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A Numerical Simulation Model for Conjunctive Water Use in Basin Irrigated Canal Command Areas

Prabir Biswas[1] · Anirban Dhar[2] · Dhrubajyoti Sen[2]

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Abstract Basin irrigation is a common practice for growing water intensive crops like paddy. Irrigation water, when supplied through a network of canal, is often found to be inadequate to meet the crop water requirement uniformly throughout the irrigated command area. The most deprived are the cultivators of the lower end of the command, who resort to supplementing the crop water requirement by extractions from the ground. This practice is noticeable in irrigation system without a proper canal water distribution schedule and often result in water logging in the upper command regions contrasted with excessively depleted groundwater table in the lower commands. The present contribution attempts to model the conjunctive water use of such a canal irrigated command using physically based numerical sub-models for simulating surface flow, groundwater flow and the interlinking process of moisture movement through the unsaturated zone for a given quantum of supplied water and crop water demand. Individual models are validated to demonstrate their applicability in an integrated framework. Various plausible conjunctive water use scenarios are tested on a hypothetical command area practising basin irrigation to identify the best possible water distribution strategy under given constraints.

Keywords Numerical simulation · Basin irrigation · Conjunctive water use

✉ Anirban Dhar
anirban@civil.iitkgp.ernet.in

Prabir Biswas
prabiriit@gmail.com

Dhrubajyoti Sen
djsen@civil.iitkgp.ernet.in

[1] Water Resources Investigation and Development Department, Government of West Bengal, West Bengal, India

[2] Department of Civil Engineering, IIT Kharagpur Kharagpur, West Bengal, India

1 Introduction

Paddy is the staple food for almost entire south-east Asia (Calpe 2003) and basin irrigation is its preferred cultivation technique. Very low height "bunds" or dykes along the peripheries of basins or cultivation plots help in holding water for longer periods of time and as required by the crop growing within. The application of water in basin irrigated plots is either by direct conveyance of water to the field and/or by the cascade method where the excess water from one field is conveyed to the next, lower in elevation, by gravity (Brouwer et al. 1989). The water entering a basin, either through an unregulated outlet of a watercourse or through an opening in the bund of a donor basin, spreads over the soil surface as it progresses towards the far end of the basin. Simultaneously, water infiltrates into the soil from the wetted area behind the moving front. Inflow into each basin is from openings in the bunds bordering the watercourse in the form of unregulated outlets. As the water enters the basin from the opening(s) in the bunds, a front of water spreads over the soil surface as it progresses towards the far end of the basin. Simultaneously, water infiltrates into the soil from the wetted area behind the moving front. The flow within each basin is largely two-dimensional as the depth of water is much smaller compared to the horizontal extent of the basin. As the water completely fills up a basin, it starts accumulating, or inundating the basin, a phenomenon commonly termed as "ponding". It may be appreciated that as the slope of a basin is generally low, the dynamic nature of the flow assumes importance only during the advancement of the water front. During ponding, which occurs over a longer period of time, only mass conservation plays a role between the inflowing sources and losses due to infiltration and evapotranspiration. The water infiltrating from the basins moves vertically through the unsaturated layer of soil to meet the unconfined groundwater aquifer. This body of water moves laterally, according to the laws of gravity, towards low pressure regions dictated by pumping or other natural boundary conditions. Both water-logging due to over-irrigation or over exploitation of unconfined aquifer by pumping are harmful for command area systems. The present work focuses on quantifying the water balance using a physically based simulation model in a system of conjunctively-irrigated basin-cultivated area, the prime water source of which is through a canal network. Figure 1 shows a typical network of canal branch hierarchy to distribute water to a command area.

The water distributed within a system of canal network is usually decided by Water User Associations on a sharing or rotational basis. However, often the distribution does not remain fair with more water being allocated to the cultivators at the head reaches. The deprivation of the tail-enders, and consequent over extraction of groundwater by these cultivators to meet the deficit in crop-water demand, has been recognised as a prime issue of concern in many canal command areas (DSC 2004). It may be conjectured that the lack of a quantitative water balance scheme for an equitable water distribution may be blamed at least partially on the lack of a scientific evaluation tool for water distribution across the fields. Although several studies are available on conjunctive water use by different techniques, only a few are based on physically based computational approach.

Conjunctive use of surface water and ground water have been investigated by many researchers such as Weller (1991), Matsukawa et al. (1992), Murray-Rust and Vander Velde (1994), Peralta et al. (1995), Emch and Yeh (1998), Belaineh et al. (1999), Barlow et al. (2003), Karamouz et al. (2004), Rao et al. (2004), Erduran et al. (2005), Vedula et al. (2005), Ueda et al. (2005), Deepak and Jat (2006), Sarwar and Eggers (2006), Kaledhonkar and Keshari (2006). Hanson et al. (2010) presented Farm Process (FMP) linked groundwater model with MODFLOW Harbaugh (2005). The model is capable of taking into account several agricultural processes along with infiltration, groundwater flow, and surface water flow

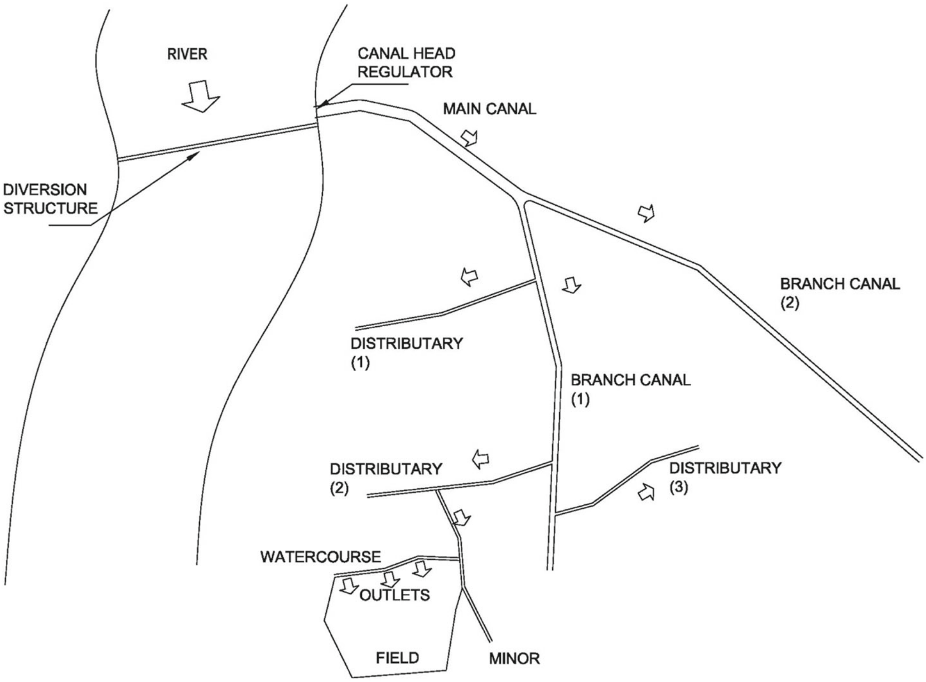

Fig. 1 Canal network system showing the hierarchy of branches

processes. Liu et al. (2013) demonstrated the use of the packages SWAP (Kroes et al. 2008), SWAT (Arnold and Fohrer 2005) and the MODFLOW (Harbaugh and McDonald, 1996) to develop an integrated surface water groundwater combined model for simulation in a canal and well irrigation region in China.

Over-utilisation of the canal water in the upper reaches forces the tail-end cultivators of a command area to irrigate their fields with water extracted from shallow (unconfined) groundwater reservoir. The source of water is primarily recharged in two ways: (a) with the precipitation falling directly over the surface and infiltrating below, and (b) by the infiltrated water from the basins fed by the surface irrigation system of the canal command areas. It is evident that the decision on water distribution in the fields in at least some canal irrigation command areas requires an appropriate rational and scientific tool for evaluating the possible scenarios scientifically. The objective of the present study is to fill in this gap with a mathematical model considering various processes of the irrigation system in a canal irrigated basin-flooded command area as closely as possible. Although the functions and capabilities of the model is demonstrated under hypothetical water distribution scenarios, it may be applied and adapted to real-world situations by incorporating relevant field data.

2 Model Development

The present work provides a deterministic, physically based numerical simulation model (with the appropriate differential equations representing the physical processes) of the various components of water distribution in the field, comprising of the several basins.

The primary source of water considered is the canal system that draws a given discharge from the head-works for a period of time (possibly, as that allocated by the canal management authorities), supplemented by water pumped from the unconfined aquifer system, to fulfil the desired crop water demand. The different components of the simulation model are stated below:

- An inter-basin flooding model replicating the field-to-field surface flooding phenomenon,
- A one-dimensional unsaturated zone model that computes the movement of water through the underlying soil of each basin, and
- A two-dimensional groundwater flow model in an isotropic, homogenous, unconfined aquifer that receives recharging water from the unsaturated zone above and also reacts to pumping of water for irrigation.

The individual models are described briefly in the following sections.

2.1 Basin Flooding Model

The bulk accumulation of water in each basin and its gradual conveyance to neighbouring basins by spilling or overtopping of the miniature dykes (called bunds) bordering the basins are considered in basin flooding model. The basic equation adopted for simulating ponding in the basins is the storage change Eq. 1,

$$A \frac{dh}{dt} = Q \tag{1}$$

where A is the cross-sectional area of the plot (L^2); h is the depth of water (L); t is the time (T), and Q is the "Source Term" (L^3T^{-1}). The Q accounts for the water loss due to infiltration, plant water consumption (evapotranspiration), cascading effect (to adjacent basins), and water received from other sources (e.g., rainfall, canal, groundwater).

The movement of water in the fields, after the flow is allowed from the watercourses through the field outlets, is assumed to fill a basin up to the bund height and then overflow to the next which, in practice, is often initiated through small cuts in the bunds. In the present study shape of the basins is conceptualized as a triangular patch of land with a specified height of border bunds (Fig. 2). The height of the bunds is fixed according to the normal standing depth required for paddy cultivation. The basic governing equations for the water depth variation with time for a single basin (or cell) that receives water from a source and neighbouring cell(s) can be derived (Cunge 1975) as follows Eq. 2,

$$A_i \frac{\Delta z_i}{\Delta t} = P_i + \sum_j Q_{i,j} + \sum_j \frac{\partial Q_{i,j}}{\partial z_i} \Delta z_i + \sum_j \frac{\partial Q_{i,j}}{\partial z_j} \Delta z_j \tag{2}$$

where A_i is the area of cell i, Δz_i is the change of the depth of flow in cell i, $Q_{i,j}$ is the flow discharge from cell i to cell j, P_i is the external input (e.g., rainfall) in cell i, Δt is the time.

The validation of the surface flow simulation model, as described above, is not presented in this article for brevity, but interested readers may find the details in Biswas (2016).

2.2 Unsaturated Zone Model

Unsaturated zone acts as an interface between the surface water and unconfined groundwater. Interaction takes place with the exchange of information in terms of infiltration,

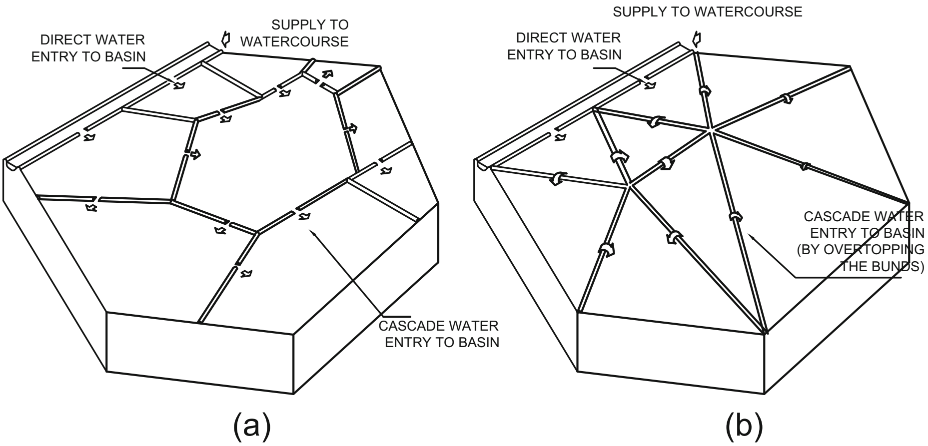

Fig. 2 Basin to basin water transfer by flooding (**a**) In practice; (**b**) Conceptualised flow model

evapotranspiration, and recharge. The integrated model may encounter saturated flow during unsaturated flow calculations. Three standard forms of Richards Equation are possible: a) head based form, b) water content based form, and c) mixed form (Celia et al. 1990). To describe the processes in unsaturated zone pressure head based and mixed form of Richards Equation are used. Head based form is valid for both saturated and unsaturated zone (Haverkamp et al. 1977). However, mixed form is not suitable for saturated zone (Lai and Ogden 2015). The one dimensional presure head based form of Richards Equation is

$$C\left(h\right)\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left[K\left(h\right)\frac{\partial h}{\partial z}-K\left(h\right)\right]+S \tag{3}$$

where h is pressure head (L), $C(h)$ is specific capacity(L^{-1}), $K(h)$ is hydraulic conductivity(L/T), S is source/ sink term, z is the vertical coordinate positive downward (L), t is time(T). The one dimensional mixed form of Richards Equation is

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}\left[K\left(h\right)\frac{\partial h}{\partial z}-K\left(h\right)\right]+S \tag{4}$$

where θ is water content. In integrated model, Richards Equation is solved using a semi-implicit finite volume approach. The soil column below each surface flow cell is divided into a number of one-dimensional unsaturated cells.

2.3 Groundwater Model

Saturated groundwater flow needs to be modelled for effective representation of interaction between surface and subsurface processes (in terms of soil moisture, infiltration, evapotranspiration). Unsaturated zone model supplies recharge information (positive or negative) to the groundwater model. The groundwater model provides information of the time-varying water table, which becomes the bottom boundary condition for the unsaturated zone soil column. Saturated groundwater flow is modelled to simulate two-dimensional lateral water movement in unconfined aquifer. Continuity (mass-balance) equation for two dimensional

(2D) transient groundwater flow in unconfined aquifer for homogenous fluid with constant density is given by the following equations:

$$S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(K_x E \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y E \frac{\partial H}{\partial y}\right) + W \tag{5}$$

where S_y is the Specific Yield, H is the groundwater head (L) and K_x, K_y are the hydraulic conductivity (L/T) in the x- and y- directions respectively, E is the thickness (L) of fully saturated groundwater inside the aquifer, W is the source/sink term (L^3/T) and t is time (T).

2.4 Integrated Model

Finally all individual models are integrated into unified computational framework that executes each individual model in a loosely coupled sequence. The various inputs, logic, computations and linkages between the different components of the model are shown in the flow chart of Fig. 3.

3 Model Validation

Validations are carried out to show the efficacy of individual process models.

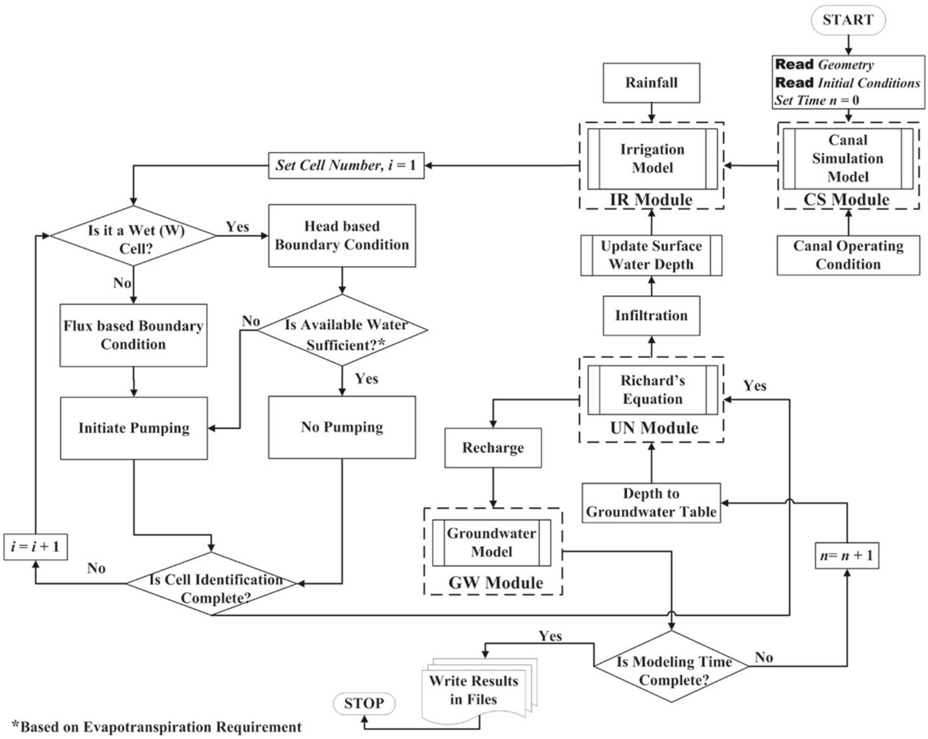

Fig. 3 Flow chart depicting the algorithm of the integrated simulation model

3.1 Basin Flooding Model

The basin flooding model has been validated with the results obtained by the two-dimensional hydrodynamic flow simulation software package, MIKE 21 (DHI 2012), details of which is available in Biswas (2016).

3.2 Unsaturated Zone Model

Performance of the unsaturated zone is evaluated using a head controlled top and bottom boundary condition where a sharp gradient exists due to sudden increase in hydraulic head at soil surface. The model parameters are chosen from Celia et al. (1990) and Aravena and Dussaillant (2009). Starting from an initial condition of $h = -1000$ cm unsaturated profile is generated after 24 h simulation with $h_{top} = -75$ cm and $h_{bottom} = -1000$ cm. Total 100 cells are considered during simulation with $\Delta t = 1$ s. Figure 4 shows a comparison of the predicted values of pressure head computed using the proposed algorithm and existing ones. The plot shows good agreement of the results.

3.3 Groundwater Model

The present groundwater model for two dimensional, isotropic, homogeneous and unconfined aquifer was run for an illustrative area of 1 km^2 including recharge and withdrawal for steady state condition. The domain is divided in MODFLOW with 400 square cells each having an area of 2500 m^2. The same domain is divided into 220 unstructured triangular irregular cells. The boundaries for northern side and southern side are considered to be 15 m and 14 m above a datum respectively. The western side and eastern side boundaries are considered to be no-flow. The specific yield and hydraulic conductivity of the aquifer material are taken as 0.35 and the 1.27 m/day respectively. The present model and MODFLOW

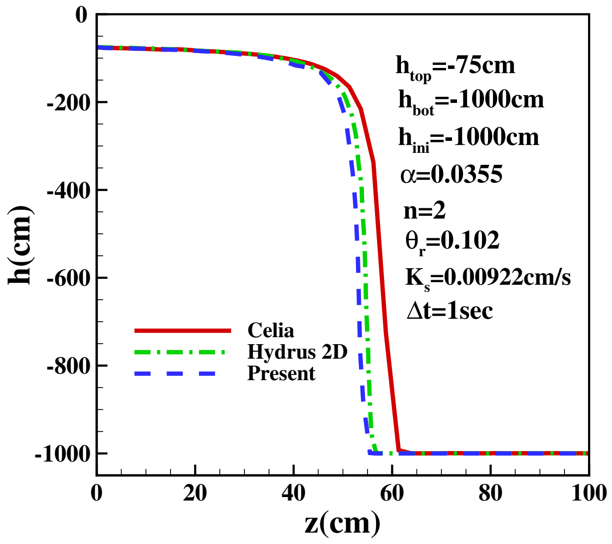

Fig. 4 Results of sample problem considered to validate the present model with the reported results of Celia et al. (1990) and Hydrus 2D result reported in Aravena and Dussaillant (2009)

are simulated for steady state condition considering pumping from five wells, i.e, location A(475 m,475 m), B(725 m,225 m), C(225 m,770 m), D(275 m,225 m) and location E(825 m,865 m) along with an uniform recharge of 100 *mm* per year. Groundwater head at maximum drawdown point simulated by MODFLOW and present model was found to be 10.23 m and 10.28 m respectively. The root mean square error (RMSE) of the simulated heads between present model and MODFLOW is 0.225. Low RMSE value can be seen as validation indicator. Groundwater head contour map for the aforesaid scenario is presented in Fig. 5. Difference in contour values can be attributed to the difference in discretization. The proposed model can be used efficiently for simulating groundwater variations.

4 Application of the Integrated Model

The integrated model (Fig. 3) is applied to simulate four plausible conjunctive use (surface and ground water) scenarios for an illustrative area (Fig. 6). The scenarios are selected to investigate the situations i) the ground water withdrawal is a minimum due to local deprivation of surface water, ii) rise of the water table is alarmingly high due to local over-irrigation. The illustrative area has a central watercourse bifurcating into two branches. The main canal as well as the branches have a series of field outlets on either side which may be opened for allowing water to enter the adjacent cell. The plot measures 3.5 km in length and 2.59 km in width, discrtetised into 348 triangular basin cells. The general land gradient is 0.0001 from West to East. A cross slope is also assumed to exist towards the north and the south (slope 0.00005) from a central median line cutting through the field along the alignment of the main watercourse channel. The isotropic and homogeneous groundwater aquifer (30 m thick) is assumed with (i) specified constant head boundary on the East (26 m) and West (27 m) sides, and (ii) no-flow boundary on the North and South sides. Initially the soil in the unsaturated zone is considered to be dry with an uniform pressure head of -1000 cm

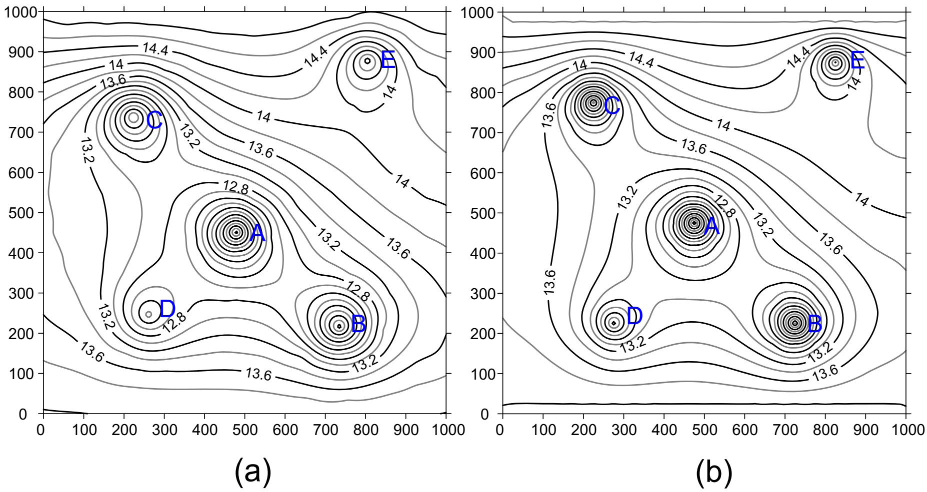

Fig. 5 Groundwater contour map with 0.2 m contour interval of steady state flow (**a**) the present model, and (**b**) MODFLOW for five wells with discharges of 60 m^3/day, 80 m^3/day, 100 m^3/day, 100 m^3/day and 100 m^3/day, and recharge of 100 $mm/year$

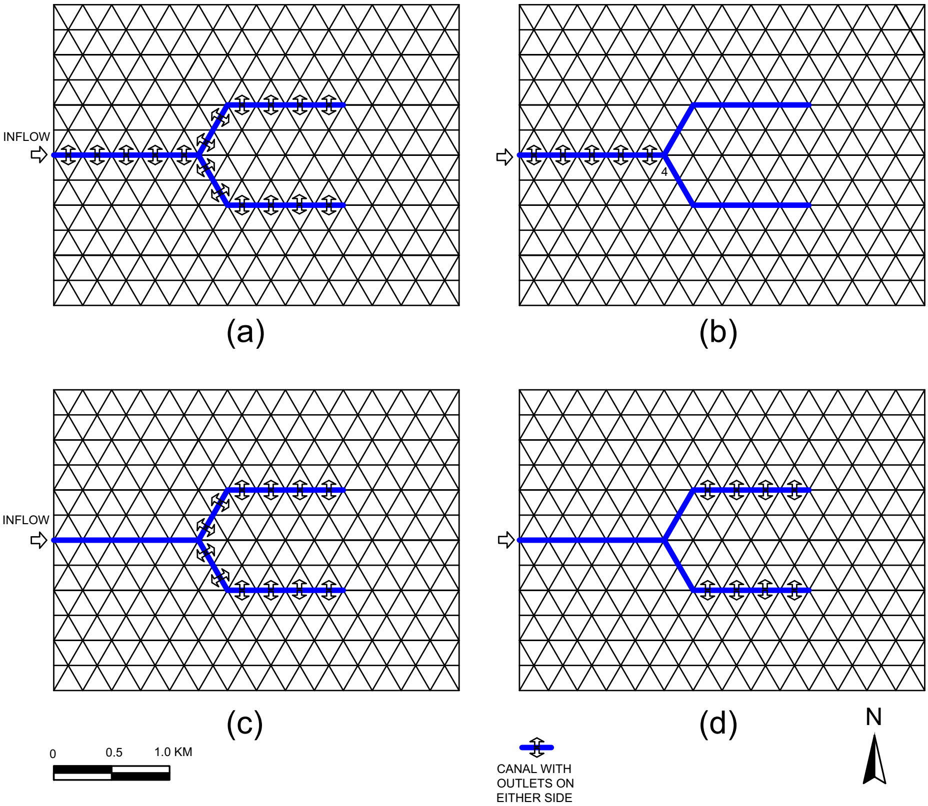

Fig. 6 **a** Canal opening in Scenario I, **b** Canal opening in Scenario II, **c** Canal opening in Scenario III and (**d**) Canal opening in Scenario IV

throughout the vertical soil profile. van Genuchten soil water retention model is considered with the following model parameters, $n = 1.31$ and $\alpha = 0.025$. The saturated and residual water contents are taken as 0.46 and 0.083 respectively. Saturated hydraulic conductivity value for both the unsaturated and saturated zones is 0.37 m/day. Specific yield of the unconfined aquifer is taken as 0.38. The following four possible scenarios are tested:

– All branches of the canal network distribute the available surface water uniformly across the field (Fig. 8a). This is the ideal situation that is desirable in an irrigation command.
– Water being distributed only at the head reaches, with the lower branches being deprived of water (Fig. 8b). This is the usual tail-ender deprivation scenario.
– Water distributed only through the lower branches (Fig. 8c). This is a hypothetical situation, chosen as a complementary scenario to case 2 above.
– Water distributed only through the lower half of the branches (Fig. 8d). This is again a hypothetical situation but chosen to investigate the consequences of providing surface water only at the extreme tail-end (represents an imaginary "head-end deprivation" case).

Table 1 summarises the different conditions prevailing for the four scenarios. As indicated, the total water being delivered at the head of the canal is same in all the four cases, as

Table 1 Different conjunctive water use scenarios

Scenario	Discharge (m^3/s)	Crop water use (mm/day)	Pairs of outlets open in main watercourse	Pairs of open outlets in branch 1	Pairs of open outlets in branch 2	Discharge of each outlet pair (m^3/s)
I	5	6	5	6	6	0.294
II	5	6	5	0	0	1.000
III	5	6	0	6	6	0.417
IV	5	6	0	4	4	0.625

is the crop water requirement (constant over time). The flow through the outlets, however, have been proportionately distributed depending upon the number of outlets in active operation for a given scenario. The integrated model, for all the four scenarios considered are run upto 30 days assuming a typical crop having one month of watering season and with a crop water requirement of 6 mm/day. All the cells in the illustrative field are assumed to be growing the crop uniformly all over.

Indicative results for the spread of surface water across the cells at the end of the 30th day is shown in Fig. 7. The following inferences can be drawn from the obtained results:

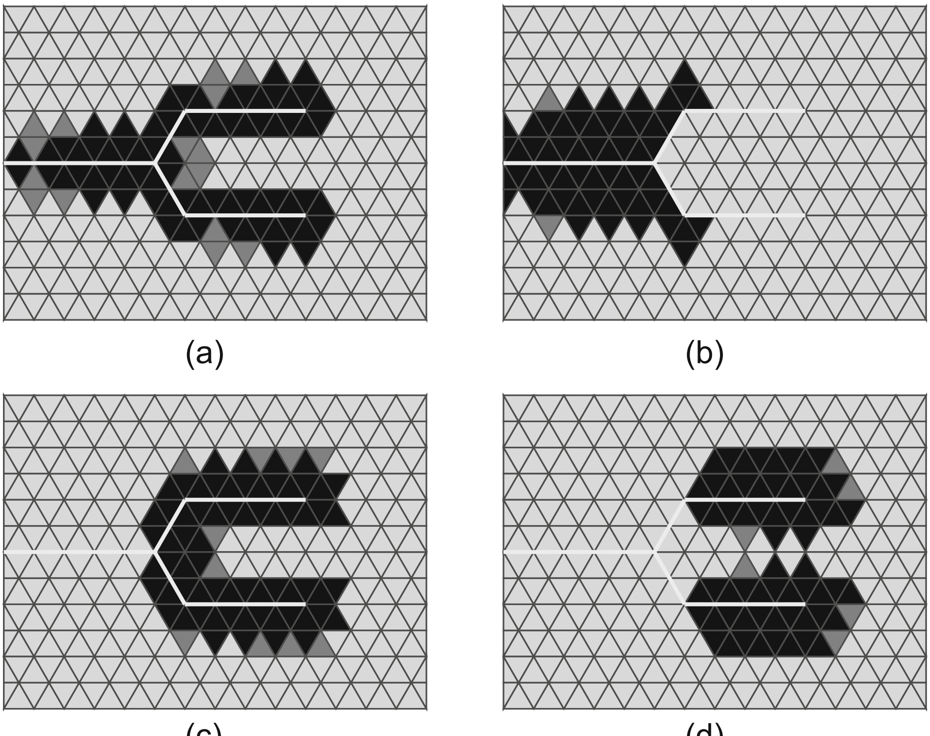

Fig. 7 **a** Surface water spread in Scenario I, **b** Surface water spread in Scenario II, **c** Surface water spread in Scenario III and (**d**) Surface water spread in Scenario IV on 30th Day

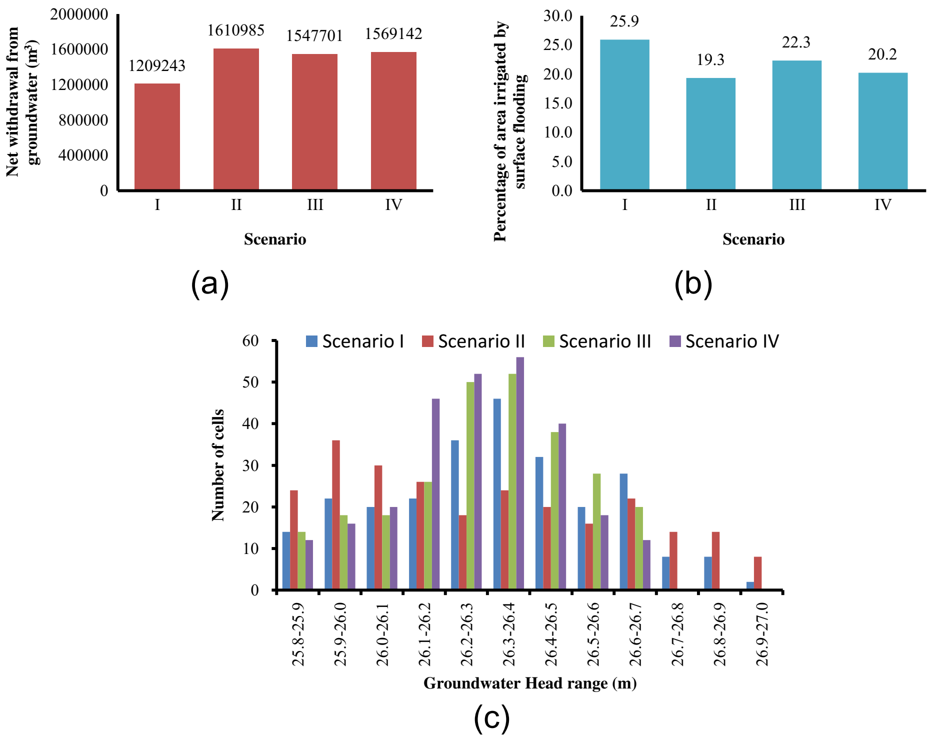

Fig. 8 **a** Net Groundwater Withdrawal for different scenarios upto 30th day, **b** Percentage of area irrigated by surface flooding (steady state condition) under different scenarios, and **c** Distribution of cells for different range of groundwater head for different scenarios on 30th Day

– The number of cells receiving surface water is maximum for Scenario I, i.e., when water is distributed evenly through all the field outlets of the canal and its branches. It is the least when only the upper portion of the canal network is used to distribute water to the fields (Scenario II). This scenario is the typical tail-water deprivation condition faced in many Indian irrigated agricultural command areas. On the other hand, Scenario III, with no water at the head reach but distributed through the lower half of the canal network produces somewhat better distribution of surface water, though not as good as the uniform distribution scenario (Scenario I) (Fig. 8b).
– Considering the initial distribution of ground water heads as evenly distributed amongst the cells between an elevation of 26 and 27 m above the datum, only few cells in the lowest range of head remain untouched initially for all the scenarios. However, at the end of the simulation period (30 days, in this case), it is seen that Scenario I and II (that is, uniform canal flow distribution and tail water deprivation cases, respectively), cause mounding up of water than the other two cases. Of course, Scenario II shows a more severe rise of the free water table, as compared to Scenario I.
– Scenario II is seen to cause depletion of groundwater table in the maximum number of cells, followed by the other three. Scenario III shows the best (uniform) distribution of groundwater head across the cells.

5 Conclusions

An integrated numerical framework combining the simulation models of the principal processes of basin irrigation is demonstrated with runs on an illustrative field that receives water from a canal network with supplementary water provided by an unconfined groundwater source. The study aims at drawing meaningful inferences regarding conjunctive water use in irrigated agriculture. In a given agriculture area practising flood irrigation and one which has the opportunity to utilise water from both surface and groundwater sources, a greater spread of surface irrigation water is possible by distributing the water as much as possible through a network of canal branches. Shorter lengths of the canal system only restricts the region receiving surface water. The rest of the area then needs to be irrigated by ground water sources. The maximum spread of surface water by flooding also ensures the minimum dependence on ground water. Conversely smaller areas served by surface water requires larger withdrawal of ground water. Thus, for the same amount of surface water delivered, a more sustainable solution would be to get it across the fields as much as possible, through a dense network of canal system (branches, sub-branches etc.). There is a tendency by the farmers of the head reaches of the canal network to utilise disproportionate water from the surface water system. This causes the tail end farmers to get deprived of surface water. It is concluded that there is mounding up of water, leading to water logging in the head reaches. In order to compensate the loss, the tail end areas are seen to withdraw excessive ground water leading to a heavy drawdown. These demonstrative results shows applicability of the integrated model for command area systems.

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