Journal of Hydrology 512 (2014) 16–26

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Feasibility of groundwater recharge dam projects in arid environments

H.H. Jaafar *

Dept. of Agriculture, American University of Beirut, 11-0236, Beirut 1107 2020, Lebanon

ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 17 February 2014
Accepted 19 February 2014
Available online 28 February 2014
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Dams
Water management
Arid regions
Artificial recharge
Feasibility
GIS

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

---

* Tel.: +961 1350000 4570.
E-mail address: hj01@aub.edu.lb

http://dx.doi.org/10.1016/j.jhydrol.2014.02.054

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

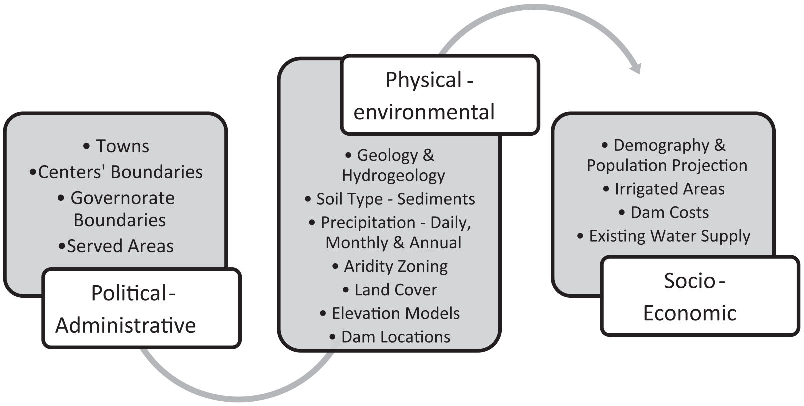

Fig. 1. Illustration of data requirements and factors involves in the decision making process.

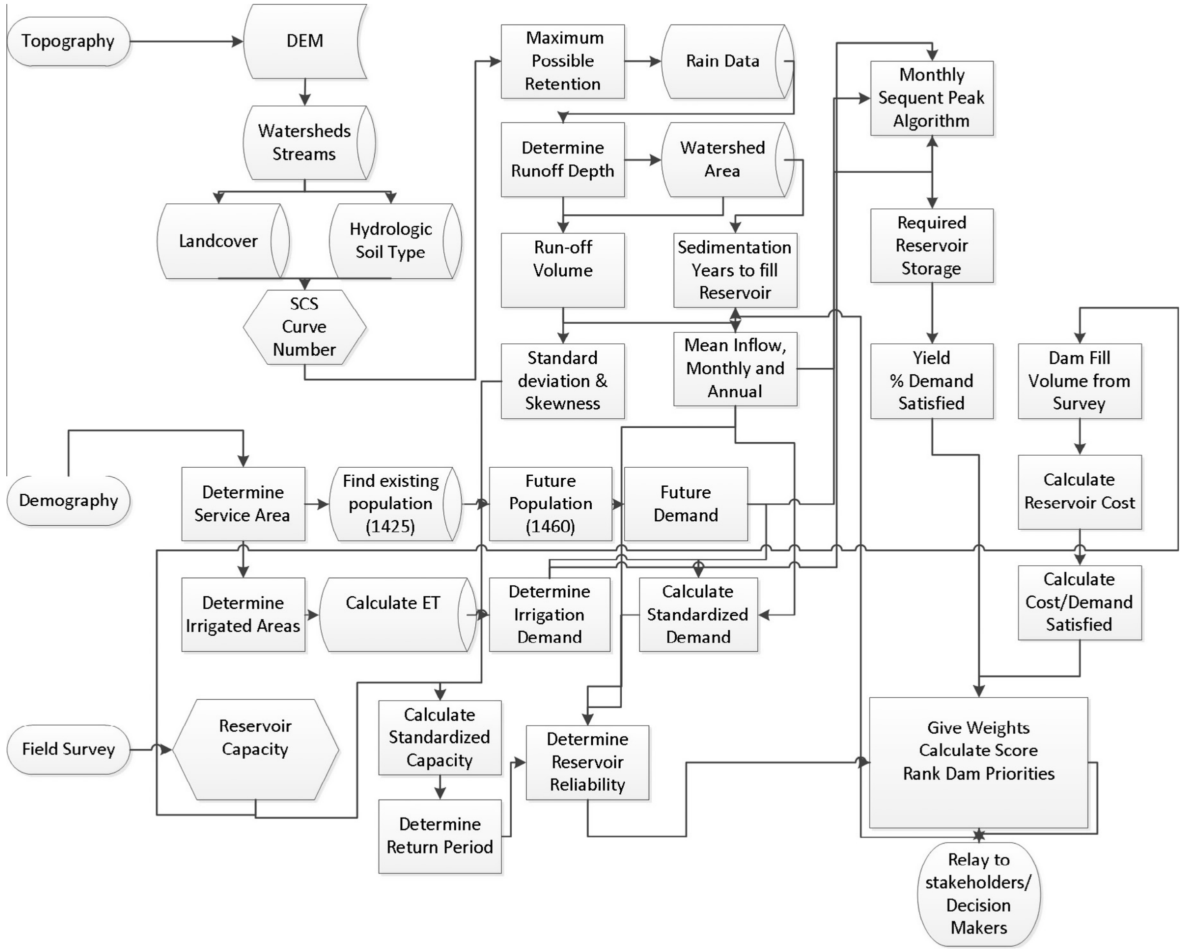

Fig. 2. Summary of criterion used in developing the methodology.

land cover datasets. Mean curve number for each catchment/part of catchment was calculated spatially using the "compute local parameters" command of the attribute tools within Archydro in ArcGIS. Geo-HMS (geographic hydrologic modeling software) was used to model the spatial distribution of the curve number based on hydrologic soil groups and overlying land cover for the catchments of interest. A curve number grid covering the study area was generated. The runoff grid serves as an input to the spatial hydrologic modeling process. Rainfall was analyzed as follows. Thiessen polygons for the rainfall stations were generated using Spatial Analyst Extension in ArcGIS^{TM}. Catchment areas were divided into zones of precipitation events based on the aerial precipitation adjustment. For each catchment intersecting with the thiessen polygon, adjusted daily precipitation depths were transformed into daily runoff depths using the NRCS curve number method. The adjusted depths were derived from point-precipitation using the adjustment method described in Section 2.3.1. Dam catchments were assigned stations based on the centroid location for the catchment. The resulting data was aggregated in the spreadsheet into monthly and yearly time series. The yearly values were imported into MATLAB for statistical analysis. Runoff values were found to fit a log-normal distribution, especially near the 50% non-exceedance probability. The monthly values were used for determining the reservoir storage – yield relationship using the sequent peak algorithm. Mean annual inflow, annual standard deviation, skewness coefficient, and coefficient of variation were calculated for each dam site. These parameters were used in reservoirs reliability calculations.

2.3.1. Meteorology

The region of Assir in Southwest Saudi Arabia of the country is distinguished in terms of the precipitation pattern that is affected by the monsoons from Southeast Asia to the east and the low pressure systems dominating the Nile Valley to the West. The weather systems are governed by a continued low along the axis of the Red Sea, especially in the month of March, which favors a warm southerly wind activities leading to a rise in temperature along the west coast. This contributes to the increased amounts of clouds and precipitation on the Southern and Western Highlands leading to heavy rains on the area. The rainfall gauging stations in the study area are the major sources of data required for the analysis herein. There are 36 rainfall stations with periods of record varying between 19 and 41 years. The mean annual rainfall in the Assir Province varies between 53 mm/yr and 413 mm/yr, increasing with elevations and sharply decreasing inland and to the north east. The rainfall station network density was less than 1 station/2000 km^2. A GIS-based mean annual precipitation grid was generated using krigging method of interpolation. Daily Precipitation data for 36 rainfall stations distributed over the area of Assir was used to simulate historic runoff data. The historical time-series rainfall was used for runoff generation. An aerial reduction factor for point precipitation was applied to avoid assuming a uniform rainfall over the watershed area. Reduction factors were determined based on the depth-area curves initially published by U.S. Weather Bureau in 1957–1960 and known as TP-29 (U.S. Weather Bureau, 1958a,b).

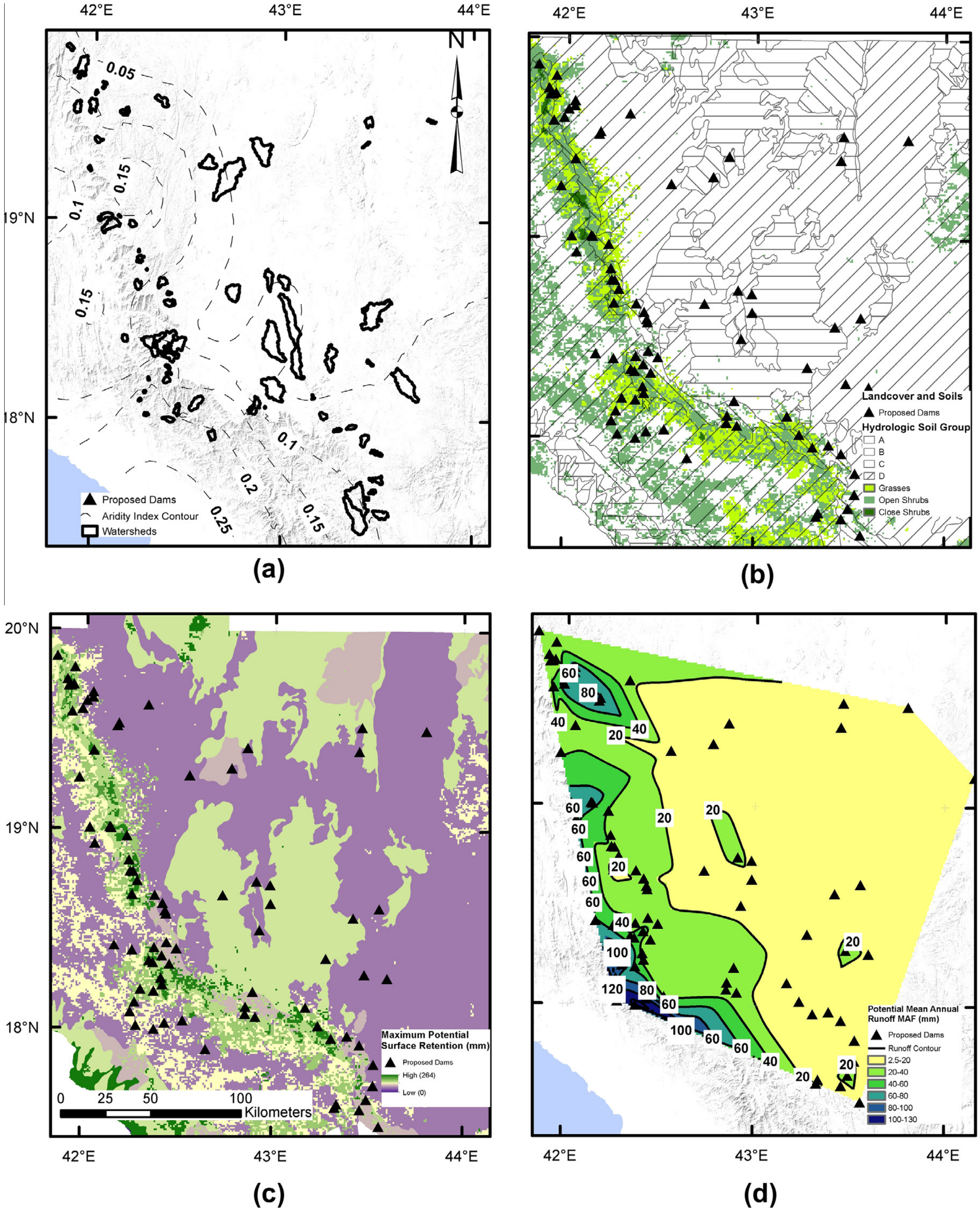

Fig. 3. (a) Assir area topography, proposed dams and catchments, aridity index mapping, (b) soils and landcover, (c) generated maximum potential surface retention (s) grid the study area and (d) runoff grid (kriging interpolation of mean annual runoff at the proposed dam sites) generated using the NRCS curve number equation with Ia = 0.2s Ia = initial abstraction.

2.3.2. Soils and land cover

Soils and land cover data were analyzed to generate the curve numbers for the proposed dams' catchment areas. Soil maps (Department of Land Management, 1985) at the 1:250,000 scales were scanned, geo-referenced and digitized into polygons in a GIS environment. Attribute data for the soils was derived from accompanying soil description. Each soil map code was attributed with the soils-corresponding characteristic. Twenty-four different soil types were identified. The soils were mapped into four hydrologic soil group classifications (Natural Resources Conservation Service, 1997) based on permeability and slope characteristics for incorporation into the rainfall–runoff modeling. The permeability of downstream soils was used for estimating recharge percentage. Soils and Land cover data was used to generate a curve number grid for the rainfall–runoff modeling. Land-cover data was downloaded from the Global Land-cover facility (NASA, 2008), (Bartholomé and Belward, 2005). The data has a spatial resolution of 3-arc minutes (approximately 900 m at the area's latitude). A land-cover grid was extracted and clipped for the area and a composite curve number was calculated for each watershed, along with mean annual runoff ratio (Fig. 3b–d).

2.4. Hydrogeology

The formations in the Assir Province ranges from sedimentary deposits such as limestone, sandstone, alluvial deposits, Sabkhah deposits to Igneous intrusions such as gabbro, granodiorite, diorite, and granites, and also contains metamorphic rocks of igneous and sedimentary origins. The geology of dam sites was examined based on the available geology maps of the 1:100,000 and 1:250,000 scale and reports (Saudi Geological Survey, 2008) was used to delineate scanned geology maps. Reports of the maps were analyzed to provide a rapid assessment of the geologic structures around the proposed dam locations. The potential for artificial groundwater recharge is high as the area is highly faulted. 50% recharge efficiency was assumed on sandy silt soils and 95% recharge efficiency was assumed on sandy soils. This has been confirmed by field measurements on some dams in Saudi Arabia (Al-Turbak and Al-Muttair, 1989) and Oman (Haimerl, 2004). All of the proposed dam sites in this study had shallow wells downstream of the site. All sites were visited by a hydro-geologist assigned by the concerned authority and a report of hydro-geologic feasibility and appropriateness of rock type was prepared prior to this study. Detailed hydrogeological investigations at dam sites need to be conducted to accurately describe the surface–subsurface water interactions. However, prior to commissioning such analysis that could be very costly. It is crucial first to assess the inflow to the dams and their expected costs and water productivity.

2.5. Demand calculations

2.5.1. Demography and domestic demand

Requests for dam construction in the study area are usually based on the requests of communities within the dam neighborhood. Nearly all dams are in the vicinity of small towns and villages. Topographic maps at the scale of 1:50,000 coupled with recent high resolution satellite imagery were used to identify the names and locations of the serviced areas. National census reports were used to estimate the population for the served areas. Served population ranged from 50 to 7000 inhabitants. Population projection parameters for each governorate were obtained and used in estimating the projected domestic demand increase for the next 30 years. For towns greater than 5000 inhabitants, the daily domestic demand was assumed to be 250 l/capita (2737 m^3/annum). For smaller towns, the rate of 150 l/day/capita (1643 m^3/annum) was assumed.

2.5.2. Agricultural demand

Agriculture is a wide spread practice in Assir Area. The sector relies on groundwater from shallow water wells and on torrential spring-rains. Most of the farmed areas rely on wells, seasonal streams, and precipitation. Dams for artificial recharge serve the purpose of increasing the water level in shallow wells for domestic and stock water use as well as irrigation. To determine the extent of farmed areas downstream of each dam, recent satellite images (2000–2009) were used to delineate the farmed field boundaries. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra Satellite, LANDSAT 7 Enhanced Thematic Mapper, LANDSAT 5, and Google Earth Imagery are the types of imagery that were utilized based on availability and cloud free coverage whenever applicable. All maps were geo-referenced to the Universal Transverse Mercator Zones 37 and 38 of the WGS_1984 geographic coordinate system. Vegetation analysis was performed by manually digitizing irrigated parcels using satellite imagery for locations immediately downstream of the proposed dam sites. Gridded spatial reference evapotranspiration (ET) data from the World Water and Climatic Atlas was used to estimate the maximum possible consumptive use of the agricultural areas. While the actual evapotranspiration is expected to be lower in some situations depending on crop type and growth stage, it was not feasible to survey the crop types and crop rotations due to the large extent of the study area. The ET grid had a resolution of 16 km. Monthly evapotranspiration grids were added to calculate the annual evaporation grid in Map algebra extension of ArcGIS^{TM}. Crop consumptive use was calculated for only 3 months of the year: June, July and August (the period during which the consumptive use is highest). Crop requirements were assumed to be equal to the potential evaporation. Irrigation demand period was then limited to 3 months set to those 3 months. Rains in the area are mainly distributed over the months of March, April and May. There are 67 recharge dams for which irrigation demand was considered.

2.5.3. Dam costs

Cost for the proposed dams need to be considered in the decision making process. To estimate the costs of dams, the dam type and the excavation and fill volume need to be estimated. Dam sites were visited and surveyed in the field using Global Positioning System equipment. The survey was used to create a three-dimensional surface of the reservoir lake. The volume at the spillway elevation and the corresponding reservoir area were calculated using ArcGIS^{TM}. A storage – area – elevation relationship could be derived from the reservoir surface model that was generated from the survey data. The cost was calculated in relation to the dam fill volume estimate based on actual cost data for existing dams in the country (Directorate of Projects Implementation, 2006). The existing data were determined based on the dam height, length, and type (concrete, earthen, rock fill). The dam capital construction cost was estimated after calculating the fill volume and the type of dam.

$$AC_{dam} = CC_{dam} \times i \times \frac{(1+i)^n}{\{(1+i)^n - 1\}} + AOM_{dam} \tag{1}$$

where AC is the annualized dam cost, CC is capital cost of the dam, i is interest rate, n is dam life, and AOM is the annual operation and maintenance cost. The operation and maintenance cost was assumed to be 1%, and the annualized dam cost was calculated based on a 5% interest rate. The dam life expectancy was assumed to be 50 years. The capital cost was annualized over the dam life time. The annualized dam cost was important in estimating the cost of a cubic meter of water demand satisfied. That is, this value is a function of the reservoir-yield storage-demand values. Sedimentation in dams could be cleaned up during the lifetime of the dam. For small dams, sediment clean-up is always a choice as it is easier than the large dams. Flushing of sediments through dam gates is a practice in existing dams in the study area. It was assumed that the proposed dams will be regularly cleaned from large sediments and that the operation of the recharge dams will flush out smaller sediments out of the reservoir. Other costs (for example appropriation costs, obstacle removal costs) were not included in this analysis. The dam-fill size volume and the capacity of proposed reservoir at the proposed spillway elevation were estimated using ArcGIS^{TM} 3D Analyst. There are three main types of proposed dams in the study area: earthen dams, rock-fill dams and concrete dams. The slopes of dam structures assumed in this study were based on the type of the proposed dams. The results were used to estimate the dam costs and consequently the cost of demand satisfaction. The steps required to prepare for the yield and reliability analysis are summarized in Fig. 4.

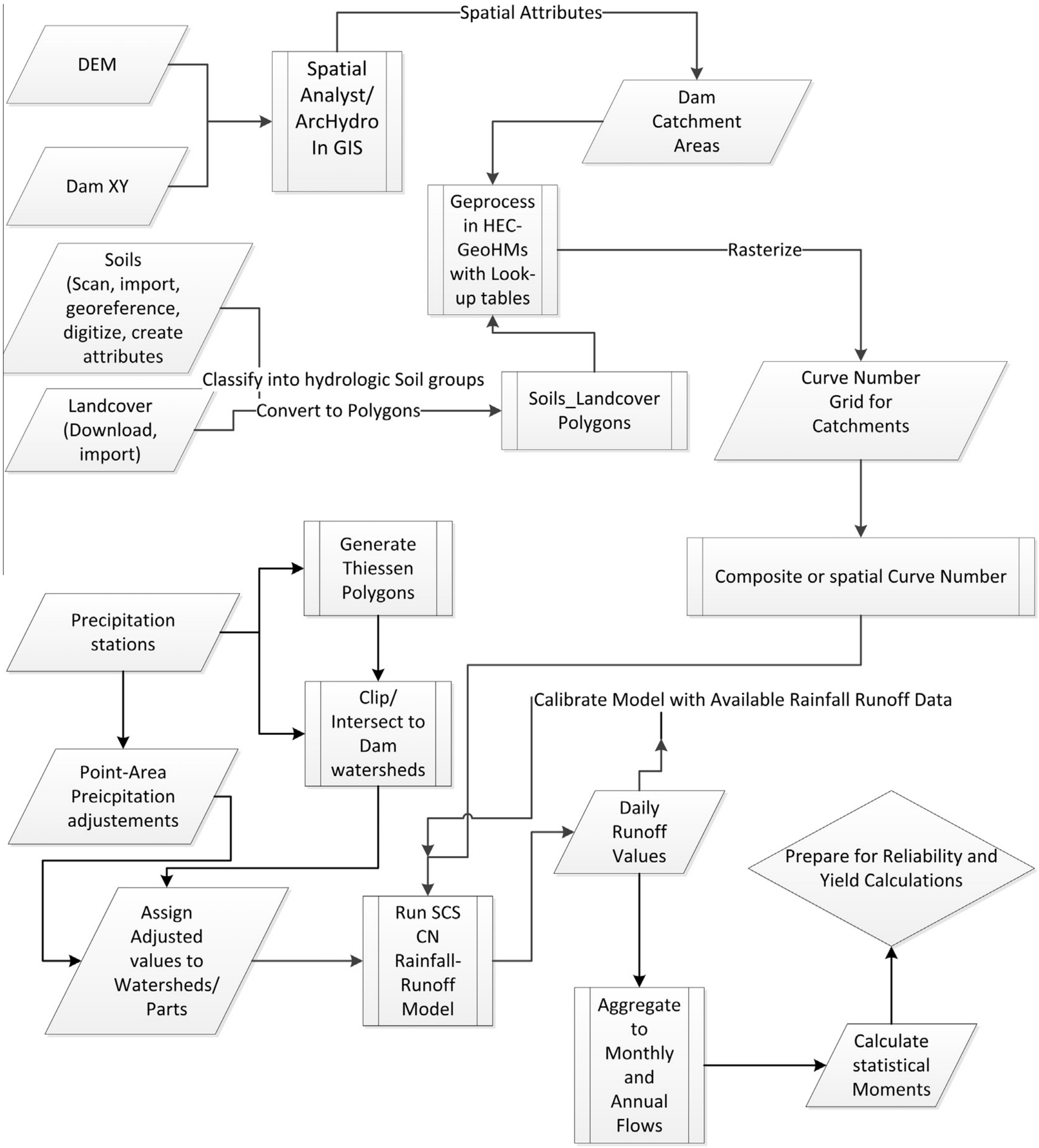

Fig. 4. GIS processing required for reliability and yield analysis.

2.6. Yield analysis

Yield analysis was one of the criteria used in the priority ranking. Numerous traditional approaches for determining firm yield from reservoirs exist in Literature. These approaches have been thoroughly reviewed by (Koustoyiannis, 2004). The sequent peak algorithm with a monthly time step was used in this analysis. Relationships between the reservoir active storage vs. proposed reservoirs' yield at their site-surveyed capacities were derived for a range of combined irrigation and domestic demands, as well as domestic demands alone. Reservoir yields were derived for 50% Irrigation demand + domestic demand, 80% of Irrigation demand + domestic demand, domestic demand only, and 100% of Irrigation and domestic demand. The generated daily time series of reservoir inflows was aggregated into monthly values and used in this analysis via a mass-balanced based computation algorithm. In this study, the storage was constrained by the on-site surveyed topography. The limitations of the dam height, corresponding spillway height, and the corresponding reservoir storage were used to determine the required storage capacity based on the sequent peak

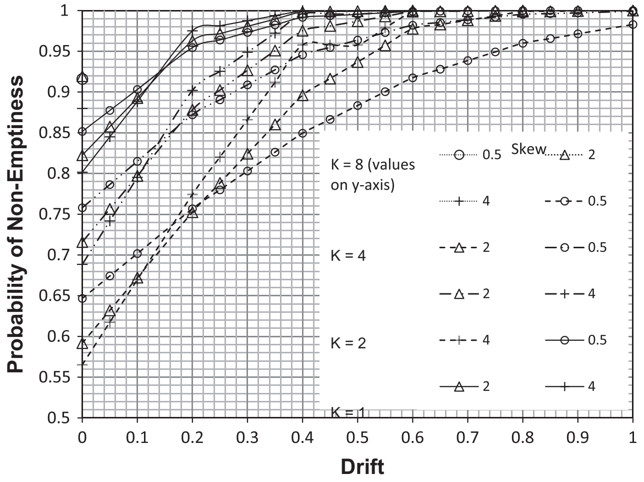

Fig. 5. Probability of emptiness for various skewness, standardized reservoir sizes (k), and drifts for log-normally distributed flows.

Table 1
Recharge dams and their associated demographic, physical and structural characteristics: population served (Pop), Length (*L*), Height (*H*), Volume (*V*), Mean Annual Flow (MAF), Coefficient of Variation of MAF (CV), Standardized Reservoir Size (SRS), Reliability of Domestic Demand, and Reliability of Total Demand, AC = annualized cost per cubic meter of yield/total demand satisfied, Final Score for Total Demand (Index_T), Rank, and Priority (H = High, L = low, N = Not feasible) (sorted by priority).

Dam name	Pop.	Irrigated areas (ha)	*L* (m)	*H* (m)	*V* (m^3)	MAF (mm)	CV	SRS	R_D (%)	R_T (%)	AC/m^3 of Yield/DS	Index_T	Rank	Priority
Shaibain	233	0	108	8	996,100	43	0.78	1.61	99.9	99.9	1.6	74.5	1	H
Bakim	669	23	150	9	230,500	16	2.71	0.28	23	19	0.4	72.9	2	H
Shawas	145	21	164	12	1,035,600	28	1.13	0.94	99.8	98	0.8	71.9	3	H
Shaab	233	8	62	12	233,700	14	2.88	0.67	53	45	0.7	65.6	4	L
Katna	2483	0	242	9	635,000	8	1.17	0.4	38	38	0.7	65.4	5	L
Kintan	155	0	76	5	40,400	14	1.59	0.11	11	11	0.5	61.2	6	L
Fiah	3104	66	112	7	696,400	28	1.29	0.74	71	50	0.4	55.7	7	L
Lazma	1109	57	387	13	1,073,300	31	0.8	0.45	45	45	1.8	55.7	8	L
Matrak	312	6	48	15	44,300	31	1.14	0.12	12	12	0.7	55.6	9	L
Ghol	2967	83	310	10	584,856	11	0.87	0.35	35	34	0.7	52.3	10	L
Sayil	982	0	170	10	725,069	12	1.06	0.49	48	48	6	51.5	11	L
Fatah	340	18	202	22	920,500	26	1.23	0.42	42	42	4.9	49.8	12	L
Hamita	949	0	221	8	261,700	9	1.17	0.28	27	27	2.3	47.9	13	L
AlKaaban	540	38	179	7	395,200	23	2.38	0.46	40	31	3.7	47.1	14	L
Nidba	141	0	169	15	190,000	99	0.63	0.2	20	20	21.8	40.5	15	L
Ihlali	493	2	131	15	145,700	35	1.07	0.12	12	12	2.2	40.1	16	L
Esh	1062	0	74	11	76,700	38	1.05	0.19	19	19	0.9	39.4	17	L
Ghadfa	208	0	41	12	13,800	32	1.12	0.78	59	59	6	37.8	18	L
Mijzaa	725	83	168	20	336,800	26	1	0.27	26.9	25.3	1.5	37.5	19	L
Katarat	310	7	76	15	109,100	7	3.75	0.04	4	4	1.7	37.5	20	L
Mahaba	190	0	95	18	81,200	71	0.89	0.07	7	7	18.7	36.4	21	L
Kahis	2483	0	65	20	173,993	26	0.98	0.8	68	68	6.8	34.9	22	L
Rakib	182	22	111	14	98,100	24	0.95	0.32	32	30	1	33.3	23	N
BaniRazam	1479	36	95	24	295,100	30	0.85	0.56	56	53	2.5	30.3	24	N
Bithatha	2332	95	111	10	52,900	78	0.6	0.05	5	5	0.6	28.3	25	N
Sola	238	7	51	15	70,600	12	1.13	0.38	38	36	2.4	27.9	26	N
Akhdar	443	22	240	20	948,800	24	0.95	37.28	93	0	4.4	23.6	27	N
Kadaa	700	59	69	15	188,100	47	1.01	0.13	13	13	1.1	23.4	28	N
Gharsa	95	23	136	15	378,900	40	1.02	6.97	100	0	1.5	22.1	29	N
Khalala	419	25	47	11	52,100	39	0.82	0.1	10	10	0.9	21.3	30	N
Rawda	2519	0	149	8	43,600	14	1.58	0.65	0	0	0.6	21.1	31	N
Mirba	1772	0	76	10	53,100	26	0.97	0.09	9	9	2.4	19.6	32	N
Fatha	1561	0	48	14	54,900	21	1.22	0.09	9	9	1.4	19.3	33	N
Rihan	345	27	72	12	220,054	10	1.14	0.47	46	40	6.9	18.2	34	N
Karis	1608	0	61	10	82,400	32	1.11	0.28	27	27	2.4	18.0	35	N
Shafan	152	74	294	7	242,100	4	1.51	0.84	92	0	1	17.1	36	N
Kibkab	602	0	129	10	46,900	32	1.11	0.47	44	44	11.6	16.4	37	N
Yaod	394	8	218	14	97,300	4	5.64	0.83	0	0	9.9	16.0	38	N
WastMirma	1077	151	80	15	203,200	19	2.45	0.04	4	4	1.2	14.2	39	N
Dabe	310	24	39	13	21,900	61	0.94	0.04	4	4	1.3	13.4	40	N
Misna	903	25	71	18	80,100	10	3.24	0.02	2	2	2.6	12.7	41	N
Malah	1417	22	111	8	77,000	11	3.29	0.22	14	0	2.2	12.5	42	N
Kowa	203	9	76	18	39,900	36	0.94	0.27	27	26	15	12.5	43	N
Talha	116	11	90	7	38,200	53	1.5	0.06	6	6	2.4	12.3	44	N
Farasha	172	11	76	10	70,000	28	0.92	2.04	99.5	0	5	10.9	45	N
Mijaza	2707	110	35	9	24,100	12	3.1	0.02	2	0	1.4	10.0	46	N
Rida	202	17	37	15	30,700	51	0.81	0.07	7	7	4.4	10.0	47	N
Hadaja	310	5	47	7	14,500	22	0.97	0.15	15	14	4.8	9.9	48	N
Kian	12,450	0	80	10	287,190	7	1.2	0.76	0	0	1.9	9.8	49	N
Salmana	1465	17	65	11	35,700	82	0.76	0.14	14	13	4	9.6	50	N
Wahi	1465	17	75	13	46,100	82	0.76	0.11	11	11	9.1	7.6	51	N
Shaiq	931	721	842	7	791,100	16	0.95	0.4	40	0	2	7.5	52	N
Hosn	621	18	35	16	19,387	29	1.18	0.11	11	7	4.5	7.5	53	N
Hanjour	1109	76	223	9	331,200	13	1.06	12.98	0	0	3.8	7.0	54	N
Azila	977	39	161	8	221,200	72	0.97	2.36	96	0	3.5	6.4	55	N
Jalal	141	71	65	13	70,300	132	0.9	0.05	5	5	4.1	6.1	56	N
Kari	208	0	32	7	3900	123	0.92	0.02	2	2	7.5	5.7	57	N
Khabibi	817	28	69	18	29,600	31	1.02	0.27	26	0	5.4	5.4	58	N
BijadSaad	308	16	47	11	17,300	26	1.25	0.03	3	3	7.7	5.3	59	N
Sadwan	150	15	90	18	36,800	34	1.09	1.12	99	0	10.6	5.2	60	N
Tiblasim	994	39	34	9	8100	13	3.07	0.05	0	0	2.9	5.2	61	N
Hweib	832	80	181	19	283,500	24	1.01	2.55	99	0	7.3	5.1	62	N
Misali	904	16	62	10	46,000	40	1.55	0.04	4	4	6.6	5.0	63	N
Milhan	392	34	85	19	72,900	38	0.9	0.61	60	0	6.4	4.4	64	N
Khaior	1313	0	53	5	7803	11	1.8	0.03	3	3	9.5	3.7	65	N
Aina	257	31	83	11	25,800	89	0.94	0.08	8	6	23	3.5	66	N
Mihjir	1156	6	90	11	32,700	47	1.53	0.3	19	0	7.7	3.3	67	N
Farha	823	58	50	13	19,900	2	6.94	0.11	0	0	5.3	3.1	68	N
Harim	1673	3	37	9	4200	70	0.86	0.11	0	0	4.9	2.9	69	N
Wadtha	322	0	121	6	1700	101	0.62	0	0	0	24.1	2.5	70	N
Halifa	271	33	169	7	65,700	72	0.97	0.29	29	0	6.1	2.1	71	N

Table 1 (*continued*)

Dam name	Pop.	Irrigated areas (ha)	L (m)	H (m)	V (m^3)	MAF (mm)	CV	SRS	R_D (%)	R_T (%)	AC/m^3 of Yield/ DS	Index_T	Rank	Priority
Farsh	1318	32	148	17	106,400	30	1.12	3.22	0	0	15	1.9	72	N
Washa	998	130	80	7	26,400	49	1.49	0.15	13	0	7.6	1.7	73	N
Ain	345	22	30	20	10,500	80	0.98	0.08	8	0	16.7	1.4	74	N
Mirar	190	4	95	10	4500	118	0.92	0.03	3	3	34.5	1.4	75	N
Katha	1521	80	75	12	83,800	21	1.2	1.88	0	0	13.6	1.3	76	N
Rabi	291	11	33	7	10,300	25	1.5	0.45	0	0	16	1.1	77	N
Malih	1673	14	51	11	5600	70	0.86	0.12	0	0	18.3	1.0	78	N
Bakra	1040	430	120	20	480,100	63	0.89	0.22	22	0	19.8	1.0	79	N
Sahn	1356	107	69	7	7800	10	1.11	0.32	0	0	13.9	0.9	80	N
Atwa	508	29	141	8	15,800	19	1.22	1.68	0	0	75.3	0.5	81	N

algorithm. Evaporation from recharge reservoirs with prolonged storage in central Saudi Arabia has been estimated using field measurements. Estimated volumes account to 10% of the storage (Abdulaziz et al., 1989). It was considered in the algorithm by calculating the average area of the reservoir at the beginning and end of the period when water was stored in the reservoir. Recharge dam was assumed to be emptied over a two-week period to allow for downstream shallow well recharge. Calculated daily run-off for the simulated rainfall events from the meteorological data was aggregated into monthly runoff for inclusion in this procedure. Monthly domestic and irrigation demand were calculated as specified above. The monthly aggregation was necessary to account for the seasonal variation in simulated inflows as a yearly time step would not capture the potential yield of the dams in dry land and would underestimate their effectiveness. For each reservoir, a graph was plotted that shows the required storage to meet a certain demand. The capacity limitation of each reservoir and the fraction of demand satisfaction were calculated indicating the amount of demand that could be satisfied from storing the reservoir capacity at the dam site. The required inputs for this process are the calculated monthly inflows of the dam catchment area, the monthly water demands based on the irrigated areas and projected population, required dam capacity to meet total demands, and available storage capacity based on the spillway height and the site topographic surveys. The output is the reservoir yield based on the actual reservoir capacity from which the percent demand satisfaction could be calculated. Cost per cubic meter of demand satisfied was estimated from the dam construction cost (Section 2.5.3).

2.7. Reliability analysis

Reliability of dams is a major criterion used in the prioritization of the ranking procedure. The reliability analysis method needs estimates of standardized reservoir size, net annual inflow, standard deviation of flows, skew, and standardized demand. Pegram's (1980) approach was used to determine the reservoir size-yield reliability relationship. The method is based on finite difference and integral equations, which employs the reservoir dynamics in a probabilistic context to determine the return period of emptiness. The generated flows were determined to be independent and log-normally distributed. The results are several relationships between the standardized reservoir size κ, the standardized inflow or drift ε, and the probability of non-emptiness α (herein referred to as the reliability); $\kappa := c/\sigma$, where c is the reservoir size (capacity at spillway height), σ is the standard deviation of annual net inflow X_t; $\varepsilon := (\mu - \delta)/\sigma$, where δ is the annual demand, μ is the mean of annual net inflow X_t; for known inflow moments, the reliability α for known reservoir size, the drift and skew can be determined from the combinations summarized in Fig. 5.

2.8. Index calculations

An index was created for every proposed dam for prioritization purposes. The index is composite, based on (1) percent total demand satisfied index (2) annual cost/m^3 of yield or percent demand satisfied index, and (3) probability of non-emptiness (herein used interchangeably with the term reliability). Two main scenarios were considered for reliability calculations: reliability of domestic demand only and reliability of domestic and irrigation demand. The rationale for the first scenario is as follows: shallow wells in rural areas in arid climate are used primarily for domestic uses. If water for irrigation demand cannot be reliable, this should not infer that the dam should receive a low priority or that it should be considered infeasible.

The dams are prioritized according to the following model:

$$PR_{Dam} = R_{Dam} \times \sum_{Crit} RI_{Crit} \times M_{Dam\ jth\ Crit} \qquad (2)$$

where $RI_{jth\ Crit}$ is the a measure of the relative importance of the jth criteria of the dam;

$$\sum_{Crit} RI_{Crit} = 1 \qquad (3)$$

where PR_{Dam} is the priority ranking (or total value index) for the dam; R_{Dam} is score reduction for the dam – a measure of the type and number of obstacles at the proposed dam site; and $M_{Dam\ jth\ Crit}$

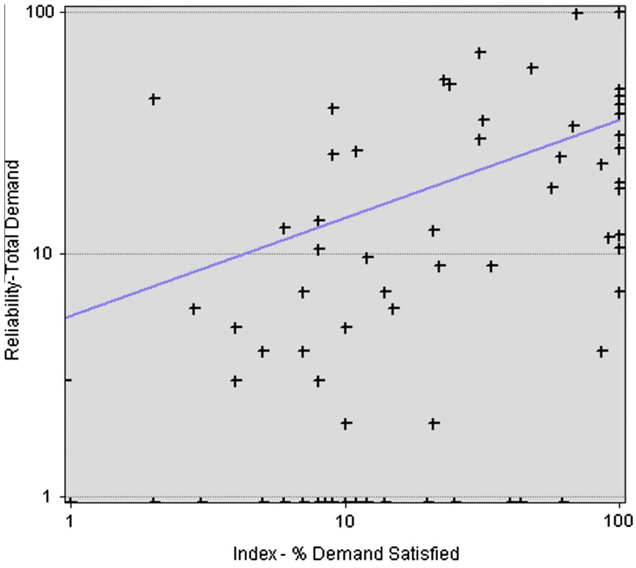

Fig. 6. Reliability (total demand) vs. Index of percent of total demand satisfied.

Table 2
Average of summary indices and results for dams grouped under three categories.

Average values	Priority		
	High	Low	Not feasible
Capital cost (MUSD)	0.94	3.15	1.42
Annualized cost (MUSD)	0.21	0.135	0.095
Yield*1000 (m^3)	281	160	26
AC/m^3 of Yield/DS	0.93	4.3	8.3
Reliability – domestic demand	74	34	22
Reliability – total demand	72	31	7
Mean annual flow (mm)	29	28	40
Index, total demand	73	47	10

is the a measure of the relative physical state of the *j*th criteria of the dam described by the following:

$$M_{dam\ jth\ Crit} = 100 - \left\{ \left(\frac{V_{Dam\ Crit}}{V_{Crit\ max}} \right) \times 100 \right\} \quad (4)$$

where $V_{crit\ max}$ is the maximum absolute value of the assessed physical criterion. The summation is over the entire assessed prioritization criterion. To avoid inducing a high degree of subjectivity, the score reduction factors were not estimated in this study.

3. Results and discussion

3.1. Structural, physical, and demographic characteristics

The dam catchment areas were characterized by relatively high curve numbers (a minimum value of 79), mainly due to the rugged topography and bare-soil characterizing landscape within Assir. Population served ranges from less than 100 to more than 12,000. Majority of the dams (80%) serves a population less than 2000. 75% of the dams had a catchment areas less than 20 sq. km. Majority of the dams (62%) were concrete, 26% were earthen, and only 12% were rock fill with a concrete core. Irrigated areas served range from 0 to 721 ha per dam. Dam heights varied from 5 m to 24 m. Dam lengths varied from 30 m to 842 m. Storage capacities ranged from less than 1700 m^3 to more than 1 MCM. Half of the dams have a capacity of less than 73,000 m^3, and half of them had a mean annual runoff less than 28 mm. The reason that small storage dams were included in the analysis is to avoid subjectivity in pre-screening of the dams and to assess the methodology effectiveness. The irrigated areas downstream of the proposed dams range between a minimum of 2 ha and a maximum of 721 ha. Potential annual evaporation ranges from 1770 mm to 2420 mm per year, depending on the location. The 3-month seasonal consumptive use varied between 582 mm and 822 mm. The total farmed areas for all the dams amount to 3372 hectares.

3.2. Yield, demand satisfaction and reliability results

Table 1 shows the studied dams along with their associated demographic, physical and hydrologic characteristics. Examples include the annualized cost/m^3 of yield-demand satisfied, and reliability results for the proposed dams. Shown also are the calculated mean annual runoff from dam sites, their corresponding coefficient of variation. Nearly 60% of the dams had a coefficient of variation (CV) of the mean annual flow greater than 1, indicating a large variation in the mean annual flows. The lowest CV was 0.6. 44% of the dams had a capital cost (CC) less than 1 MUSD. Domestic demand satisfaction according to the sequent peak method was more than 100% for 41% of the dams vs. only for 1% of the dams when considering total demand.

Nearly 64% of the dams had a reliability of less than 10% when considering total demand (domestic + agricultural), compared to 42% of the dams having a reliability of less than 10% when considering domestic demand only. Reliability of some dams was zero (17% dams when considering domestic demand only compared to 38% when considering domestic and irrigation demand). Of these 38%, all but 6% had an irrigation demand. Only 10% of the dams had reliability values above than 90% when considering domestic demand. The percentage dropped to less than 4% when considering total demand (Irrigation demand clearly reduced the reliability). 58% of the dams had a domestic reliability less than 20% vs. 74% when total demand was considered. 26% of the dams had a domestic reliability between 20% and 60% vs. 21% when total demand was considered, and 4% of the dams had a domestic reliability between 60% and 80% vs. 2% when total demand was considered. 11% of the dams had a domestic reliability greater than 80% vs. 2.5% when

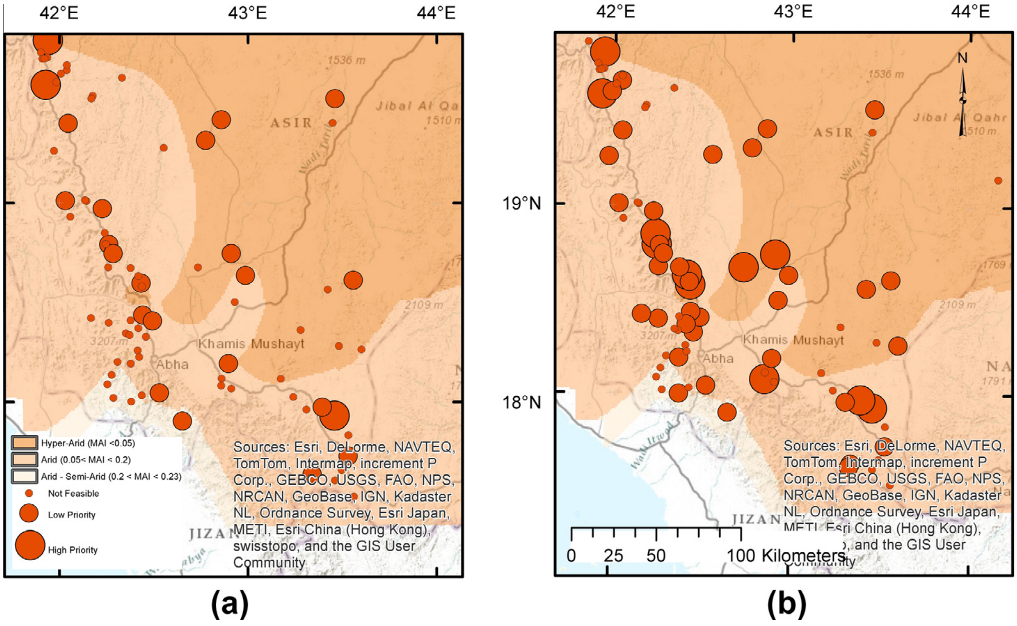

Fig. 7. Spatial distribution of dams according to priority and demand: (a) total demand; and (b) domestic demand.

total demand was considered. Including the irrigation demand in the yield and reliability calculations significantly lowered the reliability of the reservoirs by causing the drift to be negative (percentage of dams with negative drift increased from 13% to 37%). While only 3 months of the irrigation demand was included, the yield of the dams at the proposed storage was significantly reduced. Fig. 6 shows the reliability vs. the index of % total demand satisfied. In general, the reliability increases when the satisfaction of demand increases. The regression coefficient is small (0.2). The results are sorted by the index for in descending order (best scoring dams first). On Average, dams with the highest index have the lowest annualized cost/m^3 of demand satisfied, higher yield and highest reliability. Some dams have a high reliability given the storage-inflow-demand relationships.

The priority of the dams was divided into three groups: high, low, and not feasible. Table 2 presents an average summary of the results of the groups for both scenarios (domestic demand only and total demand). Including the irrigation demand lowered the feasibility of the dams and their priority. In the domestic demand scenario, the number of high priority dams increased from 3 to 11, and the number of low priority dams increased from 20 to 35. The number of infeasible dams decreased from 58 to 35 (from 71% of total to 43%). Fig. 7 shows the spatial distribution of the dams according to priority for the two scenarios. No significant relationship between the aridity index and dam importance/index was noted. All regions (hyper-arid, arid, and arid-semi-arid) had all priority dams when applying the domestic demand. The majority of the dams in the total demand scenario are infeasible, making the decision to pursue commissioning these dams hard to make. Given that there are no other options for water supply for the remote areas of some regions in Assir, the prioritization scheme is important for commissioning the dams within a same group of priority as it provides an objective method for such a process. It is recommended to look for better locations for some of the infeasible dams in terms of mean annual runoff with low CV and sites which can accommodate higher reservoir capacities. The GIS-based methodology presented herein will be a great aid in such a process.

4. Conclusion

Dam detailed studies and commissioning prioritization is a complex process that should involve the consideration of a multitude of factors. The following parameters that were assessed proved critical for the prioritization process; reliability, yield (or fraction of demand satisfied at the proposed storage), and annualized cost of satisfied demand. For investment planning purposes, a quick hydrogeological assessment using site information can prove effective in aiding the modeling process (especially determine the yield and the reliability – as the effective recharge percentage can be incorporated in both modeling processes). The contribution of this work is mostly in framing an integrated methodology that can serve as a baseline for prioritizing dams and studying their feasibility in similar environments. Dam prioritization should not rely on a single factor (for example reliability or yield). Several factors including cost have to be weighted for an effective investment decision making. The reliability and sequent peak method used for determining yield at reservoir capacities can be an effective duality in highlighting unfeasible dams. However, even at low reliability and demand satisfaction, the low cost of the dam can overrule the decision to not to build the dam, given that there are no other options for groundwater recharge in remote locations where the cost of other water supply options can be very high. The methodology developed herein does not include other factors that might be integrated in the prioritization process such as projected dam risk assessment. Other factors that could be incorporated in future work are to more accurately simulate the effect of the proposed dams on groundwater recharge, possibly by a suitable groundwater or a comprehensive watershed model. Given the lack of data in this respect, this was not tried at this stage. The methodology developed and presented herein is robust and can be applied to other agricultural recharge dam projects in arid regions, especially in areas where runoff measurement is lacking or insufficient.

Acknowledgements

The author is thankful for the late Engineer Hassan Youssef of Saudi consulting Engineering Company, who provided the rainfall data necessary for the completion of this work. This research was funded in part by the American University of Beirut Research Board (URB).

References

Adiat, K.N., Nawawi, M.N., Abdullah, M., 2012. Application of multi-criteria decision analysis to geoelectric and geologic parameters for spatial prediction of groundwater resources potential and aquifer evaluation. Pure Appl. Geophys. 170 (2013), 453–471.

Al-Muttair, F., Sendil, U., Al-Turbak, A., 1994. Management of recharge dams in Saudi Arabia. J. Water Resour. Plann. Manage. 120 (6), 749–763.

Al-Qurashi, A., McIntyre, N., Wheater, H., Unkrich, C., 2008. Application of the Kineros2 rainfall–runoff model to an arid catchment in Oman. J. Hydrol. 355, 91–105.

Al-Turbak, Abdulaziz S., Al-Muttair, Fouad F., 1989. Evaluation of dams as a recharge method. Int. J. Water Resour. Dev. 5 (2), 119–124.

Andersen, G.R., Cox, C.W., Chouinard, L.E., Hover, W.H., 2001. Prioritization of ten embankement dams according to physical deficiencies. J. Goetech. Geoenviron. Eng. 127, 335–345.

Bartholomé, E., Belward, A.S., 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. Int. J. Remote Sens. 26 (9), 1959–1977.

Chouinard, L.E., Andersen, G., Torrey, V.H., 1996. Ranking models used for condition assessement of civil infrastructure systems. J. Infrastruct. Syst. 2, 23–29.

Department of Land Management, 1985. General Soil map of Saudi Arabia. Ministry of Agriculture and Water, Riyadh.

Directorate of Projects Implementation, 2006. Dams in Saudi Arabia. Ministry of Water and Electricity, Riyadh.

Haimerl, G., 2004. Groundwater Recharge in Wadi Channels Downstream of Dams – Efficiency and Management. Institute of Hydraulic and Water Resources Engineering, Munchen.

Hydrology Division, 1983. Hydrological Publication No. 98. Department of Water Resources Development. Ministry of Agriculture and Water, Riyadh.

Jarvis, A., Reuter, H., Nelson, A., Guevara, E., 2008. Hole-filled seamless SRTM data V4. Retrieved from CGIAR-CSI SRTM 90m DEM Digital Elevation Database: <http://srtm.csi.cgiar.org/>.

Koustoyiannis, D., 2004. Reliability Concepts in Reservoir Design. In: Lehr, J.H. (Ed.), The Encyclopedia of Water. Wiley, Athens.

Lange, J., Leibundgut, C., Greenbaum, N., Schick, A.P., 1999. A noncalibrated rainfall–runoff model for large, arid catchments. Water Resour. Res., 2161–2172.

Maidment, D.R., 2002. Arc Hydro: GIS for Water Resources. ESRI Press, Redlands, California, USA.

Mcintyre, N., Al-Qurashi, A., 2009. Performance of ten rainfall–runoff models applied to an arid catchment in Oman. Environ. Model. Softw. 24, 726–738.

Michaud, J., Sorooshian, S., 1994. Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed. Water Resour. Res. 30 (3), 593–606.

Ministry of Water and Electricity, K. o. (2013, 2 25). Information and Statistics Center. Retrieved from Planning and Development Division. <http://intranet.mowe.gov.sa/Dams/>.

NASA. (2008, June 15). UMD Landcover classification. Retrieved from Global Lancover Facility Website: <http://glcf.umiacs.umd.edu/data/landcover>.

Natural Resources Conservation Service, 1997. National Engineering Handbook – Part 630- Hydrology. United States Department of Agriculture, USA.

Pegram, G., 1980. On reservoir reliability. J. Hydrol. 47, 269–296.

Pilgrim, D.H., Chapman, T.G., Doran, D.G., 1988. Problems of rainfall–runoff modeling in arid and semiarid regions. Hydrol. Sci. J. 33 (4), 379–400.

Rijsberman, F.R., 2006. Water scarcity: fact or fiction? Agric. Water Manage. 80 (1–3), 5–22.

Saudi Geological Survey. (2008, June 1). How to Order. Retrieved from Saudi Geological Survey Web site: <http://www.sgs.org.sa/English/Products/Pages/HowToOrder.aspx>.

Shovic, H.F., Hazelton, J.M., Roylance, S.M., Christenson, L., 2010. Water resources improvement in southeast Afghanistan: remote project planning and decision support modeling. In: Watershed Management 2010: Innovations in Watershed Management under Land Use and Climate Control. American Society of Civil Engineers, Washington, pp. 1094–1064.

Tizro, A.T., Voudouris, K.S., Eini, M., 2007. Groundwater balance, safe yield and recharge feasibility in a semi-arid environment: a case study from western part of Iran. J. Appl. Sci. 7 (20).

U.S. Weather Bureau, 1958a,b. TP-29, Rainfal Intensity-Frequency Regime, Parts 2–3. U.S. Department of Commerce, Washington DC.

UNEP, 1997. World Atlas of Desertification. United Nations Programme, London.

Zakhem, B.A., Hafez, R., 2012. Chemical and isotopic methods for management of artificial recharge in Mazraha Station (Damascus Basin, Syria). Hydrol. Process. 26 (24), 3712–3724.