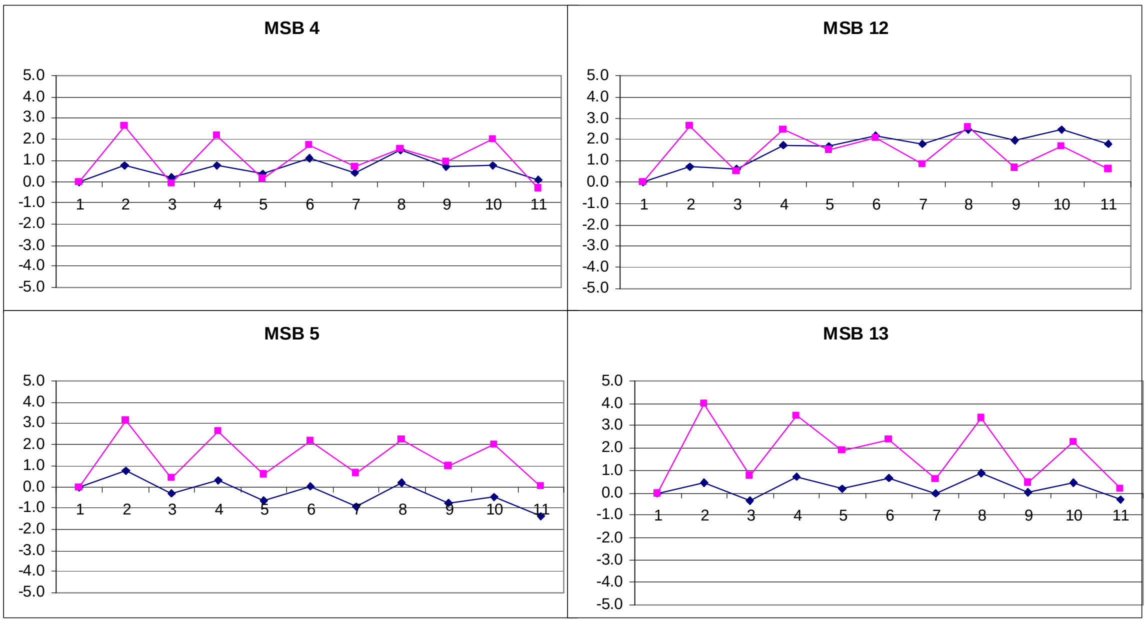


Figure 29- Observed (red) and predicted (blue) GW Depths for 15% Sy in Tail Reach



ii Saturated Infiltration

As discussed earlier, the saturated infiltration (i.e. saturated hydraulic conductivity or deep percolation) varies approximately from 3 mm/day to 5 mm/day for a medium soil. For this reason, a value of 4 mm/day has been considered and the sensitivity analysis has been carried out for 3 and 5 mm/day values.

Figure 30 and Figure 31 show the results of base case with 3 mm/day. The results are fairly expected, suggesting deeper groundwater depth compared to RSAC or calibrated values. Figure 32 and Figure 33 present the results of base case with 5 mm/day. Once again, they are consistent, resulting in slightly skewed to shallower depth because of increased recharge. There is a 17% decrease in groundwater recharge with 3 mm/day whereas a 12% increase in groundwater recharge with 5 mm/day saturated infiltration. This variation can be considered significant, indicating that the model is sensitive to the choice of this parameter. For this reason, a field-based study of such parameter is desirable to make the model even more realistic.

Figure 30- Predicted GW depths for the base case and 3mm/day saturated infiltration

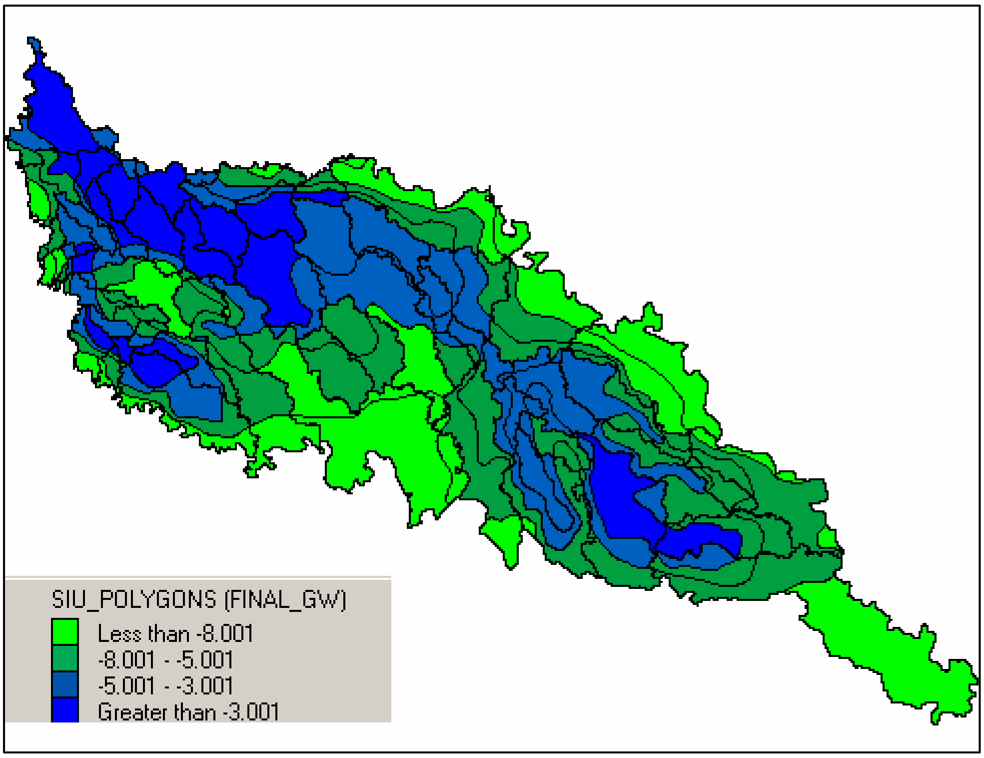


Figure 31- Scatter plot of GW Depths for Base Case and 3mm/day Saturated Infiltration

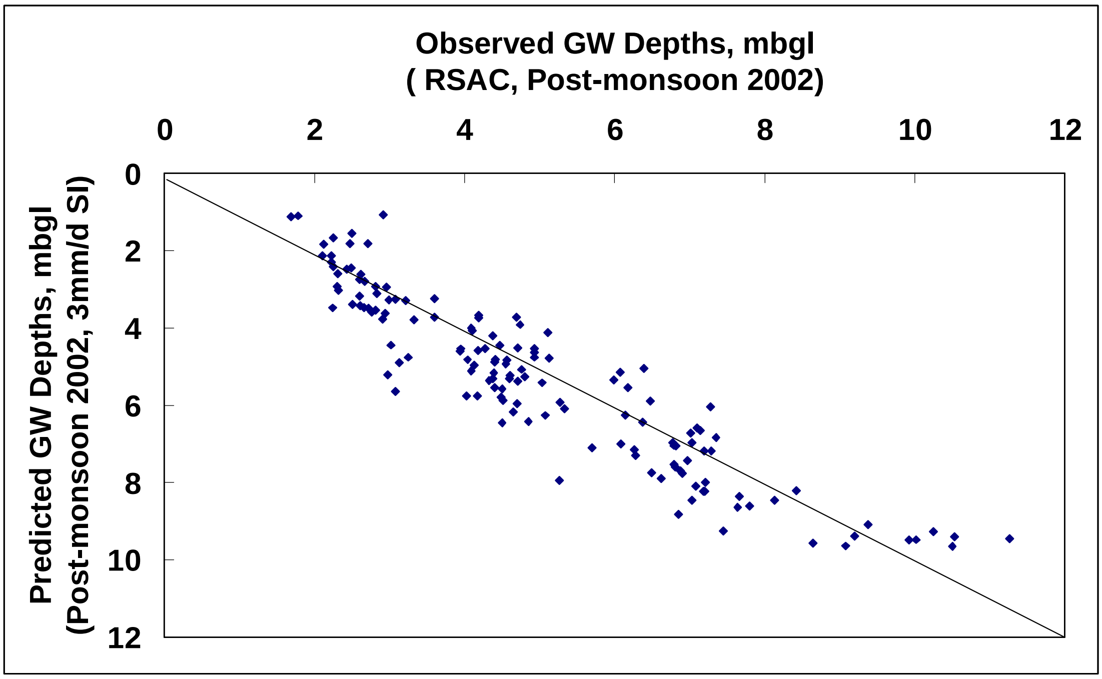


Figure 32- Predicted GW depths for the base case and 5mm/day Saturated Infiltration

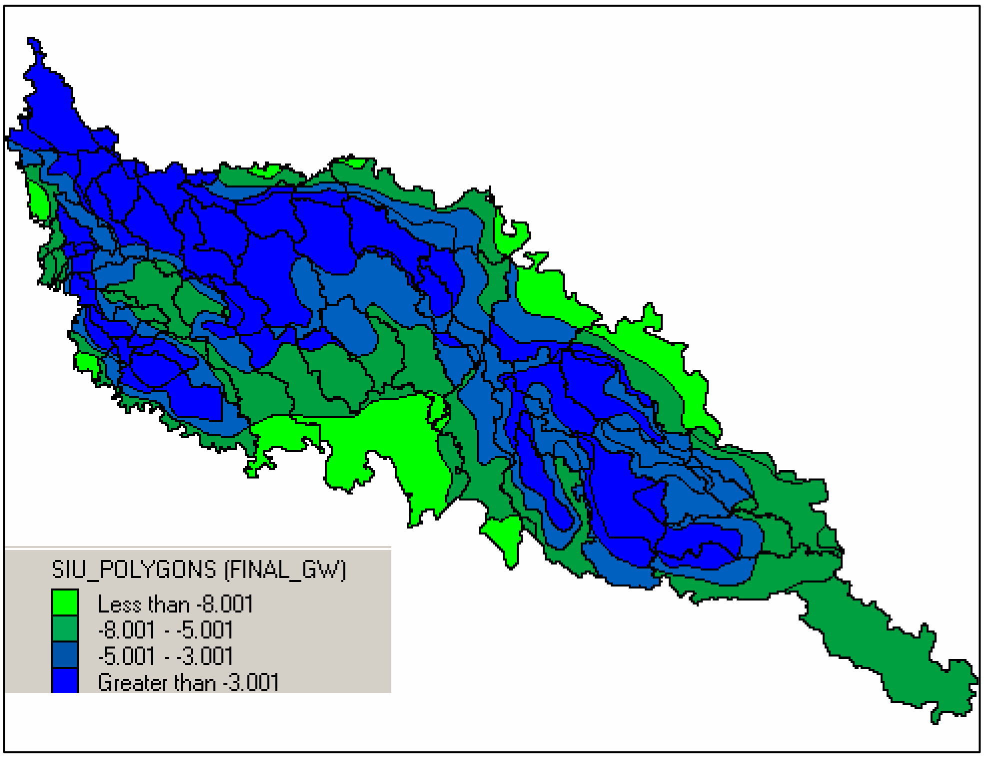
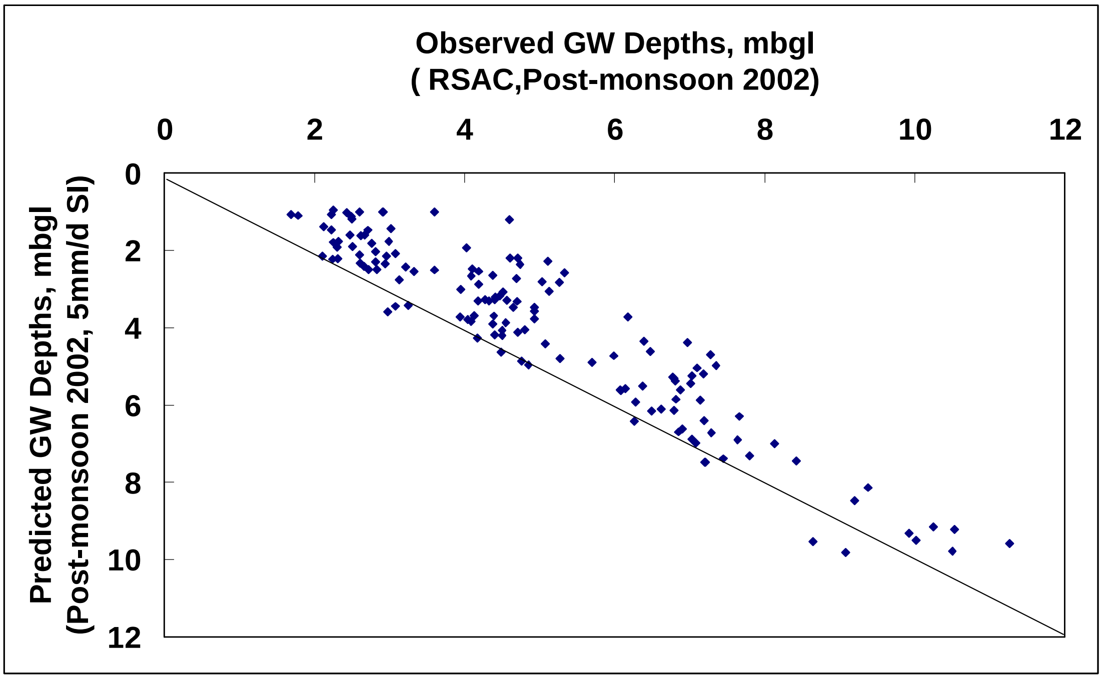


Figure 33- Scatter plot of GW Depths for Base Case and 5mm/day Saturated Infiltration



Similarly, the sensitivity analyses for rainfall, evapotranspiration, canal infrastructure data (canal capacities), drainage reuse, canal conveyance efficiency etc. The model results are sensitive to rainfall, evapotranspiration, canal infrastructure data whereas they are comparatively less sensitive to the drainage reuse and conveyance efficiency. Major issues have been identified with some of thes data as part of the data review which are discussed in Appendix A. Most of these data are primary data not only for the water resources planning but also for operations. Therefore, review of current monitoring network and quality assurance procedures would be highly desirable.

iii Canal Seepage

The revised Sharda Sahayak report suggests the canal seepage rates as 2.5 cusecs for monsoon months and 5 cusecs for non-monsoon months per million sq. ft. wetted area. These values have been used in the model. However, Ministry of Irrigation recommends that a value of 1 cusec per million sq. ft wetted area is used for all design considerations. Meanwhile, in certain sections of Sharda Sahayak Project, IRI Roorkee measurements suggest much higher values (Sharda Sahayak 1985). As a result, the variations are significant among these values from different sources. For this reason, the analyses have been carried out to assess the model sensitivity with respect to this parameter, considering two values 1 cusec and 7.5 cusecs per million sq. ft. wetted area irrespective of wet or dry months.

Figure 34 clearly demonstrates the effect of canal seepage rates on the groundwater depths. Depths to GW with higher seepage rate of 7.5 cusecs/ million sq ft wetted area are much shallower in comparison with those with lower seepage rate of 1 cusecs/ million sq ft wetted area. This suggests that the model is sensitive to the canal seepage rate. For this reason, a more detailed investigation is required to determine the parameter. However, from Figure 35 which represents the depths to GW maps for two different seepage rates, it is clear that the extent of severely water-logged areas (0-3 mbgl) is not much different in two cases. This provides an important observation that the water-logging is predominantly because of canal seepage and possibly, excessive canal water use near the canal. This can be corrected only with conjunctive use.

Figure 34- Comparison of depths to GW due to different seepage rates

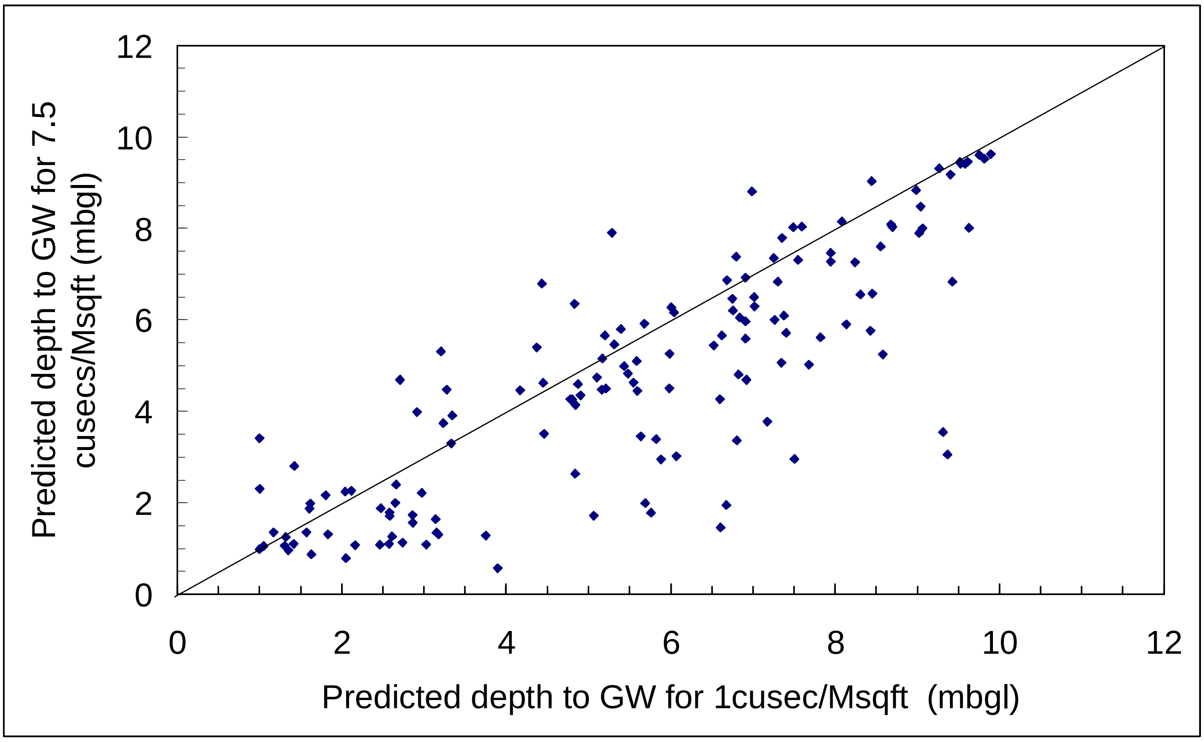
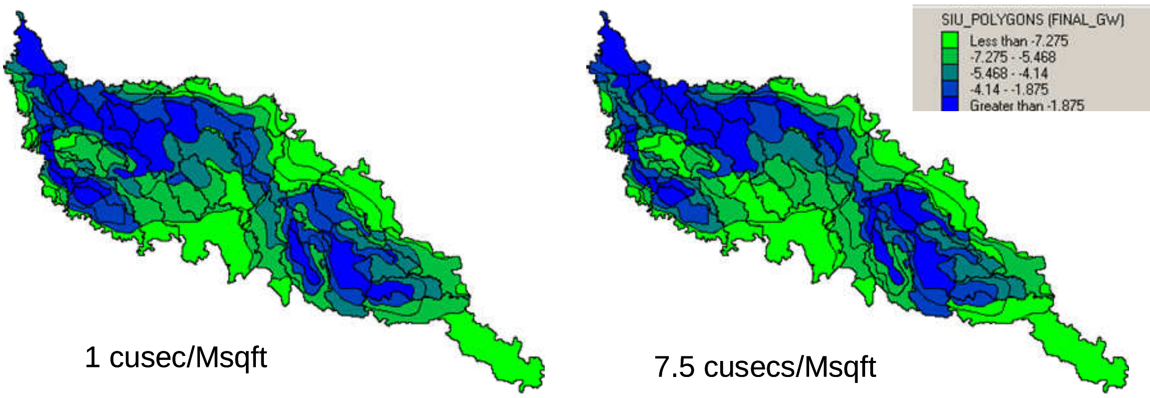


Figure 35- Comparison of GW depth maps for different seepage rates



2.5 CONCLUSIONS

The following conclusions can be drawn from the analyses in the preceding sections:

- The iCROP model simulation of all hydrological processes and historic canal operation is realistic and consistent;

- The MSBs close to main canal shows excessive water-logging due to canal seepage as well as use of canal water under the current canal operation policy;
- The MSBs at the tail ends of the canals, where canal water hardly reaches under the current canal operation, show a groundwater depleting trend because of unsustainable groundwater use;
- The model predictions can be made even more realistic by use of most up-to-date groundwater, rainfall and canal discharge data;
- More detailed site-specific investigation of input parameters such as specific yield, saturated infiltration, canal seepage, canal capacities etc is required for accurate estimation of parameters;
- The model calibration and validation must be carried out on a regular basis as more data and/or accurate data is available.

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