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Modelling Hydrological Impacts of Continuous Contour Trench Conservation Systems

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ABSTRACT: Continuous Contour Trench (CCT) system, developed for plantation in non-arable lands in low rainfall areas, has been found to be very effective in soil and water conservation, leading to considerably high groundwater recharge. In the present study, physically based distributed hydrological modelling system MIKE SHE was applied to a CCT treated watershed for assessing the impact of the conservation treatment. The MIKE SHE simulated the groundwater levels, soil moisture, surface runoff and peak runoff rates satisfactorily. Further, the model was observed to be capable of simulating the hydrological balance correctly even for the past years, in spite of non-availability of extensive data. The model was found to be sensitive to grid size; vertical and horizontal hydraulic conductivities, Strickler's roughness coefficient for overland flow and vegetation parameter, C_2. The CCT system resulted in 89–100% reduction in surface runoff, 32% increase in groundwater recharge and 30% increase in the plant evapotranspiration with respect to the untreated watershed.

Keywords: Continuous Contour Trench, Hydrological Modelling, Hydrological Water Balance, Watershed Management.

INTRODUCTION

Throughout the world and particularly in India, Watershed Development Programme has evolved as a comprehensive development concept for sustainable and efficient utilization of natural resources for the benefit of the local community with special attention to the rural poor. Watershed development approach aims at optimizing the use of land, water and vegetation in an area to alleviate drought, prevent soil erosion, improve water availability and finally increase food, fodder, fuel and agriculture production on a sustainable basis (Planning Commission, 2001). For planning and development, watersheds are mainly divided into three groups based on the major land use, *viz.*, arable lands, non-arable lands and drainage lines. Presently most of the Watershed Development Programmes focus on the arable lands used for cultivation. However, development of non-arable lands, i.e., public lands in the form of reserve forest, revenue lands and community lands as well as class IV and worse lands (as per Land Use Capability Classification) that are being used by farmers for cultivation, in spite of their low and uncertain productivity, is equally important. Scientifically these lands should get first priority for development as these are mostly situated in upper reaches of the watershed and consequently, runoff from these lands causes major erosion hazard for the arable lands in lower reaches.

For management of non-arable lands, afforestation and pasture development is recommended and adopted since long. For the development of perennial systems under rainfed situations, either soldier planting with small pits or staggered trench layout is usually adopted. However, these systems are found to be less effective in establishing the uniform plantation and arresting runoff, and thus result in low groundwater recharge (Bharad *et al.,* 1993). To overcome the drawbacks of these systems, Continuous Contour Trench (CCT) system for plantation has been developed in the World Bank aided Pilot Watershed Development Project (1983–93), to improve the non-arable lands. Under this Project, a micro-watershed has been developed with CCT layout at Dr. Panjabrao

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Deshmukh *Krishi Vidyapeeth* (Agricultural University), Akola. The system has been found to be very effective in soil and water conservation, leading to considerably high groundwater recharge by reducing surface runoff. It has also been reported that about 25–30 per cent of total area can be brought under irrigation with the conserved groundwater. These conclusions, however, are based on preliminary research, experience and visual observations only, as no scientific hydrological methodology has been adopted while planning, implementation and monitoring. Thus, it is essential to study the detailed hydrological behaviour of such a treated micro-watershed to assess the effectiveness of the conservation treatment.

To study the rainfall-runoff transformation process, several hydrological simulation models have been developed over the years. These include the lumped conceptual models, models incorporating geo-morphological parameters and physically based models (Singh and Woolhiser, 2002). However, for studies dealing with detailed hydrological behaviour of the model area, including effect of land use changes, use of physically based models has been propagated. Such models use parameters related directly to the physical characteristics of the catchments, *viz.*, topography, soil, vegetation and geology; and spatial variability in both physical characteristics and meteorological conditions. Though a few physically based distributed models have been reported, one of the major developments in this field is Systeme Hydrologique Europeen (SHE). MIKE SHE (Refsgaard and Storm, 1995), a further development based on SHE modelling concept, is a deterministic, fully distributed and integrated hydrological modelling system, which can describe the important flow processes in the land phase of the hydrological cycle. It has consistently received top rank in recent reviews as a professional simulation tool for integrated groundwater/surface water studies (Henriksen *et al.*, 2003). However the model is sensitive to different parameters. Bathurst (1986) showed that the model output could be as sensitive to model grid spacing and time step as to the catchment parameters. Peak overland flow and total overland flow were very sensitive to flow resistance parameters, while peak aquifer discharge and total aquifer discharge were sensitive to the horizontal hydraulic conductivity in the saturated zone but vegetation parameters or specific storage coefficient are insignificant (Xevi *et al.*, 1997). Considering the above facts in view, the present research focuses on the application of the physically based distributed modelling system MIKE SHE for the hydrological modelling of a CCT treated watershed, and to evaluate the performance of the Continuous Contour Trench.

MATERIALS AND METHODS

MIKE SHE Model

MIKE SHE is a comprehensive deterministic, distributed and physically based modelling system, capable of describing the entire land phase of the hydrological cycle in a given watershed (Refsgaard and Storm, 1995). The model area is discretized by two analogous horizontal-grid square networks for surface and groundwater flow components. These are linked by vertical column of nodes at each grid representing the unsaturated zone. A finite difference 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 modelling. MIKE SHE modelling system is designed with a modular structure. Its core module is MIKE SHE water movement module (MIKE SHE WM). Other MIKE SHE modules are built around this core module. MIKE SHE WM includes hydrologic process components for unsaturated and saturated ground water flow, overland flow, channel flow, and evapotranspiration. Each component solves a corresponding equation as follows: 3-D Boussinesq Equation for saturated ground water flow, 1-D Richards' Equation for unsaturated ground water flow, 2-D diffusion wave approximation of the Saint Venant equations for overland flow, and 1-D diffusion wave approximation of the Saint Venant equations for river flow. MIKE SHE uses the Kristensen and Jensen method for calculating actual evapotranspiration based on potential evaporation, leaf area index, root depth for each vegetation type, and a set of empirical parameters.

Study Area and Data

Two adjacent micro-watersheds, micro-watershed-1 and 5, having an area of 3.56 ha and 3.59 ha respectively, were selected for this study. These micro-watersheds belong to a 25 ha Model Watershed, developed at Agro-Ecology and Environmental Centre, Central Research Station, Dr. Panjabrao Deshumkh Agricultural University, Akola, Maharashtra, India. The climate of the area is semi-arid, with the normal annual rainfall (mean of 25 years data) of 842.6 mm, 90 per cent of which occurs during South-West monsoon period, i.e., between July and October.

Figure 1 shows the details of the Model Watershed with different micro-watersheds. Micro-watershed-1 (MW-1) has been treated with Continuous Contour Trenches (CCT) since 1987 and has horticultural plantations like Ber (*Zizyphus mauritiana lamk.*), Custard apple (*Anona squamosa*) and Anola (*Emblica officinilis Goerln.*). The adjacent micro-watershed-5 (MW-5) is untreated, and is used occasionally for seasonal agronomical crops. During the period of data monitoring for this study, i.e., 1998 and 1999, the watershed was kept as cultivated fallow. Hereafter, MW-1 and MW-5 are referred to as "Treated" and "Control" watershed respectively.

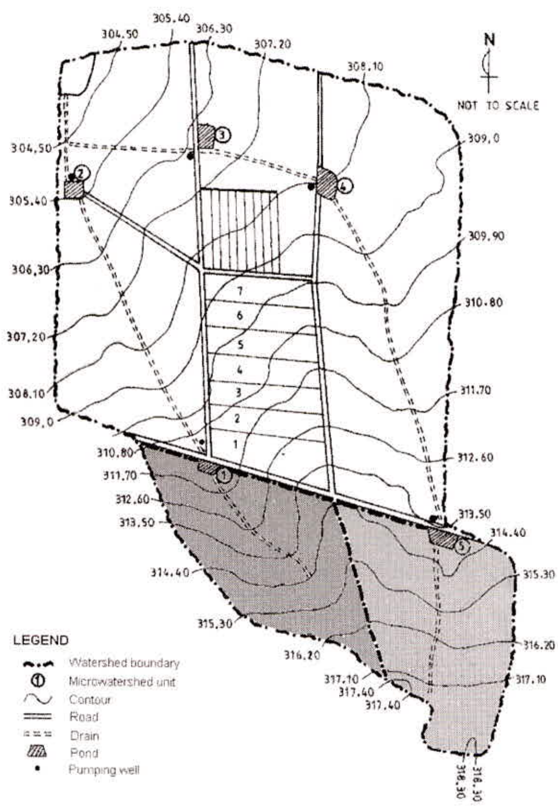


Fig. 1: Study area with selected watersheds

A siphon type automatic raingauge and a standard USWB class A pan evaporimeter were installed in the Model Watershed to monitor daily rainfall and pan evaporation data. The annual rainfalls received during 1998 and 1999 were 808 mm (96% of the normal) and 997.6 mm (118% of the normal) respectively. Data regarding other weather parameters were collected from the Meteorological Observatory of the University.

Soil survey of the watersheds was carried out by traversing, and sites for soil profiling was selected based on variations in soil characteristics and land use. Falling head permeameter was used to determine the saturated hydraulic conductivity of the soils. The soil water retention curve was determined using pressure plate apparatus. Infiltration was determined by the double ring infiltrometer at seven sites within the treated watershed. The average infiltration capacities of the soils were found as 41.47, 32.60 and 20.62 mm h^{-1} under *Custard apple*, *Anola* and *Ber* respectively.

A calibrated neutron probe was used to monitor the weekly volumetric soil moisture content in both watersheds. The monitoring was done at 30, 60, 90, 120 and 150 cm (only at the particular location) depths at each site. Groundwater levels were monitored weekly using the electrical water level indicator in the observation wells.

Pre-fabricated 'H' flumes of 60 cm depth were installed at the outlet of both the watersheds. Automatic stage level recorders were used to monitor the continuous temporal variations of runoff water depth in the flume.

The auger-hole method was used to measure the saturated hydraulic conductivity *in-situ* below water table. Hydraulic conductivity measurements were made in 10 observation wells, i.e., 6 in treated and 4 in control watersheds. The average horizontal hydraulic conductivities were estimated as 0.85 and 0.62 m day^{-1} for the treated and control watersheds respectively.

Specific yield was estimated by evaluating the ground water storage, using the simple hydrologic budget equation. The average specific yields were estimated as 13.33 and 5.66 per cent for the treated and control watersheds respectively.

The bed levels, bank levels and width of the drainage lines were measured at 20 m interval in both watersheds. The length of the drain was found to be 150 and 160 m for the treated and control watersheds respectively, whereas the depth of the drain at the outlet was 0.6 and 0.7 m respectively.

Model Setup, Calibration and Validation

Model setup of MIKE SHE WM was prepared for both control and treated watersheds. For this study, saturated zone, unsaturated zone, evapotranspiration, overland and channel flow; and exchange components were included for the simulation.

MIKE SHE was first calibrated and validated for both treated and control watersheds independently with 1998 and 1999 data. For both watersheds, model was calibrated using 1998 data. Here, the data of pre-monsoon period, i.e., 1 January to 5 June 1998, was used as 'warm up' period (to prepare the "Hot-Start" file in MIKE SHE terminology). Calibration was then performed from 6 June to 31 December 1998. The parameters calibrated were; saturated hydraulic conductivity and the exponent N of the hydraulic conductivity function for different soil layers, roughness coefficients for the overland and channel flows, and vertical and horizontal soil hydraulic conductivities. A quantitative comparison of the spatial and temporal variations between the simulated and observed data was used in the calibration process. The model outputs used for comparison were runoff at the watershed outlet, soil moisture at selected sites and groundwater levels at selected observation wells. The calibrated models were finally validated using the data of 1999. Two dimensionless statistical performance criteria, *viz.*, Modelling Efficiency (ME) and Coefficient of Residual Mass (CRM) were used to evaluate the model performance quantitatively.

The validated MIKE SHE model of treated watershed was used to simulate the hydrological water balance during monsoon periods of 1990, 1991 and 1992 (6 June to 31 October). These years were selected because rainfall in these years was above normal (1990), below normal (1991) and close to normal (1992). Subsequently, the model simulated runoff in different cases was compared with their observed counterparts. This is because during 1990–1992, intensive data monitoring was not prevalent and thus, only observed runoff data were available. Since even runoff data were not available for the control watershed, model simulations for the selected years were confined to treated watershed.

Sensitivity Analysis

The sensitivity analysis of MIKE SHE was performed to discriminate between insensitive and sensitive model parameters. The identification of sensitive parameters can serve as a guideline for field data collection, i.e., the sensitive parameters must be determined (measured) accurately. For this purpose, a basic set of single valued parameters, assumed to represent the average conditions within the catchment, was selected. The parameters were varied once at a time, within their feasible limits, from their calibrated values. The parameters selected for carrying out the sensitivity analysis were: grid size in the catchment file; roughness coefficients in the overland and channel flow component; vertical and horizontal saturated hydraulic conductivities of subsurface soil; and vegetation parameters like C_{int}, C_1, C_2 and C_3. The effect of variations in parameter values was assessed quantitatively on surface runoff at the outlet; peak runoff rate at the outlet; and recharge to the saturated zone.

For this purpose, the calibrated and validated MIKE SHE model for the control watershed was used. This was primarily because runoff data (volume as well as rate), used for quantitative assessment of the variations in parameter values, were available only for the control watershed (as usually there was either nil or negligible runoff in the treated watershed).

RESULTS AND DISCUSSIONS

Calibration and Validation of Models

The MIKE SHE model setup for both treated and control watersheds were calibrated for 6 June to 31 December 1998, and subsequently validated with 1999 data.

Treated Watershed

Figure 2 presents the temporal variation of observed and simulated groundwater levels at the observation well no. 1. As evident, the simulated depths to phreatic surface match the observed depths reasonably well here. Similar results were obtained for observation wells 3 and 5 as well. ME varied between 0.986 and 0.995, whereas CRM statistics remained close to zero. This shows that the simulated groundwater levels match the observed ones quite well. Similarly, comparison of observed and simulated soil moistures, at access tube_1 shows that ME values vary from 0.115 to 0.768, whereas CRM statistics lies between –0.036 and 0.005. Thus, it is obvious that though CRM values are near their optimum, ME ranges from poor to very good (Henriksen *et al.*, 2003). Jayatilaka *et al.* (1998) also reported that obtaining a good match between observed and simulated soil moisture is difficult compared to other variables. However, in spite of slight mismatch between simulated and observed soil moisture at times, the overall results are satisfactory here. Similar results were also obtained for other locations, i.e., at access tube_3 and access tube_5. During the calibration run, the simulated surface runoff in the watershed was nil, which was consistent with the field observation as not a single event of surface runoff occurred during the calibration period, i.e., 6 June 1998 to 31 December 1998. In the field condition, this was due to the presence of recharge trenches in the CCT treated watershed, which was included in the model setup in the form of separated overland flow areas. Above results show that the model calibration was satisfactory as the observed and simulated values of the groundwater levels and soil moisture matched well and the resulting simulated runoff was nil. Also the ME and CRM statistics were acceptable. Consequently, the model setup was considered as calibrated.

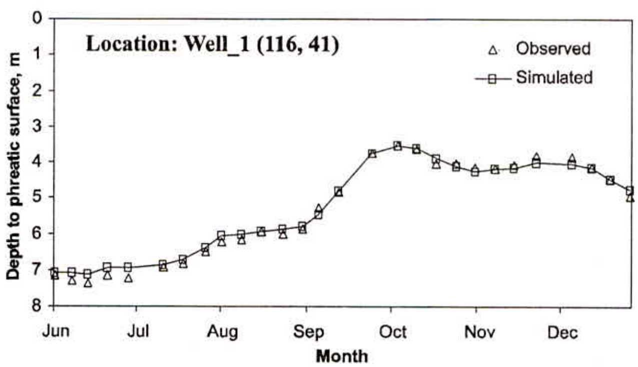


Fig. 2: Temporal variation of observed and simulated phreatic surface depths during calibration (Treated Watershed)

Figure 3 presents the temporal variation of observed and simulated depths to phreatic surface at the observation well no. 2 during validation. As evident, the simulated depths to phreatic surfaces matched the observed depths reasonably well, similar results were obtained for observation well nos. 4 and 6. ME varied from 0.529 to 0.972, whereas CRM statistics remained close to zero. This shows that the simulated groundwater levels match the observed ones well. For soil moisture, ME values varied from 0.368 to 0.852, whereas CRM statistics varied between –0.041 and 0. This shows that simulated and observed soil moistures match reasonably well during validation. In the validation run, runoff occurred in the treated watershed, unlike the calibration case. This was because total rainfall in 1999 was 997 mm, i.e., much above the normal rainfall of 842 mm in the region, and it was still higher than the total rainfall of 808 mm in 1998 (800 mm during calibration period).

Figures 4a and 4b present the temporal variations of observed and simulated surface runoff depths and peak runoff rates at the watershed outlet for the validation case. ME and CRM statistics were estimated as 0.973 and 0.142 respectively, which shows a reasonable good match between observed and simulated runoff depths. However, when observed and simulated peak runoff rates were compared, it was seen that the observed peaks were well simulated for two of the three events, though the peak was grossly overestimated for the third event. Consequently, ME and CRM values were relatively poor at 0.444 and –0.446 respectively. This discrepancy may be due to very low magnitude of runoff rates resulting from the watershed.

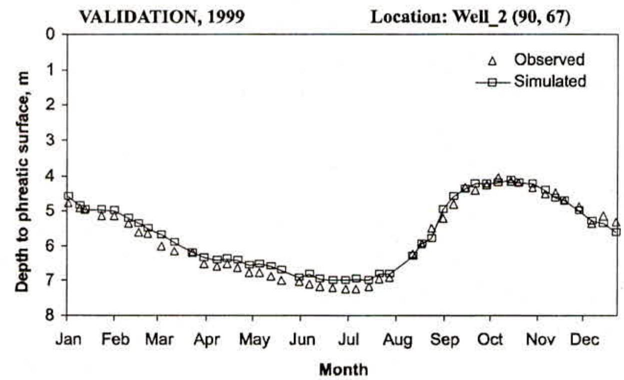
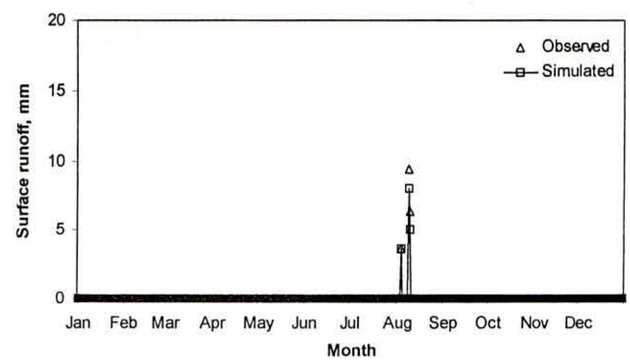
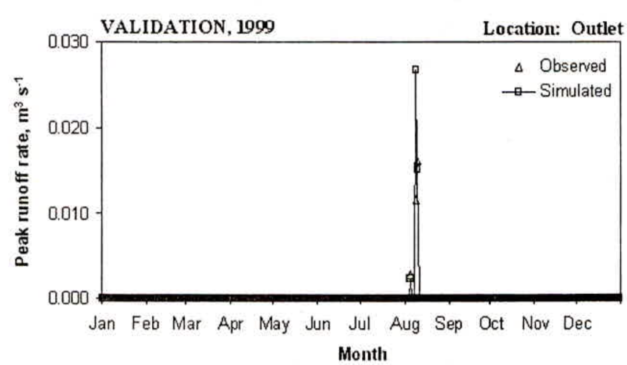


Fig. 3: Temporal variation of observed and simulated phreatic surface depths during validation (Treated Watershed)



(a) Surface runoff



(b) Peak runoff rate

Fig. 4: Temporal variation of observed and simulated runoff in treated watershed during validation

Control Watershed

Figure 5 presents the temporal variation of observed and simulated depths to phreatic surface at the observation well nos. 7. ME and CRM were estimated as 0.976 and 0.988, and –0.039 and 0.001 for observation well nos. 7 and 9 respectively. This shows that in this watershed also the simulated groundwater levels matched the observed ones well. Analysis of simulated soil moisture show close match with the average observed values except at 60 cm depth. Here also ME and CRM followed the trend as was seen in the case of the treated watershed. ME values vary over 0.192–0.666, whereas CRM statistics lies between 0.007–0.041. Figure 6 presents the temporal variations of observed and simulated surface runoff depths at the watershed outlet. As evident, the simulated runoff depths matched the observed runoff depths reasonably well. This is also established by the ME and CRM statistics, which were estimated as 0.984 and –0.106 respectively. However, when observed and simulated peak runoff rates were compared, the observed peaks were over-estimated at times. Consequently, the ME and CRM values were relatively poor at 0.444 and –0.265 respectively. However, this discrepancy may also be due to very low runoff rates resulting from the watershed.

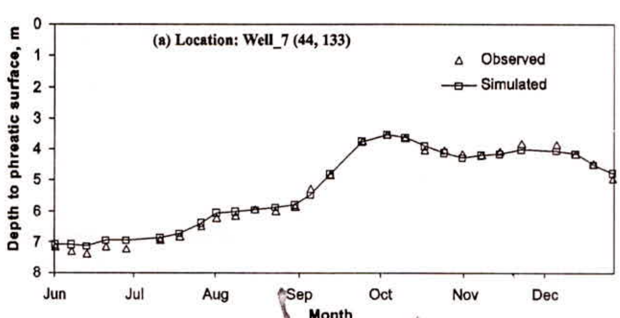


Fig. 5: Comparison between observed and simulated phreatic surface depths during calibration (control watershed)

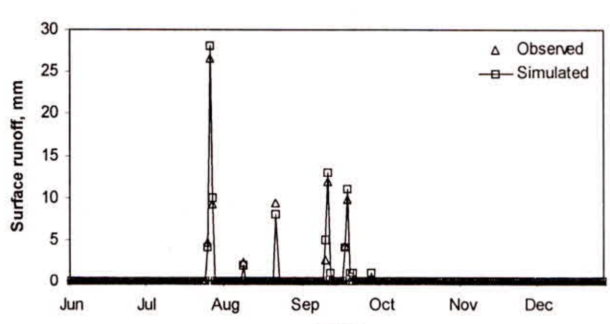


Fig. 6: Temporal variation of observed and simulated surface runoff during calibration (control watershed)

Figure 7 presents the temporal variation of observed and simulated depths to phreatic surface at the observation well no. 8 during validation. ME and CRM statistics were estimated as 0.933 and 0.886, and 0.01 and –0.039 for observation well nos. 8 and 10 respectively. This shows that the simulated groundwater levels matched the observed ones reasonably well. ME and CRM statistics for observed and simulated soil moisture vary from 0.381 to 0.832 and –0.086 to 0.012 respectively. Thus, the results here are similar to those obtained for the treated watershed. The simulated runoff depths and peak runoff rates match the observed value reasonably well (Figure 8).

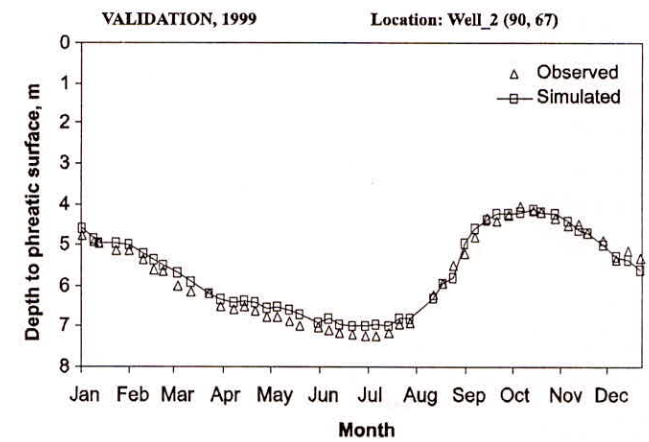
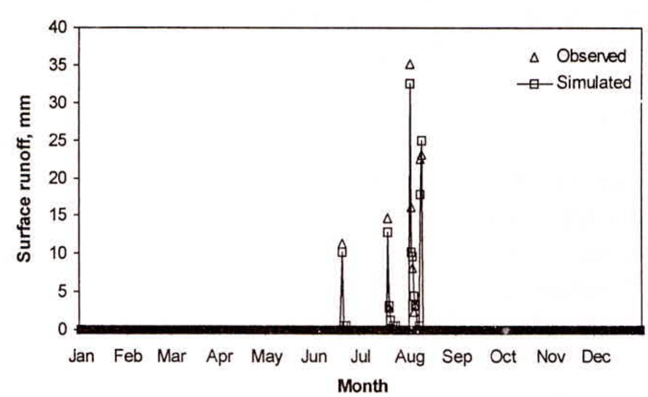
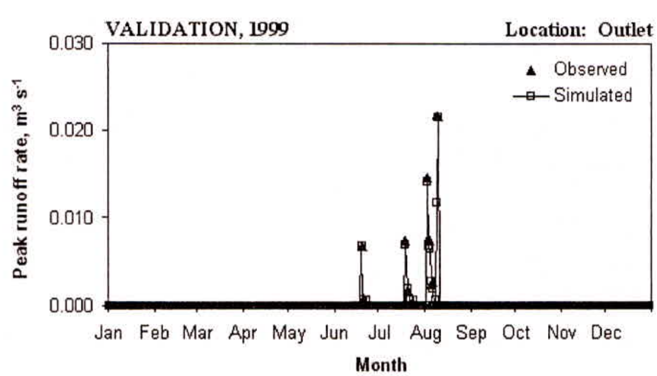


Fig. 7: Temporal variation of observed and simulated phreatic surface depths during validation (control watershed)



(a) Surface runoff



(b) Peak runoff rate

Fig. 8: Temporal variation of observed and simulated runoff in control watershed during validation

This is also established by the ME and CRM statistics for runoff depths, which were estimated as 0.972 and –0.043 respectively. Similarly, the ME and CRM statistics for simulated peak runoff rates, were estimated as 0.923 and 0.106 respectively. The model simulates the peaks well in this case, unlike the calibration case, because the peak values here were quite high due to higher rainfall in the year. This establishes the earlier observation, i.e., in the calibration run for the control watershed and validation run for the treated watershed, that model did not simulate peak runoff rates well due to their low magnitude.

Based on these results, here also it is concluded that the calibrated MIKE SHE model for the control watershed performs well in the validation run and, hence, the results obtained can be confidently used in subsequent analyses.

SENSITIVITY ANALYSIS

Grid Size

Figure 9 presents the effect of variations in structural parameter 'grid size' on CPU-time and per cent change in simulated runoff. As evident, the grid size has a pronounced effect on both CPU-time and simulated runoff, as also reported by Bathurst (1986b) and Xevi *et al.* (1997). The CPU-time decreased from 18 min to about 6 min (for a Pentium-IV personal computer) when grid size was increased from 2 m to 20 m, whereas the simulated runoff increased by about 24%. The effect of varying grid size on simulated runoff shows that the larger grid size alters the catchment characteristics by dampening the effect of variations in soil and vegetation characteristics. Since the reduction in CPU-time is inconsequential for the present generation personal computers, the user has the option to use smaller grid size and consequently aim for higher simulation accuracy.

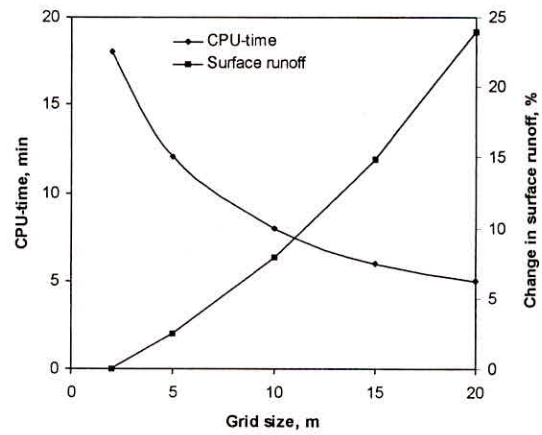


Fig. 9: Effect of grid size on CPU-time and surface run-off

Vertical and Horizontal Saturated Hydraulic Conductivities

Table 1 presents the effect of variations in vertical and horizontal saturated hydraulic conductivities on surface runoff depth, peak runoff rate and groundwater recharge. As evident, the increase in vertical saturated hydraulic conductivity of the subsurface soil results in decrease of both surface runoff depth and peak runoff rate with an associated increase in groundwater recharge. This is because the fluxes through the soil surface are functions of this parameter. Consequently, when the vertical saturated hydraulic conductivity was increased from 2.6×10^{-7} m/s (calibrated value) to 1×10^{-6} m/s, the surface runoff and peak runoff rate decreased by 70.4% and 73.4% respectively, whereas the groundwater recharge increased by 15.6%. However, when this parameter was decreased to

Table 1: Sensitivity to Vertical Saturated Hydraulic Conductivity, Horizontal Saturated Hydraulic Conductivity and Roughness Coefficient

Parameter	*Value*	*Surface Runoff*		*Peak Runoff Rate*		*Groundwater Recharge*	
		Magnitude, mm	*Per cent Increase/ Decrease*	*Magnitude, m s^{-1}*	*Per cent Increase/ Decrease*	*Magnitude, mm*	*Per cent Increase/ Decrease*
Vertical hydraulic saturated conductivity, m s^{-1}	1.0×10^{-6}	26.65	–70.4	0.0021	–73.4	116.8	15.6
	2.6×10^{-7}	89.0	0.0	0.0077	0.0	101.0	0.0
	1.0×10^{-8}	168.7	89.6	0.0118	53.8	89.3	–11.5
Horizontal hydraulic saturated conductivity, m s^{-1}	1.0×10^{-5}	66.2	–25.6	0.0048	–36.8	1363.5	1250.0
	7.2×10^{-6}	89.0	0.0	0.0077	0.0	101.0	0.0
	1.0×10^{-7}	218.2	145.2	0.0146	90.4	–61.1	–160.5
Roughness coefficient (Overland), $m^{1/3}$ s^{-1}	5	8.5	–90.5	0.0010	–86.4	160.2	58.6
	40	89.0	0.0	0.0077	0.0	101.0	0.0
	100	144.6	62.5	0.0119	55.0	78.5	–22.3

1×10^{-8} m/s, the surface runoff and peak runoff rate increased by 89.6% and 53.8% respectively, whereas the groundwater recharge decreased by 11.5%. The horizontal saturated hydraulic conductivity in the saturated zone also has a pronounced effect on the surface runoff and groundwater recharge. When this parameter was increased from 7.2×10^{-6} m/s (calibrated value) to 1×10^{-5} m/s, the surface runoff and peak runoff rate decreased by 25.6% and 36.8% respectively, whereas the groundwater recharge increased by 1250%. Similarly, when this parameter was decreased to 1×10^{-7} m/s, the surface runoff and peak runoff rate increased by 145.2% and 90.4% respectively, whereas the groundwater recharge decreased by 160.5%.

Roughness Coefficient

Table 1 also presents the effect of variations in roughness coefficient (Stickler's) for the overland flow on surface runoff depth and peak runoff rate. As evident, the roughness coefficient of overland flow affects the surface runoff depth and peak runoff rate considerably. This is because when the roughness coefficient increases, the overland flow is routed towards the channel reach at a faster rate, thus increasing the surface runoff and peak runoff rate. Consequently, there was an increase of 62.5% and 55% in the surface runoff depth and peak runoff rate respectively, when this parameter was increased from 40 (calibrated value) to 100. Similarly, when this parameter was decreased from 40 to 5, the surface runoff depth and peak runoff rate decreased by 90.5% and 86.4% respectively. Attempt was also made to study the effect of channel roughness coefficient on the above mentioned variables, but it was found that varying this parameter from its calibrated value of 30 did not significantly affect the considered variables.

Vegetation Parameters

The empirical vegetation parameters C_1, C_2 and C_3 are used to simulate the interception, actual transpiration and soil evaporation. Consequently, these parameters influence the water uptake and soil moisture content, and subsequently the surface runoff volume and peak runoff rate. Table 2 presents the effect of variations in the empirical vegetation parameters C_1, C_2 and C_3 on surface runoff depth and peak runoff rate. It is seen that out of these three parameters, only C_2 affects the considered variables. The effect of C_1 was unclear as both surface runoff depth and peak runoff rate increased when this parameter was either increased or decreased, whereas the affect of C_3 was negligible as there was just 2–3% variation in the considered variables, even when its value was decreased from 20 mm/day (calibrated value) to 1 mm/day. However, when the value of C_2 was decreased from 0.18 (calibrated value) to 0.01, the surface runoff and peak runoff rate increased by 3.7% and 9.5% respectively, whereas these variables decreased by 15.4% and 75.2% respectively, when C_2 was increased to 1. The effect of variation in interception coefficient, C_{int}, was also studied but it was found to have no significant affect on the considered variables. This shows that interception is primarily governed by the leaf area index.

MIKE SHE Simulations

The validated MIKE SHE model of the treated watershed was used to simulate the hydrological water balance during monsoon period, i.e., 6 June to 31 October, 1990 (above normal rainfall), 1991 (below normal rainfall) and 1992 (close to normal rainfall). Table 3 presents the observed and simulated runoff magnitudes for the three cases. As evident, MIKE SHE model performs very well in simulating the runoff magnitude as simulated runoffs are 62 mm and 34 mm in 1990 and 1992, compared to the observed magnitudes

Table 2: Sensitivity to Vegetation Parameters

Parameter	*Value*	*Surface Runoff*		*Peak Runoff Rate*	
		Magnitude, mm	*Percent Increase/Decrease*	*Magnitude, $m^3 s^{-1}$*	*Percent Increase/Decrease*
C_1	0.01	93.094	4.6	0.0082	–73.4
	0.30	89.0	0.0	0.0077	0.0
	1.00	92.738	4.2	0.0088	53.8
C_2	0.01	92.293	3.7	0.0084	–36.8
	0.18	89.0	0.0	0.0077	0.0
	1.00	75.294	–15.4	0.0019	90.4
C_3,	1	86.152	–3.2	0.0075	–2.5
mm day^{-1}	20	89.0	0.0	0.0077	0.0

of 60 mm and 35.3 mm. Moreover, in 1991, i.e., the year with below normal rainfall, both observed and simulated runoffs are nil. As mentioned earlier, only observed and simulated runoff data were matched here because during 1990–1992 intensive data monitoring was not prevalent in the watershed and only observed runoff data were available (Bharad *et al.*, 1993). This shows that in spite of the non-availability of extensive data, the validated model is capable of simulating the hydrological water balance correctly even for the past years.

Table 3: MIKE SHE Simulation Results for Different Types of Rainfall Years

Sr. No.	*Year*	*Rainfall, mm*	*Surface Runoff, mm*	
			Observed	*Simulated*
1.	1990	1120.5	60.0*	62.0
2.	1991	393.0	–	–
3.	1992	835.0	35.3*	34.0

**Source:* Bharad *et al.* (1993)

Evaluation of CCT Performance

The performance of the conservation measure adopted in the treated watershed, i.e., existing CCT, was evaluated by comparing the relevant components of the hydrological cycle of the treated and control watersheds. Figures 9a and 9b present the comparison of selected (relevant) components of the hydrological cycle for treated and control watersheds for 1998 and 1999 respectively. As evident, the CCT adaptation considerably influences the runoff generation in the treated watershed. Consequently, for the treated watershed the runoff was estimated as zero (0% of input rainfall) and 15 mm (1.5% of input rainfall) in 1998 and 1999 respectively, compared to corresponding runoff of 89 mm (11% of input rainfall) and 134 mm (13% of input rainfall) for the control watershed. This shows that CCT results in about 100 and 88.81% reduction in runoff in 1998 and 1999 respectively, leading to moisture conservation.

This is obvious from the enhanced groundwater recharge in the treated watershed in both years, e.g., in 1998 the groundwater recharge for treated and control watersheds was estimated as 155 mm (19.4% of input rainfall) and 101 mm (12.6% of input rainfall), whereas in 1999 the corresponding values were 163 mm (16.3% of input rainfall) and 116 mm (11.6% of input rainfall). Thus, on an average CCT enhanced groundwater recharge by about 42 percent in the treated watershed. This enhanced recharge is over and above the abstraction of 15 mm and 27 mm in the treated watershed during 1998 and 1999 respectively. Furthermore, CCT provides favourable environment for plant growth, which is evident from about 30% increase (448 mm and 589 mm compared to 337 mm and 457 mm in control watershed in 1998 and 1999 respectively) in the plant ET in the treated watershed. Here, it may be noted that ET from control watershed primarily represents soil evaporation as it was kept as cultivated fallow.

SUMMARY

The calibration and validation results of MIKE SHE for both treated and control watersheds show that the model simulates the groundwater levels, soil moisture, surface runoff and peak runoff rates satisfactorily over the model area, with calibration parameters remaining within their reasonable limits. MIKE SHE simulation results for the treated watershed show that the model is capable of simulating the hydrological water balance correctly even for the past years, in spite of the non-availability of extensive data. Sensitivity analysis of the model show that it is sensitive to the structural parameter like gird size, and model parameters like vertical saturated hydraulic conductivity of the sub-surface soil, horizontal saturated hydraulic conductivity in the saturated zone, roughness coefficient for the overland flow and vegetation parameter C_2. Performance evaluation of the existing CCT shows that its adoption results in 89–100 per cent reduction (compared to control watershed) in runoff, leading to moisture conservation and enhanced groundwater recharge to the tune of 47 per cent. CCT also provides favourable environment for plant growth as plant ET enhances by about 30 per cent. The results, therefore, clearly show the advantages of CCT in low rainfall areas as a moisture conservation measure as well as for utilising non-arable lands for plantations and agronomical crops.

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