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Optimal land and water resources allocation policies for sustainable irrigated agriculture

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ABSTRACT

Conjunctive use of surface water and groundwater is being practiced in many regions of the world to bring more areas under irrigation, increase agricultural production and productivity, and also maintain overall system balance. Successful agricultural water management policies put the physical, hydro-geological, and socio-economic constraints on these integrated water supplies. To sustain these constraints, a linear programming (LP) model has been developed for optimal land and water resources allocation in various sectors of the Hirakud Canal Command, a multi-purpose irrigation project on the river Mahanadi in eastern India. To enhance the decision-taking ability of the Hirakud command area development authority, a menu-driven and user-friendly software has been developed by Visual-Basic that incorporates model-base, data-base, knowledge-base subsystems along with the user-interface. The model-base subsystem includes LP, groundwater balance, and evapotranspiration models. The data-base subsystem includes the meteorological, crop, and water resources data. The knowledge-base subsystem was developed from the knowledge derived from the results of the aforementioned models. Sensitivity analysis of the LP model parameters was performed by varying the parameters that affect the optimal cropping pattern and groundwater allocation. The result indicates that conjunctive use of 87% surface water and 13% groundwater is the sustainable water allocation policy of the command area. The model results also indicate that a 20% deviation in existing cropping pattern is the best alternative as it considered socio-economic need and also meets the entire food demand of the study area.

Introduction

Agricultural production requirements of the burgeoning global population is expected to increase by about 50% in 2050 with the corresponding increase of 2.2 billion people by then (De Fraiture and Wichelns, 2010; Davies and Simonovic, 2011; Singh and Panda, 2012a,b,c; Singh, 2012a; United Nations, 2012). However, this task seems to be challenging in the backdrop of the shrinking land and water resources due to urbanization, contamination, and climate change impacts (Singh, 2014a). In many regions of the world, the surface water availability is just sufficient to meet the crop water demand during the short-span of monsoon season, while, during the non-monsoon season there is large water deficit. For instance, the lower Mahanadi river basin of Odisha State, India faces the problems of waterlogging during monsoon and water scarcity during non-monsoon season (Dash et al., 2010). The potential of fresh quality groundwater can be used to develop conjunctive use management plans for supplementing surface water supplies and to increase agricultural productivity (Khare et al., 2006). The objective of conjunctive use is to increase crop yield, reliability of supply, and general efficiency of a water resources system by combining two or more components of hydrologic cycle when a single source of water is inadequate to meet the demand with sustainability (Singh, 2012b, 2014b). Literature related to conjunctive use planning and management is plentiful and covers a broad spectrum regions (Castle and Lindeborg, 1960; Maknoon and Burges, 1978; Illangasekare et al., 1984; O'Mara, 1988; Onta et al., 1991; Reichard, 1995; Philbrick and Kitanidis, 1998; Watkins and McKinney, 1998; Karamouz et al., 2004; Vedula et al., 2005; Khare et al., 2007; Chiu et al., 2010; Gaur et al., 2011; Lu et al., 2011; Singh and Panda, 2012d).

Eastern India receives 92% of annual rainfall during four monsoon months (June–September). To capture this large quantity of water against flooding in the downstream and to generate hydroelectricity, surface reservoirs and/or barrages are constructed across the river system. But the stored water in surface reservoirs during monsoon season cannot be used productively because

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of relatively low irrigation water demand and fixed canal capacity. Whereas the entire groundwater reservoir is recharged during monsoon season, leading to waterlogging in some areas due to excess recharge against discharge and existing geological formations. During non-monsoon season, the stored groundwater is used to supplement surface water supplies as well as stabilize groundwater level within the permissible limit. Therefore, the need of mathematical modeling is very much imperative in the aforementioned complex water resources systems where some of the components are associated with uncertainties and cannot be predicted/measured accurately. As a result, various models and software are found to be effective and popular tools in the field of water resources management (Simonovic, 1996a,b; Bharatia et al., 2008; Singh, 2013; Singh and Panda, 2013). One of the recent trends of solution of water resources management problems is to aggregate several models into an integrated software that focuses on interaction between the user and data, models and computers (Fredericks et al., 1998; Bouman et al., 2007).

Various researcher have developed models and associated software for application in drought management (Raman et al., 1992), irrigation water management (Prajamwong et al., 1997; Carvallo and Lasdon, 1998; Singh, 2014c), surface water planning in river basin (Ito et al., 2001), water quality management (Arnold and Orlob, 1989), flood warning (Ford, 2001), operation of reservoir systems (Arumugam and Mohan, 1997; Eschenbach et al., 2001; Fallah-Mehdipour et al., 2013), and for conjunctive use management of surface water and groundwater (Sethi et al., 2006; Marques et al., 2010; Singh, 2015).

Optimization models can often provide prescriptive results to water resources problems. Several researchers have applied a number of simulation and optimization models to derive planning and operating strategies for irrigation reservoir systems (Gorantiwar and Smout, 2003) and integrated floodplain management plan. In irrigated agriculture, where various crops are competing for a limited quantity of land and water resources, LP is one of the best tools for optimal allocation of land and water resources (Paudyal and Gupta, 1990; Peralta et al., 1995; Singh et al., 2001; Moradi-Jalal et al., 2007).

In this paper, a menu-driven user-friendly software for optimal land and water resources allocation and management policies has been developed under interseasonal and multicrop situations for the Hirakud canal irrigation system in Odisha State, eastern India so as to cater the need of surface water, groundwater, and agricultural authorities at the systems level. The developed model will enhance the decision-taking ability of the command area concerned. There is very clear interlinking between the three subsystems of the model. The typical phases of software development, i.e., analysis of its requirements, detailed specifications, design, programming, testing, and maintenance are relatively easier than many of the existing software. Particularly, the testing and application of this software is very user friendly.

Materials and methods

Study area

The study area comprises of canal commands of the Mahanadi irrigation project, which is bounded by North latitudes 20°53′–21°36′ and East longitudes 83°25′–84°10′. This is a reservoir based flow irrigation system providing irrigation either fully or partly to five administrative blocks of Sambalpur district, six blocks of Bargarh district, two blocks of Suvarnapur district, and one block of Bolangir district in the State of Odisha, eastern India. The canal command area has been divided into four sectors with ridge canals and major rivers. The elevation of land surface varies from 120 to 180 m above the mean sea level. The study area features sub-humid climatic conditions with an average annual rainfall of 1170 mm. The temperature ranges between a minimum of 10 °C during January to a maximum of 43 °C during May. The average daily evaporation ranges between 3 mm in December–January (winter) to 7 mm in May (summer). The year is divided into two principal cropping seasons, monsoon (*kharif*, June–October) and winter (*rabi*, November–April). Based on food habits of the people, rice is the major crop cultivated during monsoon and winter seasons in about 91 and 44% of the cultivable command area, respectively. Pulses, millets, oilseeds, vegetables, condiments, and sugarcane are also cultivated in small areas. Double paddy cropping in monsoon and winter seasons, undulating topography, supply-based canal operation policy, scarce groundwater withdrawal, canal seepage, waterlogging, and inequitable distribution of surface water (excessive supply in the head and middle reaches and deficit supply at the tail reaches of the canal system) are some of the major land and water resources issues of the study area.

Optimization model formulation

The model consists of an objective function and a set of constraints. The objective is to maximize the net annual return from different crops grown in the command area in different seasons.

$$\text{Max} \quad Z_i = \sum_{i=1}^{4}\sum_{j=1}^{2}\sum_{k=1}^{n} a_{ijk}A_{ijk} - \sum_{i=1}^{4}\sum_{j=1}^{2}(C_{ij}^{SW}SW_{ij} + C_{ij}^{GW}GW_{ij}) \quad (1)$$

where i = index for sectors of command area; j = index for crop growing seasons, j = 1 for monsoon season and j = 2 for the winter season; k = index for crops = 1, 2, ..., n (number of crops); a_{ijk} = net return for crop k in season j of sector i (Rs/ha); A_{ijk} = area allocated to crop k in season j of sector i (ha); C_{ij}^{SW} = unit cost of surface water in season j of sector i (Rs/Mm^3); C_{ij}^{GW} = unit cost of groundwater in season j for sector i (Rs/Mm^3); SW_{ij} = surface water allocated in season j for sector i (Mm^3); GW_{ij} = groundwater pumped in season j for sector i (Mm^3).

The objective function (Eq. (1)) is subjected to the following constraints.

Water allocation

The irrigation requirement of all the crops must be fully satisfied during all the seasons from the available surface water and groundwater resources. The total volume of irrigation water required in each season depends on the area of each crop and its net irrigation requirement, which can be estimated by subtracting effective rainfall from ET_{crop}.

$$10^{-2}\sum_{i=1}^{4}\sum_{k=1}^{n} NIR_{ijk}A_{ijk} - \sum_{i=1}^{4}\alpha_1(\beta_1 SW_{ij} + GW_{ij}) \leq 0; \quad \forall j \quad (2)$$

where α_1 = field water application efficiency; β_1 = conveyance efficiency of surface water; and NIR_{ijk} = net irrigation requirement of crop k in season j of sector i (m).

Land area

$$\sum_{k=1}^{n} A_{ijk} \leq TA_{ij}; \quad \forall i, j \quad (3)$$

where TA_{ij} = total cultivable command area of sector i in season j (ha).

Water availability

(a) $SW_{ij} \leq TSW_{ij}; \quad \forall i, j$ (4)