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# Expert knowledge based modeling for integrated water resources planning and management in the Zayandehrud River Basin

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SUMMARY

This study highlights the need for water resource planning and management using expert knowledge to model known extreme hydrologic variability in complex hydrologic systems with lack of data. The Zayandehrud River Basin in Iran is used as an example of complex water system; this study provides a comprehensive description of the basin, including its water demands (municipal, agricultural, industrial and environmental) and water supply resources (rivers, inter-basin water transfer and aquifers). The objective of this study is to evaluate near future conditions of the basin (from Oct./2015 to Sep./2019) considering the current water management policies and climate change conditions, referred as *Baseline* scenario. A planning model for the Zayandehrud basin was built to evaluate the Baseline scenario, the period of hydrologic analysis is 21 years, (from Oct./1991 to Sep./2011); it was calibrated for 17 years and validated for 4 years using a *Historic* scenario that considered historic water supply, infrastructure and hydrologic conditions. Because the *Zayandehrud model* is a planning model and not a hydrologic model (rainfall–runoff model), an Adaptive Network-based Fuzzy Inference System (ANFIS) is used to generate synthetic natural flows considering temperature and precipitation as inputs. This model is an expert knowledge and data based model which has the benefits of Artificial Neural Networks (ANN) and Fuzzy Inference Systems (FIS). Outputs of the ANFIS model were compared to the Historic scenario results and are used in the Baseline scenario. Three metrics are used to evaluate the goodness of fit of the ANFIS model. Water supply results of the Baseline scenario are analyzed using five performance criteria: time-based and volumetric reliability, resilience, vulnerability and maximum deficit. One index, the Water Resources Sustainability Index is used to summarize the performance criteria results and to facilitate comparison among trade-offs. Results for the Baseline scenario show that water demands will be supplied at the cost of depletion of surface and groundwater resource, making this scenario undesirable, unsustainable and with the potential of irreversible negative impact in water sources. Hence, the current water management policy is not viable; there is a need for additional water management policies that reduce water demand through improving irrigation efficiency and reduction of groundwater extraction for sustainable water resources management in the Zayandehrud basin.


## 1. Introduction

Rapid population growth, high agricultural use and industrial development, coupled with climate changes during the past few decades have caused increasing pressure on land and water resources in almost all regions of the world. The challenge is how to improve the management of water resources for present and future generations. Water resources planning and management requires the deep understanding of the special value of water for human life, interaction of human beings and nature, and the social significance of water resources for national economic development (Rosenberg, 2008). Water resources planning and management tries to meet the water requirements of all the water users, although, sometimes this is not possible. Frequently, conflicts among water users arise because water is a scarce and shared resource. The difficulties increase when the systems become large with numerous water users, several types of use, with unequal spatial distribution and such scarcity that water cannot be re-distributed without affecting other water users. Nowadays, this seems to be the common pattern of water allocation in large basins (Sandoval-Solis and McKinney, 2014).

Historically, fragmented water resources management has resulted in degradation of rivers and water bodies in many of the

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watersheds in the world, especially in arid and semi-arid regions (e.g. Aral Sea). Today, integrated water resources management (IWRM), especially in areas facing limited water resources, has become an indispensable approach. IWRM was introduced in 1980s to optimize water uses between different water demand sectors and water sources (Ludwig et al., 2014). The goal of this approach is to balance water availability and demand, human and environmental water requirements, taking into account all the available water sources (surface water, groundwater, reclaimed and desalinated water) which provides sustainability of water resources (Molinos-Senante et al., 2014; Dukhovny, 2004).

Meire et al. (2008) argue that the IWRM concept was originated at the first United Nations (UN) conference on the human environment in Stockholm in 1972. According to Porto and Porto (2008), the Dublin Principles and the 1992 UN summit at Rio de Janeiro reinforced this concept through the agenda 21's principles (Coelho Maran, 2010). It is important to note that IWRM is a process, not a product, and that it serves as a tool for assessment and program evaluation. IWRM does not provide a specific blueprint for a given water management problem but rather is a broad set of principles, tools, and guidelines, which must be tailored to the specific context of the country or region or a river basin (Xie, 2006). Stakeholder participation is the key point in IWRM approach. That is the empowered community has the responsibility to address local issues in a coordinated and integrated way (Matondo, 2002).

Many scientists and experts believe that water resources modeling is one of the most important preconditions that facilitate the application of IWRM in large basins. Models help to organize information related to water availability and water requirements of stakeholders. Using a "bottom-up" approach stakeholders can evaluate local alternatives for IWRM, while whole basin regulations can be evaluated using a "top-down" approach, taking into account physical limitations of existing infrastructure (Cai, 1999; Cai et al., 2006; Dukhovny and Sokolov, 2005). It is important to note that during the implementation of IWRM, there is no need to seek universal and stereotyped approaches that are acceptable for all (IWRM Toolbox, 2003). Due to these justifications, many researches have documented many IWRM case studies using different decision support systems (DSS). For instant, Letcher et al. (2006a,b), developed a DSS for Mae Chaem catchment in Northern Thailand. This DSS contains models of crop growth, erosion and rainfall–runoff, as well as household decision and socioeconomic impact models; Weng et al. (2010) developed an integrated scenario based multi-criteria support system for planning water resources management in the Haihe River basin. They defined some policy parameters or policy scenarios such as: water saving intensity, excessive volumes of groundwater extraction, volume of untreated wastewater and the amount of water supplied from transfer project for IWRM implementation to develop a DSS model that used a fuzzy multi-criteria decision analysis as the evaluation model. During the construction of DSS, special attention should be given to the definition of scenarios (Katsiardi, 2005; Liu et al., 2007; Soussa and Vekerdy, 2005; Van beek and Meijer, 2006; ZhenGfu et al., 2009; Ni et al., 2012). Gaiser et al. (2008) developed the Model for Sustainable Development of Water (MOSDEW) in the Neckar basin in South-west Germany. There are nine sub-models covering large scale hydrology, groundwater flow, water demand, agricultural production, point and non-point pollution and chemical as well as biological water quality. One of sub-models was the agroeconomic sector model, referred as ACRE model, developed by Henseler et al. (2005, 2009). This model is very useful for IWRM but it is very complex due to its hybrid modeling nature; Davies and Simonovic (2011), employed a system-dynamic integrated assessment model that incorporates socio-economic and environmental change. Their model includes global climate system, carbon cycle, economy, population, land use and agriculture, and novel versions of the hydrological cycle, global water use and water quality. Also, some of researchers focused on effects of IWRM implementations at the catchment scale. For instant, Ako et al. (2010), investigated methods to improve water resources management in Cameroon and to implement IWRM at the catchment scale. Coelho et al. (2012) employed a multi-criteria DSS for IWRM implementation in the Tocantions-Aragauia River Basin in Brazil. Safaei et al. (2013) applied the concept of IWRM to Zayandehrud River Basin in Iran. These studies considered stakeholder participation, scenario analysis, dispute resolution and climate change conditions. Also Georgakakos et al. (2012), Dawadi and Ahmad (2012), and Vargas-Amelin and Pindado (2014) surveyed the impacts of climate changes in water management in Northern California, Colorado River and Spain, respectively.

Nowadays, water resources planning and management processes are moving away from top down approaches to bottom up approaches. There is a variety of generic software platforms used to evaluate water planning and management policies and to facilitate stakeholder involvement during the planning and decision-making process (Assata et al., 2008). The models such as MODSIM, River Basin Simulation Model (RIBASIM), MIKE Basin, Water balance Model (WBalMo), MULti-sectoral, Integrated and Operational Decision Support System (MULINO-DSS), Water Evaluation and Planning System (WEAP) can be used for planning purposes at catchment scale, evaluation of current and alternative water allocation policies, river flow routing, reservoir routing, water demand analysis, rainfall–runoff modeling, water balance, water quality and sedimentation transport, and in general, watershed management (Mugatsia, 2010). The comparisons of these tools are described in Mugatsia (2010) and Jakeman et al. (2008).

WEAP is one of the IWRM platforms that seamlessly integrate water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements. New versions of WEAP consider demand priority and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches (Yates et al., 2005a,b). WEAP has been applied in Ghana to simulate the impact of small reservoirs in the Volta (Hagan, 2007), in Olifants catchment in South Africa to analyze current and future demands (Arranz and McCartney, 2007), in Perkrra catchment to analyze scenario implementation (Mugatsia, 2010), in Rio Grande/Rio Bravo transboundary basin to implement IWRM in large scale river basin (Sandoval-Solis and McKinney, 2014). These case studies show a good performance of this platform. It is clear that modeling of large basins implies sets of known and unknown parameters. Hydrologic and climatic time series, geologic data, water demands and historic water supply, and a variety of information of catchments and basins are used for modeling. However, in large basins for one period of time there is data with many gaps for a variety of known parameters. Also in many case studies there is not data at all for some important parameters.

This study presents how engineering judgment and expert knowledge could be used for integrated water resources planning and management in Zayandehrud River Basin. Modeling distributed water demands considering all sources such as surface and ground water resources and interaction between them regarding to the lack of data and information are difficulties which are surveyed in this study. Simulation of rainfall–runoff at the whole of basin to calculate natural flows due to climate change in the future is another challenges which is studied in this research. The Zayandehrud River Basin is one of the largest and most important basins in central Iran. Because of existence of different water