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Integrated urban water management modelling under climate change scenarios

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ABSTRACT

The concept of integrated water management is uncommon in urban areas, unless there is a shortage of supply and severe conflicts among the users competing for limited water resources. Further, problem of water management in urban areas will aggravate due to uncertain climatic events. Therefore, an Integrated Urban Water Management Model considering Climate Change (IUWMCC) has been presented which is suitable for optimum allocation of water from multiple sources to satisfy the demands of different users under different climate change scenarios. Effect of climate change has been incorporated in non-linear mathematical model of resource allocation in term of climate change factors. These factors have been developed using runoff responses corresponding to base and future scenario of climate. Future scenarios have been simulated using stochastic weather generator (LARS-WG) for different IPCC climate change scenarios i.e. A1B, A2 and B1. Further, application of model has been demonstrated for a realistic water supply system of Ajmer urban fringe (India). Developed model is capable in developing adaptation strategies for optimum water resources planning and utilization in urban areas under different climate change scenarios.

1. Introduction

Various forms of single or multipurpose water management are in practice. However a comprehensive approach to water management, referred as integrated water management, is still relatively uncommon, particularly in urban areas of developing countries like India (Jat, 2007). It can be defined as a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resulting economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Wolf and Hötzl, 2006). The water demand and climate change always have the risk of uncertainty involved in the future projections cautioning water managers to prepare supply-demand strategies to face future crisis of water (WaterSmart, 2006). The emphasis should be given to identify and develop the water management strategies, which lead to sustainable water resources and foolproof measures to thwart adverse effects of climate change. Such management practices are further necessary in a scenario of climate change due to uncertain precipitation and water availability. Therefore, there is a need for water sector policy makers and professionals to understand the dynamic urban environment for solving water resources related problems in urban areas, which will further aggravate in scenarios of climate change.

The concept of integrated water management considering climate change has not been well discussed and reported in literature (Asano, 1994; Kulga and Cakmak, 1997; Yang et al., 1999; Bouwer, 2002; Haddad, 2002; Liu et al., 2007; Lin et al., 2010). Further, due attention has not been given to such practices in developing countries like India (Zuidema, 1982; Tjallingii, 1988; Witter and Bogardi, 1993; Lund and Cabrera, 2002; White and Fane, 2005; Jat, 2007; Qin and Xu, 2011). Few attempts have been made to model the climate change for urbanized areas (Wigmosta and Burges, 1990; Solecki and Oliveri, 2004; Wurbs et al., 2005; Strack et al., 2008) without considering climate change impacts on water management practices. A few attempts have also been made to address the water resources management issues considering one or another issue of climate change (Taleb and Maher, 2000; Ragab and Prudhomme, 2002; Mitchell et al., 2007; Qin et al., 2008; Shao et al., 2011). However, integrated water management considering integration of various possible water sources to satisfy the demands of different users, environment protection, land and urban planning have not been considered.

The integrated approach to the water resources planning and management requires a comprehensive consideration of water requirements and characteristics (hydrological and hydraulic) of

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different available sources (such as availability, cost and reliability). There are a number of management models which have been reported in literature for rural areas and canal commands (e.g., Belaineh et al., 1999; Barlow et al., 2003; Karamouz et al., 2004; Tripathi et al., 2004; Pulido-Velazquez et al., 2006; Khare et al., 2006; Jha et al., 2008; Nikam, 2012), but a very few models are suitable for the urban areas (Dracup, 1966; Onta et al., 1993; Syaukt and Fox, 2004; Jat, 2007; Qin and Xu, 2011). The management models and strategies developed for rural and canal commands cannot be applied directly to the urban areas. The water resources system of urban areas is quite different and complex as compared to rural areas because of the dynamic nature of various hydrological processes, different type of conflicting water demands and their dynamic nature, different environmental aspects, like water pollution and wastewater generation and its consequences, and more human interference. The dynamic complexity in space and/or time found in urban water systems presents great difficulties for urban water management (Senge, 1994). It becomes a complex system than on the management of a few isolated issues. We are generally unable to relate causes with effects that are removed by time or distance (Zarghami and Akbariyeh, 2012).

The optimum allocation of water from surface sources and groundwater has been attempted using different types of the optimization techniques, like dynamic programming (e.g., Buras, 1963; Aron and Scott, 1971), linear programming (e.g., Nieswand and Grandstrom, 1971; Lakshminarayana and Rajagopalan, 1977; Vedula, 1985), simulation based models (e.g., Young and Bredehoeft, 1972; Bredehoeft, 1983; O'mara, 1984), multilevel optimization technique (e.g., Maddock and Haimes, 1975; Yu and Haimes, 1974; Morel-Seytoux and Daly, 1975; Sharma, 1987) and Non-linear programming (e.g., Kashyap and Chandra, 1982; Lefkoff and Gorelick, 1990; Mishra et al., 2005). Nishikawa (1998) presented an optimization model for the optimal management of City of Santa Barbra's water resources during the drought. Problem is formulated as a linear programming problem. Optimization model is linked to MODFLOW programme to couple the groundwater system with the management model. The objective function is formulated to minimize the cost of water supply, subjected to water demand and hydraulic head constraint to control seawater intrusion and depletion of ground water. Jenkins et al. (2004) presented the results of an economic-engineering optimization model (CALVIN) of California's water supply system. This model explicitly integrates the operation of various water facilities, sources and demands of different users. Model allocates water to maximize the economic value of statewide agricultural and urban uses. Shao et al. (2011) have developed a conditional value-at-risk (CVaR) based inexact two-stage stochastic programming (CITSP) model to a water resources allocation problem involving a reservoir and three competing water users under uncertainty.

Wang and Huang (2011) formulated an interactive two stage stochastic fuzzy programming approach for the water resources management. The developed approach was applied for the case study to demonstrate the water resources allocation problem. A set of solutions under different feasibility degrees were estimated to plan the water resources allocation based on economic efficiency, degree of satisfaction and risk of constraint violation. Wang and Huang (2012) also developed an interactive multi-stage stochastic fuzzy programming approach for identifying optimal water resources allocation strategies. Zarghami and Akbariyeh (2012) developed a model for the Tabriz's urban water system using a system dynamic approach. This model considered the water supply resources (groundwater, imported fresh water and treated wastewater), sources of demand for water resources (domestic, irrigation and industry uses) and management tools (wastewater reuse and recycling, inter-basin water transfer, water price and conservation tools). Zarghami and Hajykazemian (2013) developed a new optimization algorithm for urban water resources planning called as particle swarm optimization with mutation similarity (PSOMS). The application of PSOMS was successfully demonstrated to an urban water problem for Tabriz city of Iran. The problem was formulated with an objective function to minimize the cost, maximize water supply and minimize the environmental hazards. The pipelines capacity, ground water, the demand and the impact of conservation tools were considered as constraints. Wang and Huang (2013) applied an interval-parameter two stage stochastic fuzzy programming with type-2 membership functions (ITSFP–T2MF) approach for the water resources allocation problem under uncertainty. However, in these studies, climate change and resulting impact on water resources allocation have not been considered. In these studies individual aspects of integrated water management, within an optimization framework have been considered. Therefore, an attempt has been made to develop an integrated urban water management model suitable in developing adaptation measures in optimum integration of various sources of water for urban water supply systems in climate change scenarios.

2. Study area and data used

Ajmer urban fringe is located between 26°20′ to 26°35′ N latitude and 74°33′ to 74°45′ E longitudes (Fig. 1). It spreads over an area of about 85 km^2 and has population of 542,580 (Census 2011). In the North-East side, water flow towards Samber lake. Ajmer valley drains eastward and Pushkar valley drains westward by tributaries of Luni river. There is a large lake i.e., Anasagar in the north of city.

For demonstration of model, data related to water supply system of the Ajmer fringe like land use/cover, population, water demands and existing water supply from various sources and other relevant data have been collected from various departments and used in the present study (RUIDP, 1998; CPHEEO, 1999; Ajmera, 2000; Census of India, 2001; PHED, 2004; Jat, 2007). The gridded rainfall datasets were used in many hydrological and climatological studies worldwide, including Australia for hydroclimatic forecasting, climate attribution studies and climate model performance assessments (Tozer et al., 2012). The $0.5° \times 0.5°$ gridded data set of daily rainfall for Ajmer fringe from year 1971 to 2005 has been used which is procured from India Meteorological Department, Pune. The Canadian Global Climate Model (CGCM3.1/T47) daily output data were obtained from Canadian Centre for Climate Modelling and Analysis (CCCma) for the grids covering Ajmer fringe of base period (1971–1990) and 20s (2011–2030) for A1B, A2 and B1 emission scenarios. It uses a 360 days per year and has a spatial grid resolution $2.8° \times 2.8°$ latitude and longitude (McFarlane et al., 1992).

3. Methodology

The Integrated Urban Water Management Model considering Climate Change (IUWMCC) is a mathematical programming model, which is formulated for the optimum allocation of water from the various water supply sources to satisfy the water requirements of different users along with considering various system and geometric constraints. The integrated water management model developed by Jat (2007), has been modified and improved in the present study to include climate change effects. The model application has been demonstrated further for the actual water supply system of Ajmer urban fringe.

In the present study, climate change impacts on surface and groundwater sources have been incorporated in the model in term of variation in water availability from these sources as a result of change in rainfall and temperature due to climate change (climate change factors). The stochastic weather generator (i.e. LARS-WG)