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Hydrological modeling of a major irrigation command using MIKE SHE

M. L. SREEVIDYA, A. MISHRA, R. SINGH and N. S. RAGHUWANSHI
Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal –721302, India

Abstract
A physically based distributed hydrological model MIKE SHE, is applied to the command of the Right Bank Main Canal (RBMC) system of Kangsabati irrigation project (a major irrigation project in West Bengal) to accurately simulate the hydrologic process. Simulation is carried out from April 1, 1997 to November 1, 1997 and the water balance of the command is computed. Depth of irrigation water applied in different canal reaches is obtained from the result of MIKE 11 hydraulic model simulation and added to rainfall to represent precipitation input in the MIKE SHE. The model is calibrated by comparing the post-monsoon observed and simulated groundwater levels at five different locations in the command. A close agreement is found between the observed and simulated groundwater levels. Saturated hydraulic conductivity (Ks) and exponent (n) of the hydraulic conductivity function are considered as calibration parameters. Variation in groundwater levels and soil moisture content in the unsaturated zone along the length of the canal is studied. Sensitivity of the calibration parameters towards simulated groundwater levels and other components of water balance are also studied. The saturated hydraulic conductivity (Ks) is found to be more sensitive than the exponent (n). The results illustrate the applicability of a comprehensive hydrological modeling system to a major irrigation command.

INTRODUCTION

Irrigation development has been accepted as a major factor in increasing agricultural production. In India, canal irrigation by major and medium irrigation projects accounts for about 25 million ha of irrigated area. Despite substantial investments, the agricultural productivity of these projects has remained low (Planning Commission, 1985). Furthermore, the irrigation sector is characterized by low average yields by as little as half those obtained else where in Asia (IRRI, 1986); a low average cropping intensity of 130%; a 10% gap between irrigation potential created and area actually irrigated.

Typically, in a major irrigation project, water is delivered to farmers through a large network of irrigation canals. Ensuring reliable canal releases and matching these with the crop water demands have been found difficult, with the result that crops do not receive right quantities of water at the proper time and potential yields are not realized. In addition, in several irrigation projects non-uniform distribution of water perpetuate to rise in ground water table, water logging, increased in salinity and low irrigation intensities. Thus, the study on the effect of irrigation on the hydrological regime of a command is of utmost importance.

Hydrological simulation models are considered as useful tool in predicting responses of hydrological systems. Numerous hydrological models have been developed in the past, but traditional models are largely 'lumped', i.e., they refer to the spatially averaged condition of the entire command (Crawford and Linsey, 1963; Sittner et al., 1969; Holtan et al., 1975; Sugawara et al., 1984). Further more, their parameters have no direct physical meaning and cannot easily be derived from measurable properties of the command. To overcome such problems a more sophisticated approach to hydrological modeling is made to develop physically based distributed models (Beven et al., 1984; Rogers et al., 1985), which have the potential to overcome many of the deficiencies associated with simple approaches. Such models use parameters related directly to the physical characteristics of the command viz., topography, soil, vegetation and geology; and spatial variability in both physical characteristic and meteorological conditions. MIKE SHE (Refsgaard and Storm, 1995), a major development in this direction, is a comprehensive, distributed, and physically based modeling system capable of simulating all major hydrological processes in the land phase of hydrological cycle. MIKE SHE has been widely adopted for catchment studies (Bathurst, 1986; Refsgaard et al., 1992; Jain et al., 1992; Singh et al., 1999). Consequently, its use is gaining importance in the field of irrigation planning and management (Lohani et al., 1993; Singh et al., 1997). An important aspect concerning irrigation management is the need to simulate the hydrological processes of the command as accurately as possible to improve operational irrigation practices. In the present study, MIKE SHE has been applied to the RBMC command for simulating the hydrological water balance taking into account canal irrigation water. The model is calibrated and sensitivity analysis of different model parameters is also performed.

METHODOLOGY

Description of MIKE SHE

MIKE SHE is a comprehensive deterministic, distributed and physically based modeling system capable of describing the entire land phase of the hydrological cycle in a given command. The model area is discretized by two analogous horizontals–grid square networks for surface and ground water flow components. These are linked by vertical column of nodes at each grid representing the unsaturated zone. A finite differential solution of the partial differential equations, describing the processes of overland and channel flow, unsaturated and saturated flow, interception and evapotranspiration, is used for water movement modeling. A brief description of the components of MIKE SHE is given in the following. More detailed description can be seen in Abbott et al. (1986 a, b) and Refsgaard and Storm (1995).

Interception and evapotranspiration component : The interception process is modeled by introducing interception storage expressed as a function of leaf area index (Jensen 1983). The actual evapotranspiration is calculated based on the potential evapotranspiration using the Kristensen and Jensen model (Kristensen and Jensen 1975). The actual evapotranspiration rate, consisting of the sum of actual transpiration and soil evaporation, is further adjusted according to vegetation density and water content in the root zone. Actual transpiration depends on the density of the crop green material, described by the leaf area index, LAI, soil moisture content in the root zone and the root density.

Overland and channel flow component : The overland flow process is simulated in each grid square by solving the two dimensional diffusive wave approximations of Saint-Venant equations. For stream network channel flow, the one-dimensional form of the equation is solved in a separate node system located along boundaries of the grid squares.

Unsaturated zone component : Soil moisture distribution in the unsaturated zone is calculated by solving the one dimensional Richard's equation. Extraction of moisture for transpiration and soil evaporation is introduced via sink terms at the node points in the root zone. Infiltration rates are found by the upper boundary that may be either flux controlled or head controlled. The lowest node point included in the finite difference scheme depends on the phreatic surface level, and allowance is made for the unsaturated zone to disappear in cases where the phreatic surface rises to the ground water surface.

Saturated zone component : The saturated zone (SZ) component of MIKE SHE WM calculates the saturated subsurface flow in the catchment. MIKE SHE allows for a fully three-dimensional flow in a heterogeneous aquifer with shifting conditions between unconfined and confined conditions. The spatial and temporal variations of the dependent variable (the hydraulic head) is described mathematically by the non-linear Boussinesq equation and solved numerically by an iterative finite difference technique. The equations are nonlinear in the case of unconfined flow due to the presence of free ground water table. The storage coefficient is not a constant but will switch between two values, one for confined flow another for unconfined. Thus abrupt changes of two orders of magnitude can be expected in this parameter.

GENERAL DESCRIPTION OF THE STUDY AREA AND DATA AVAILABILITY

The Right Bank Main Canal (RBMC) system of Kangsabati command area, located in western part of West Bengal is selected as the study area. It includes 3 blocks of Bankura and 10 blocks of Midnapur districts in the state of West Bengal. Kangsabati reservoir receives its supply from river Kangsabati and its tributary Kumari. It supplies water to two main canal systems namely, Right Bank main Canal system (RBMC) and Left Bank Feeder Canal (LBFC). Total length of RBMC canal system is about 137 km and command area is about 88,867 ha. The RBMC system consists of four main canals, namely, Right Bank Main Canal (RBMC), Bhairabanki Tarafeni Main Canal (BTMC), Tarafeni South Main Canal North (TSMC (N)), and Tarafeni South Main Canal South (TSMC (S)). The designed discharge of the RBMC head regulator is 79.18 m^3/sec. The average annual rainfall in the command area is about 1400 mm. Major agricultural crops are paddy during Kharif season and wheat, potato and mustard during Rabi. Data on various aspects of the canal and its command are collected from the Irrigation and Waterways Department, Govt. of West Bengal. Groundwater data are collected from the office of the Central Ground Water Board, Calcutta. The soil survey map of the command is obtained from the National Bureau of Soil Survey and Land Use Planning, Research Station, Calcutta. The climatic data such as daily rainfall and pan evaporation of three meteorological stations are obtained from the Department of Agriculture, Govt. of West Bengal.

Model setup of MIKE SHE WM is prepared for the RBMC command. The MIKE 11 hydraulic model simulated flow data are added to the precipitation time series data file. While preparing the time series file climatic data of three meteorological stations (Bankura, Jhargram and Kharagpur) are considered.

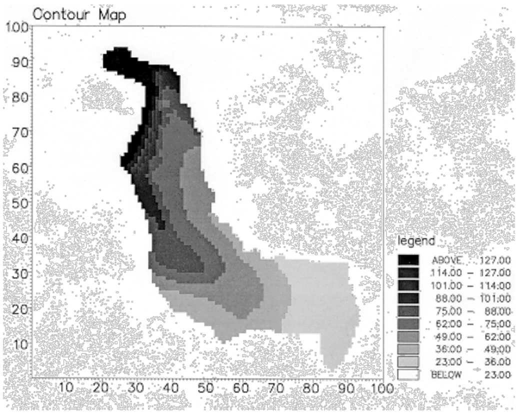

Figure 1. Contour map of the RBMC command.

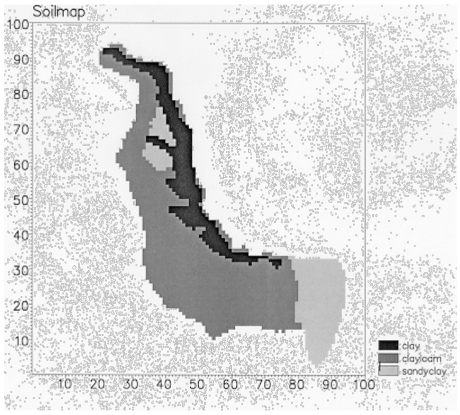

Figure 2. Soil map of the RBMC command.

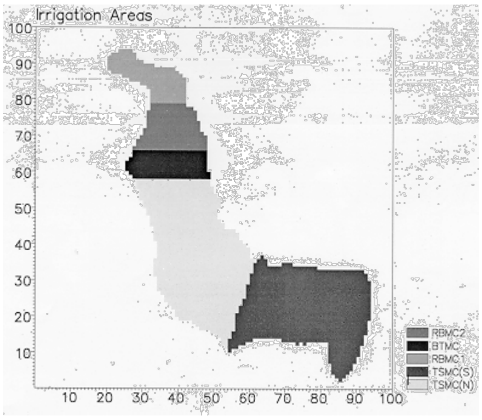

Figure 3. Irrigation and rainfall input polygons.

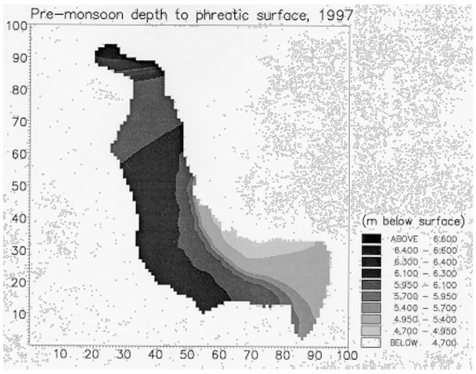

Figure 4. Pre-monsoon groundwater table depth.

Fig. 1 shows the topographic map of the area. A smooth interpolation is made for the contour levels over the entire area. An elevation drop of about 104 m is observed over the entire length of RBMC system. A gradual decline in the elevation of the command from upstream to downstream is seen. Fig. 2 shows the soil type distribution map of the area. Three major types of soils, namely, clay, clay loam and sandy clay are found in the command. Clay loam is the predominant soil of the command. Tail end of the canal system is dominated by sandy clay soil. Fig. 3 illustrates the delineation of the command area in to different polygons having different total applied water depth (sum of irrigation and rainfall). Table 1 gives total irrigation and rainfall input for head reach, middle reach and tail reach of the command. Although rainfall is almost same for all three reaches, tail reach receives quite less amount of irrigation than the head and middle reaches. Thus, uneven distribution of irrigation input over space is clearly noticed. Fig. 4 shows the depth to the phreatic surface from the ground level for the month of April, 1997. Water table depths vary from about 6.66 m at the head reach to about 4.74 m at the tail reach. A gradual reduction in depth to phreatic surface is observed from upstream to downstream side. Fig. 5 depicts the location of 5 observation wells in the command, which are more or less evenly located in the command.

Table 1. Total rainfall and irrigation inputs for different reaches.

Reach	Rainfall (cm)	Irrigation (cm)	Irrigation + Rainfall (cm)
Head reach	105.62	123.21	228.83
Middle reach	120.38	76.97	197.35
Tail reach	96.77	26.78	123.55

The pre- and post-monsoon groundwater levels at five different locations in the command of the RBMC system are used in calibrating the model. Pre-monsoon (April month) groundwater level is used as input to the model, and simulation is done up to post monsoon period (November) to compare the observed and simulated values of groundwater table depths at chosen locations. Calibration is done for the year 1997. During the process of calibration, saturated hydraulic conductivity (Ks) and exponent (n) in the hydraulic conductivity function are adjusted to obtain a close matching between observed and simulated post monsoon water table depths.

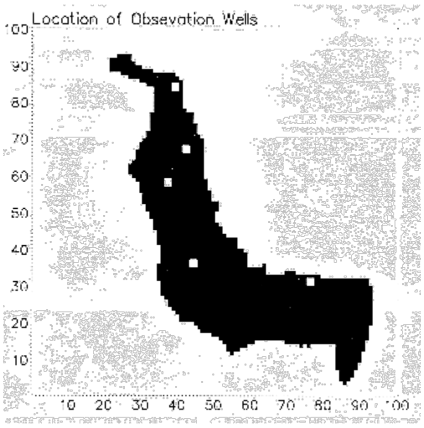

Figure 5. Location of observation wells.

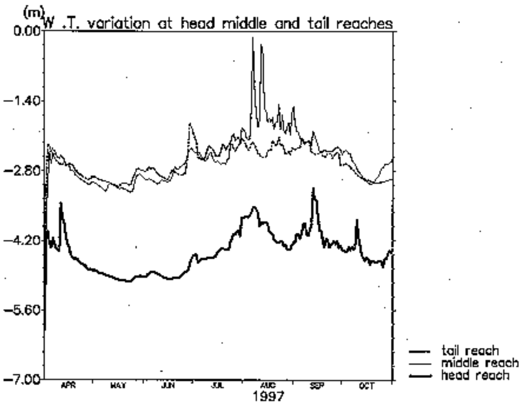

Figure 6. Groundwater level fluctuation in different reaches.

RESULTS AND DISCUSSION

Model Calibration

Table 2 presents the final calibrated values of saturated hydraulic conductivity 'Ks' and exponent in the hydraulic conductivity function 'n' for all the soil types. Observed and simulated post-monsoon groundwater levels for the selected five observation wells are shown in Table 3. It is found that observed values are in good agreement with the simulated values at all locations except at Jadavnagar and Rauthkanda. Jadavnagar is in clay soil having located at an elevation of about 68.4 m, where as, Rauthkanda is in sandy clay soil type having an elevation of 70.25 m. However, in other points, having higher elevation (Basudevpur, 90.10 m) and lower elevation (Pirakata, 30.45 m) a good match between observed and simulated values is observed. Hence, high residuals at these two points are not due to models' inability to simulate any general flow pattern occurring in the command, but due to some local variations in soil hydro-geological properties at these specific locations which have not been properly addressed while setting up the model.

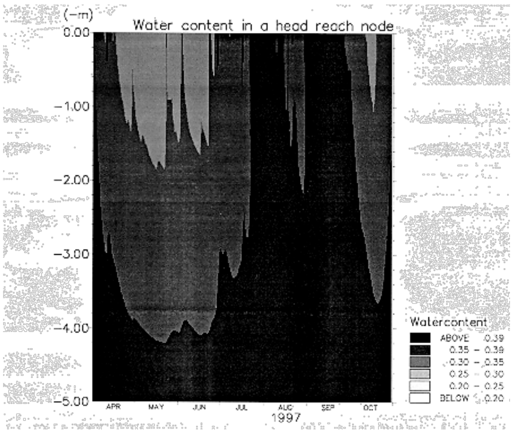

Figure 7. Water content in head reach node.

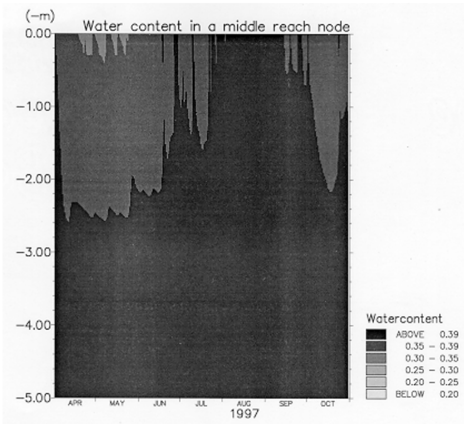

Figure 8. Water content in middle reach node.

Table 2. Calibrated soil parameters.

Soil Type	Saturated Hydraulic Conductivity (m/s) * 10^{-7}	Exponent 'n'
Clay (U)*	2.97	1.84
Clay (L)*	1.67	2.00
Clay loam (U)*	8.33	1.70
Clay loam (L)*	8.00	1.40
Sandy clay (U)*	6.00	1.90
Sandy clay (L)*	5.55	1.10

∗U = Upper soil layer
∗L = Lower soil layer

Table 3. Observed and simulated post-monsoon ground water table depths.

Observation well		Observed values (m)	Simulated values (m)	Residual (m)
SL. No.	Location			
1	Jadavnagar	3.47	4.42	0.95
2	Basudevpur	4.59	4.44	0.15
3	Rauthkanda	1.25	2.11	0.86
4	Salboni	2.3	2.53	0.23
5	Pirakata	3.04	2.96	0.08

Table 4. Average weekly water balance.

Year Month Day	Accumulated precipitation (mm)	Accumulated actual evapotranspiration (mm)	Water stored on the ground surface (mm)	Deficit in unsaturated zone (mm)	Net outflow from the top layer of saturated zone (mm)	Water balance error (mm)
97 4 1	0	0	0	-149	0	0
97 4 8	22	17	11	-187	26	-6
97 4 15	63	36	23	-239	54	-5
97 4 22	71	53	30	-242	72	-6
97 4 29	88	68	33	-261	76	-5
97 5 6	89	85	34	-260	78	-4
97 5 13	109	102	35	-264	79	-4
97 5 20	121	119	35	-214	80	-2
97 5 27	188	135	36	-221	82	-1
97 6 3	214	154	40	-240	94	3
97 6 10	223	169	45	-235	102	3
97 6 17	244	180	46	-206	105	2
97 6 24	304	192	51	-143	123	5
97 7 1	439	205	64	-177	169	6
97 7 8	487	217	81	-175	222	5
97 7 15	562	229	96	-143	268	6
97 7 22	663	243	112	-106	309	8
97 7 29	795	258	132	-98	374	11
97 8 5	925	276	157	-74	454	15
97 8 12	1133	299	201	-86	567	10
97 8 19	1261	327	207	-105	680	16
97 8 26	1393	349	230	-84	777	8
97 9 2	1555	373	254	-90	875	12
97 9 9	1687	395	280	-111	965	12
97 9 16	1796	417	304	-124	1047	10
97 9 23	1895	443	324	-138	1109	7
97 9 30	1995	472	343	-170	1171	2
97 10 7	2052	495	358	-223	1220	0
97 10 14	2060	522	367	-187	1250	3
97 10 21	2090	549	370	-233	1257	3
97 10 28	2181	574	374	-185	1272	3

Water Balance of the Command

Daily water balance simulation is performed from April 1, 1997 to November 1, 1997. Table 4 shows the weekly water balance sheet of the command. The accumulated actual evapotranspiration is found to be 574 mm out of which about 382 mm occurred in Kharif season (July to October). The deficit in the unsaturated zone varies from 264 mm to 74 mm (a variation of about 190 mm). Initially deficit is more, but later on reduced to 74 mm during mid - August due to onset of irrigation and occurrence of heavy rainfall. During 1997, Kharif irrigation began from July 19th onwards (there were 4 irrigation in total, 19th July to 13th August, 20th August to 13th September, 16th September to 4th October and 18th October to 30th October). During the first and second irrigation, deficit in unsaturated zone is decreased sharply from 175 mm to 74 mm. Deficit has remained almost constant thereafter and shows an increase in the later stages owing to decline in irrigation input and rainfall. This shows that a large portion of input water supply infiltrate into the unsaturated zone during initial part of growing season and joins to soil moisture content causing rise in the ground water table. Other components of water balance are the water stored on ground surface and out flow from saturated zone top layer. The rate of increase of accumulated storage on the ground surface as well as out flow from saturated zone top layer are low initially, and found to be increasing with the advancement of season. It is also seen that the water balance error is limited to 16 mm against the rainfall of 2181 mm, i.e., around 0.7%.

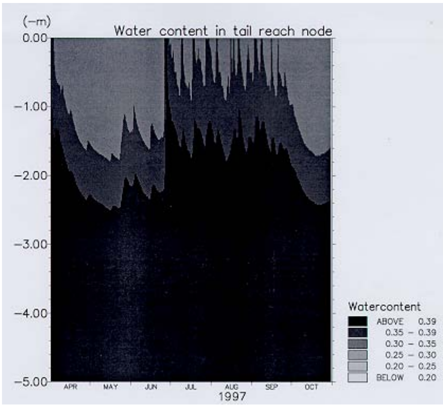

Figure 9. Water content in tail reach node.

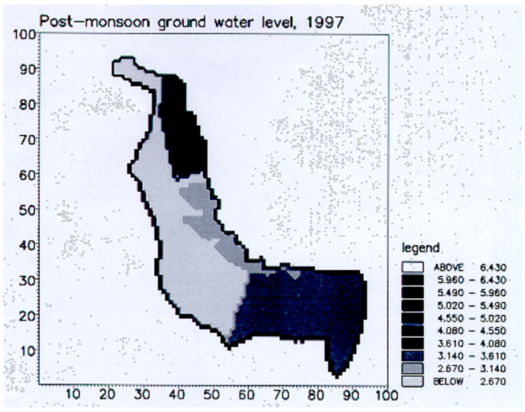

Figure 10. Post-monsoon groundwater table.

Water Table Level Variation

Fig. 6 shows the groundwater table fluctuation at a point in the head, middle and tail reaches of the command for the entire simulation period. Water level in the head reach is always found to be lower than the middle and tail reaches. This is primarily due to the high elevation of the ground surface at the head reach, which is seen from the topographic map of the command (Fig. 1). Thus, the groundwater flow may have followed the topographic gradient. Also the pre- and post-monsoon groundwater levels are deeper for head reach. Middle and tail reaches groundwater levels are similar except for a few days when middle reach water table level reached close to the ground surface. During initial period of simulation water table level of tail reach is slightly higher than middle reach. But with the onset of irrigation, middle reach water table has risen above the tail reach water table establishing the fact of more irrigation and rainfall input to middle reach than tail reach. Peaks in water table levels are showing the effect of irrigation input on water table fluctuation after the beginning of irrigation season. Peaks are more prominent in head and middle reaches compared to the tail reach. There is not much fluctuation in the water table level at the tail reach, which is possibly due to low irrigation input. Total irrigation input for head, middle and tail reaches during Kharif season are 123.21, 76.97 and 26.78 cm, respectively.

Water Content Variation in Unsaturated Zone

Water content at a point in the head, middle and tail reach up to a depth of 5 meter over the simulation period are shown in Figs. 7 through 9, respectively. From these figures it is clear that middle reach has got a better soil moisture status for major portion of the paddy growth period, since the soil moisture status of the root zone is around saturation level. As evident, tail reach has got relatively poor soil moisture status amongst the three reaches (hardly the root zone depth attains the saturation level during the crop growth period), which is possibly due to substantially low irrigation input comparing to head and middle reaches.

Water Table Distribution at the End of the Season

Fig. 10 shows the water table distribution at the end of the season. Final simulated water levels are not showing a smooth pattern. In general, ground water levels are higher towards the downstream side. A patch having low water table is seen in the head reach region. This localized ground water mound is not a true representation of the actual condition, which should have shown a smooth variation. This may be primarily due to inaccuracies in saturated zone definition. There is a need for accurately defining several geological layers and lenses that may occur in the command. Further, spatial variability in saturated zone parameters like specific yield, horizontal and vertical hydraulic conductivity is not considered in this study. In spite of all these shortcomings, there is still a good match between observed and simulated water levels at different observation wells distributed evenly throughout the command. Thus, it is inferred that the simulated post monsoon groundwater level more or less represents the actual groundwater table condition of the command.

Sensitivity Analysis

Sensitivity of the model to both the calibration parameters i.e., saturated hydraulic conductivity (Ks) and exponent (n) in the hydraulic conductivity function is studied. Either of the parameters is varied one at a time for each soil types separately and the effect on the change in ground water table and the final water balance is investigated. The saturated hydraulic conductivity 'Ks' varied from 5.4×10^{-7} to 6.4×10^{-7}, 7.9×10^{-7} to 8.93×10^{-7}, 2.57×10^{-7} to 3.57×10^{-7} m/sec for sandy clay, clay loam and clay soil type, respectively for sensitivity analysis. Similarly the exponent 'n' varied from 1.1 to 2.3, 1.1 to 2.1, and 1.44 to 2.44 for sandy clay, clay loam and clay soil type, respectively. Table 5 shows the results of sensitivity analysis carried out on different model parameters. It is seen that with the increase in 'Ks' value in the unsaturated zone definition, there is an increase in water table level, showing more water getting infiltrated. The effect of change is more prominent for observation point in that particular soil type for which the change has been made. As regards to exponent 'n', variation in water table levels and other water balance components have not shown any definite trend. Water balance components on the whole are not that much sensitive to the changes made in 'Ks' and 'n'. Only recharge to saturated zone has shown an increase and decrease with corresponding change in 'Ks' value for different soils. Thus it can be concluded that 'Ks' is more sensitive than exponent 'n'.

Table 5. Results of sensitivity analysis.

Parameters changed in different soil types						Change in groundwater level			Components of water balance			
Sandy clay		Clay loam		Clay		R* (SC)	B* (CL)	S* (C)				
K 10^{-7} m/s	n	K 10^{-7} m/s	n	K 10^{-7} m/s	n	% change from final cali-brated values			Accu. ET (mm)	Accu. Over-land flow (mm)	Deficit in UZ (mm)	Accu. Recharge to SZ (mm)
6	1.7	8.33	1.9	2.97	1.84	0	0	0	582	379	-186	1283
6.2	1.7	8.33	1.9	2.97	1.84	-2.47	-0.45	-0.44	582	380	-186	1293
6.4	1.7	8.33	1.9	2.97	1.84	-6.57	-0.53	-0.77	581	378	-186	1296
6.6	1.7	8.33	1.9	2.97	1.84	-11.61	-0.69	-1.89	580	379	-187	1298
5.8	1.7	8.33	1.9	2.97	1.84	+2.16	0.00	+0.45	583	381	-186	1288
5.6	1.7	8.33	1.9	2.97	1.84	+4.28	+0.98	+0.54	583	380	-185	1286
5.4	1.7	8.33	1.9	2.97	1.84	+4.41	+1.01	+1.04	582	379	-184	1285
6.0	1.9	8.33	1.9	2.97	1.84	+0.54	+1.28	+0.15	583	380	-185	1296
6.0	2.1	8.33	1.9	2.97	1.84	+2.32	+0.55	+0.14	583	382	-184	1285
6.0	2.3	8.33	1.9	2.97	1.84	+1.99	+0.44	+0.04	581	379	-183	1286
6.0	1.5	8.33	1.9	2.97	1.84	-0.09	+0.52	+0.17	581	379	-187	1293
6.0	1.3	8.33	1.9	2.97	1.84	-0.05	-0.15	+0.08	580	377	-187	1286
6.0	1.1	8.33	1.9	2.97	1.84	+0.18	-0.06	-0.16	580	377	-187	1296
6.0	1.7	8.53	1.9	2.97	1.84	+0.19	-1.95	-0.18	581	379	-187	1293
6.0	1.7	8.73	1.9	2.97	1.84	-0.22	-2.83	-0.91	581	376	-186	1296
6.0	1.7	8.93	1.9	2.97	1.84	+0.04	-5.78	-1.92	580	379	-187	1299
6.0	1.7	8.4	1.9	2.97	1.84	+0.18	+1.25	+0.72	580	379	-187	1285
6.0	1.7	8.2	1.9	2.97	1.84	+0.22	+2.86	+0.41	580	379	-187	1287
6.0	1.7	7.9	1.9	2.97	1.84	-0.05	+3.77	+0.95	580	377	-187	1285
6.0	1.7	8.33	2.1	2.97	1.84	+0.23	+0.53	+0.45	578	377	-186	1284
6.0	1.7	8.33	2.0	2.97	1.84	-0.05	+0.43	+0.27	578	378	-188	1296
6.0	1.7	8.33	1.7	2.97	1.84	+0.26	+0.62	+0.25	581	377	-188	1288
6.0	1.7	8.33	1.5	2.97	1.84	+0.43	+0.06	+0.52	581	378	-187	1291
6.0	1.7	8.33	1.2	2.97	1.84	-0.01	+0.15	-0.44	582	378	-187	1285
6.0	1.7	8.33	1.1	2.97	1.84	-0.43	-0.45	-0.44	583	379	-189	1286
6.0	1.7	8.33	1.9	3.27	1.84	-0.49	-0.14	-0.82	578	379	-187	1293
6.0	1.7	8.33	1.9	3.37	1.84	-0.33	-1.43	-1.90	578	380	-188	1300
6.0	1.7	8.33	1.9	3.57	1.84	-0.78	-0.86	-2.96	578	379	-188	1298
6.0	1.7	8.33	1.9	2.87	1.84	+0.30	+0.11	+0.6	582	379	-186	1297
6.0	1.7	8.33	1.9	2.77	1.84	+0.61	+0.15	+1.99	582	381	-185	1295
6.0	1.7	8.33	1.9	2.57	1.84	+0.12	+1.54	+2.23	582	381	-185	1293
6.0	1.7	8.33	1.9	2.97	2.04	+0.08	+1.02	+0.05	580	379	-187	1297
6.0	1.7	8.33	1.9	2.97	2.24	+0.21	+1.77	+0.06	582	380	-187	1300
6.0	1.7	8.33	1.9	2.97	2.44	+0.71	+2.11	+0.92	582	382	-183	1301
6.0	1.7	8.33	1.9	2.97	1.64	+0.04	+2.21	+0.01	581	383	-184	1301
6.0	1.7	8.33	1.9	2.97	1.44	+0.61	+0.08	+0.03	580	379	-185	1302

R* =Rauthkanda; S* = Salboni; B* = Basudevpur.
SC = Sandy clay: CL = Clay loam; C = Clay.

CONCLUSIONS

The hydrological water balance of RBMC command area of the Kangsabati Irrigation Project, West Bengal is carried out using MIKE SHE. The MIKE 11 simulation derived irrigation depths of different canal reaches alongwith respective rainfall amount are used as precipitation input to the model. The model is calibrated by comparing the post-monsoon ground water levels at five observation wells. Observed and simulated post monsoon water table levels are found to be in close agreement in all these points. The calibrated parameters are saturated hydraulic conductivity ‘Ks’ and exponent ‘n’ in the hydraulic conductivity function. The non-uniformity in rain and irrigation water distribution over head, middle and tail reaches of the command is seen from the groundwater table fluctuation. Simulation results showed the occurrence of low moisture content and evapotranspiration values in tail reach regions. Sensitivity analysis reveals that the saturated hydraulic conductivity is more sensitive than the exponent ‘n'. The study, thus, illustrates the applicability of the comprehensive hydrological modeling system (MIKE SHE) for understanding the effects of irrigation on hydrological regime in a major irrigation command.

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