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Feasibility of groundwater recharge dam projects in arid environments

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SUMMARY

A new method for determining feasibility and prioritizing investments for agricultural and domestic recharge dams in arid regions is developed and presented. The method is based on identifying the factors affecting the decision making process and evaluating these factors, followed by determining the indices in a GIS-aided environment. Evaluated parameters include results from field surveys and site visits, land cover and soils data, precipitation data, runoff data and modeling, number of beneficiaries, domestic irrigation demand, reservoir objectives, demography, reservoirs yield and reliability, dam structures, construction costs, and operation and maintenance costs. Results of a case study on more than eighty proposed dams indicate that assessment of reliability, annualized cost/demand satisfied and yield is crucial prior to investment decision making in arid areas. Irrigation demand is the major influencing parameter on yield and reliability of recharge dams, even when only 3 months of the demand were included. Reliability of the proposed reservoirs as related to their standardized size and net inflow was found to increase with increasing yield. High priority dams were less than 4% of the total, and less priority dams amounted to 23%, with the remaining found to be not feasible. The results of this methodology and its application has proved effective in guiding stakeholders for defining most favorable sites for preliminary and detailed design studies and commissioning.

1. Introduction

Water resources in arid regions are both scarce and precious (Rijsberman, 2006). Many of these regions lack perennial rivers. This poses a question on the reliability of dams for water supply. It has been also reported that dams can be effectively used for artificial recharge of groundwater in arid areas (Al-Muttair et al., 1994; Haimerl, 2004). These dams store storm runoff for later controlled discharge in an effort to recharge the shallow groundwater wells on which local communities depend for their livelihoods.

Despite the low rainfall in arid regions, there is a considerable amount of investments in dam construction projects. In Saudi Arabia for example, where no rivers exist, the number of constructed dams have more than doubled in the last 10 years, reaching to 394 in 2011 (Ministry of Water and Electricity, 2013). Investments decisions in water harvesting projects involve a multitude of factors to be analyzed and evaluated both individually and comparatively. Authorities funding feasibility studies of dam construction studies and commissioning are faced with multiple challenges and complexities. Challenges include prioritizing funds for dam commissioning. Complexities in funding prioritizing of dam construction projects arise due to the multitude of factors and different objectives of the water development project. Water productivity of dams greatly vary depending on stochastic factors (watershed hydrology, sediment load, and climate), and structural dam parameters (hydrogeology, site conditions, reservoir capacity). Previous works on decision making in infrastructure investments has focused on existing infrastructure maintenance and repair. An example includes the works of Chouinard et al. (1996). Ranking procedures are limited to embankment dam monitoring. Condition and risk indexing systems work is limited to old engineering facilities or dams with physical deficiencies (Andersen et al., 2001). Authorities in water challenged regions require methodologies for prioritizing their investments in water supply projects (Shovic et al., 2010). Examples of groundwater recharge estimates include mass-balance approaches (Tizro et al., 2007), and isotope techniques (Zakhem and Hafez, 2012). Other mutli-criteria decision based analysis of groundwater recharge potential examples includes the works of Adiat et al. (2012). There is no comprehensive methodology in the reviewed literature that brings together the above components into the decision making process of feasibility and prioritization. This paper presents a unique methodology for (1) studying dam feasibility in arid regions and (2) prioritizing dam commissioning and detailed studies based on weighted criteria of several physiographic and socio-economic

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factors. The method developed aims at providing decision makers with an objective approach to assess the feasibility and prioritize the construction of storage as well as artificial recharge dams in arid environments. The outcome of this method is to provide investment decision makers with a necessary tool to determine water productivity of dams and prioritize investments in such dams in arid and semi-arid regions.

2. Materials and methods

2.1. Methodology overview

This research focuses on generating a methodology for groundwater recharge dams feasibility analysis required as an input to the decision making process. The Assir province in Saudi Arabia is considered as a case study with more than 80 dams analyzed. The overall methodology is based on determining several criteria deemed necessary for the complete evaluation of the proposed dams. There are three major components that need to be carefully assessed in developing the methodology for feasibility and prioritization process: (1) political-administrative; (2) physical-environmental; and (3) socio-economic. The criteria are based on the inputs from different domains as shown in Fig. 1.

The expected outcome of the careful examination of these components will be used as an input into the prioritization process. The approach aims at assessing the hydrologic reliability of the proposed dams, their yield, and their socio-economic value. To assess these factors, a method that utilizes intensive geo-processing procedures and reliability-yield relationships is presented. The method is based on spatial hydrologic modeling, demand estimates, yield, reliability, dam cost, and water productivity cost. The dams were assigned indices based on three criteria: reliability, yield, and cost of water demand satisfaction. A flowchart summary of the method is presented in Fig. 2.

2.2. Study area

Assir is an important agricultural and tourism region in Saudi Arabia. It is one of the regions that receive the highest amount of precipitation in the Arabian Peninsula. Crops are cultivated on valley sides near and above flood plains were water is supplied from shallow water wells. In its most the region is characterized by bare topography and high runoff due to short and intense storms. The main water resources improvement projects within the area is the construction of small and medium dams for runoff storage and artificial groundwater recharge. Geographic coordinates of eighty-one proposed dams for groundwater recharge were processed in a GIS environment along with the SRTM DEM (Jarvis et al., 2008) to delineate the catchment areas. Arc Hydro (Maidment, 2002) was used as a tool for batch watershed processing and delineation of the stream networks and the proposed dam watersheds. Agro-ecological zones of the area of interest were determined. A map of aridity (mean annual precipitation/the mean annual evapotranspiration) zoning was defined for the area. The aridity index criterion of UNEP (1997) was used. The locations of the proposed dams and their associated catchments within the study area are shown in Fig. 3a. It was found that 97% of the proposed dams and their catchments lie within a hyper-arid or an arid area. The remaining 3% of the dams are on the border zone of aridity – semi-aridity.

2.3. Rainfall–runoff modeling

The complex stochasticity inherent to hydrologic processes makes modeling rainfall–runoff processes in arid and semi-arid environment a challenging process. There is a lack of reliable flood data records (Lange et al., 1999). The highly temporal and spatial variability of rainfall, soil water balance variations and peculiarity of soil water retention by native plants adds to the complexity of the required modeling process. High channel transmission losses, difficulty of uncertainty estimates, and difficulty of precipitation data generation for runoff calculations are characteristics of arid areas- see Pilgrim et al. (1988) and Al-Qurashi et al. (2008). Due to parameter variability in different events, there is high uncertainty reported in rainfall–runoff modeling approach predictions in complex as well as simple models (Mcintyre and Al-Qurashi, 2009). Literature shows that sophisticated rainfall–runoff models do no better than simple ones in arid and semi-arid regions (Michaud and Sorooshian, 1994). As the objective of the methodology was to study the feasibility and prioritize the commissioning for a multitude of dams, it was not deemed feasible to capture the detailed hydrologic analysis of every catchment. All of the studied catchments are un-gauged. Runoff data for the area of study was limited. Runoff data used to be administered by the Ministry of Agriculture and Water in during the second half of the past century (1960s and 1970s). The generated daily runoff data was checked against selected storms where both rainfall hyetograph and runoff hydrograph exist (Hydrology Division, 1983). Runoff data from selected stations was used to help validate the rainfall–runoff modeling approach that was followed in this study. The approach followed herein is as follows: the historical daily rainfall data was used to generate daily runoff data for the catchments using the well-known NRCS Curve number method. Runoff curve numbers were generated using GIS techniques from gridded soils and

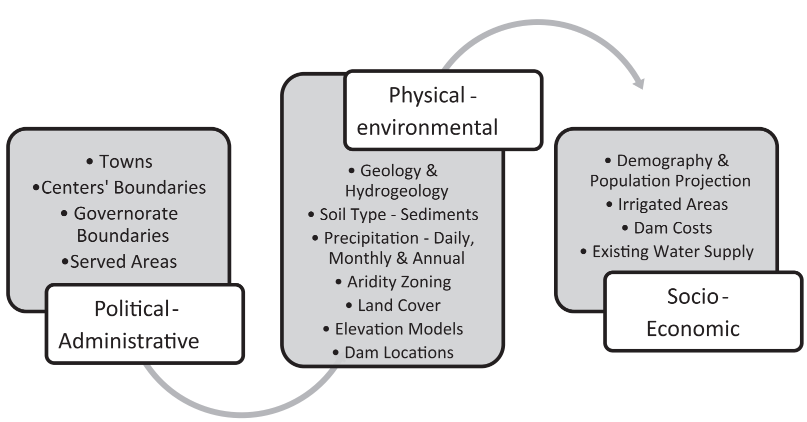

Fig. 1. Illustration of data requirements and factors involves in the decision making process.