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Chapter 2

INTEGRATED WATERSHED MANAGEMENT FOR RECHARGE DAMS IN SANA'A BASIN - YEMEN

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ABSTRACT

This chapter assesses the environmental, social and economical benefit of 10 constructed dams in small wadis within Sana'a Basin.

The average annual runoff volume available for recharge in the upper reaches of wadis (dam sites) varies between 15,000 and 258,000 m^3/yr with an average of 116,000 m^3/yr. For some dams' sites, the volume is very small and therefore they show cost ineffectiveness. Dynamic daily recharge was assessed for each site using analytical and at some sites, numerical approach (MODFLOW). The natural indirect recharge efficiency along wadi channel varies between 15% and 46%. This efficiency increased due construction of the recharge structures to varies between 57% and 94%. The shape of structure, reservoir conditions, siltation layer, and density of fractures are the controlling factors.

No additional recharge will be gained, when the outlet left open to discharge water freely along wadi channel as long as the reservoir bottom has been de-silted effectively. De-siltation of reservoir bottom should be thought of as an essential management practice to extend dam's life time. Also using open outlet will cause unresolved social conflict between upstream and downstream people at some sites. Check dams along the upper-middle lengths of wadis, where Alluvial deposits overlie Cretaceous Sandstone (e.g. Bahman) is found to be much more economical and effective in aquifer recharge terms comparing to gravity dams.

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Dams where water does not easily drain through either an outlet pipe or via a geological fault beneath the dam or due to presence of thick silt layer, there is a particular problem with total hardness and TDS. The high levels of evaporation occurring in these dams which feed the wells are likely to concentrate the minerals impacting on water quality. The need to ensure water quickly infiltrates the shallow aquifers after rainfall events via direct infiltration under reservoir is thus apparent.

The 10 dam sites studied offer significant environmental, social and economic benefits to the local communities within close proximity to dams. However, these benefits are of limited scale and do not affect the wider regional population of Sana'a Basin. Additional measures on demand side and/or conjunctive use of surface and groundwater are required to improve overall water situation. Mitigation is required to ensure the establishment and support of Water User Associations to solve people conflict, to facilitate the effective maintenance of the dam through the removal of silt, water quality and possible operation of the outlet pipe.

1. INTRODUCTION

Water availability in Sana'a City, capital of Yemen, is one of the scarcest in the world. The region has no perennial surface water runoff, and is practically entirely dependent on the use of groundwater. Over-exploitation is causing the groundwater table to deplete at an alarming rate and Sana'a Basin, with a water table drawdown of about 3 meters per annum, is amongst the worst affected areas in the country. Without resolution, the social, economic and health consequences for both rural and urban people will be severe. A solution, to at least slow down the depletion rate, was needed. Slow down of groundwater depletion will be undertaken by accelerate recharge of the shallow aquifers; persuade farmers to use that water instead of the deep primary sandstone, high quality water, World Bank (2003). Enhanced shallow aquifer recharge is one alternative to the water sustainability crisis occurring in Sana'a and many arid regions.

Intermittent and intense rainfall events over an arid watershed can lead to short term surface water availability. Without the proper management of this water resource, the excess precipitation can be quickly lost to the high evaporative environment or lost from the watershed via runoff. By ensuring that the available surface water remains within the catchment in the form of stored groundwater, a sustainable flux of water is obtained for the region, HKD (2002). Sustainability, defined in this perspective, allows a water resources manager to focus on ensuring a consistent yield corresponding to the climatically variable input. Artificial recharge may be defined as the process of replenishing ground water by augmenting the natural infiltration of rain water or surface water into under ground formations through various methods designed depending on the topographic, geologic and soil conditions. Artificial recharge is becoming more prevalent in the recent years because it can be used to buffer against climatic variability and associated floods and droughts as well as augment recharge to groundwater aquifers. Evaluation, sustainable development and management of groundwater in arid and semi-arid areas require a good understanding and accurate quantification of the main components of recharge. Uncertainty about recharge rates frequently leads to reluctance to implement aquifer management strategies and consequently may result in over-exploitation of the groundwater resources. In many areas, lack of data results in estimates of recharge rates which often vary widely, are based on a variety of assumptions and approximate calculations, and are inadequately supported by measurements.

Sana'a Basin Water Management Project (SBWMP), through their improvement supply demand has rehabilitated/constructed 10 dams' sites including a cascade dam's site within the Sana'a Basin, Figure (1).

This chapter discusses water management to be applied in these sites in two main parts:

1. Quantifying induced recharge under two distinct types of structures for artificial enhancement of groundwater from arid zone storm runoff. This composes analysis of actual field data using numerical models. Based on them, the efficiency of the recharge process is evaluated and recommendations for management strategies are given. Thus, suggestions for engineers who are planning, designing and operating recharge dams in similar arid regions are given.
2. Assessment of actual hydro-socio-economic benefit gained from these structures. For evaluation of options for resources management intervention, quantifying dynamic recharge volume alone would not be sufficient. There is need for detailed consideration of all components (technical and non-technical) to assess actual benefit of artificial recharge structure, including: environment, social and economic factors.

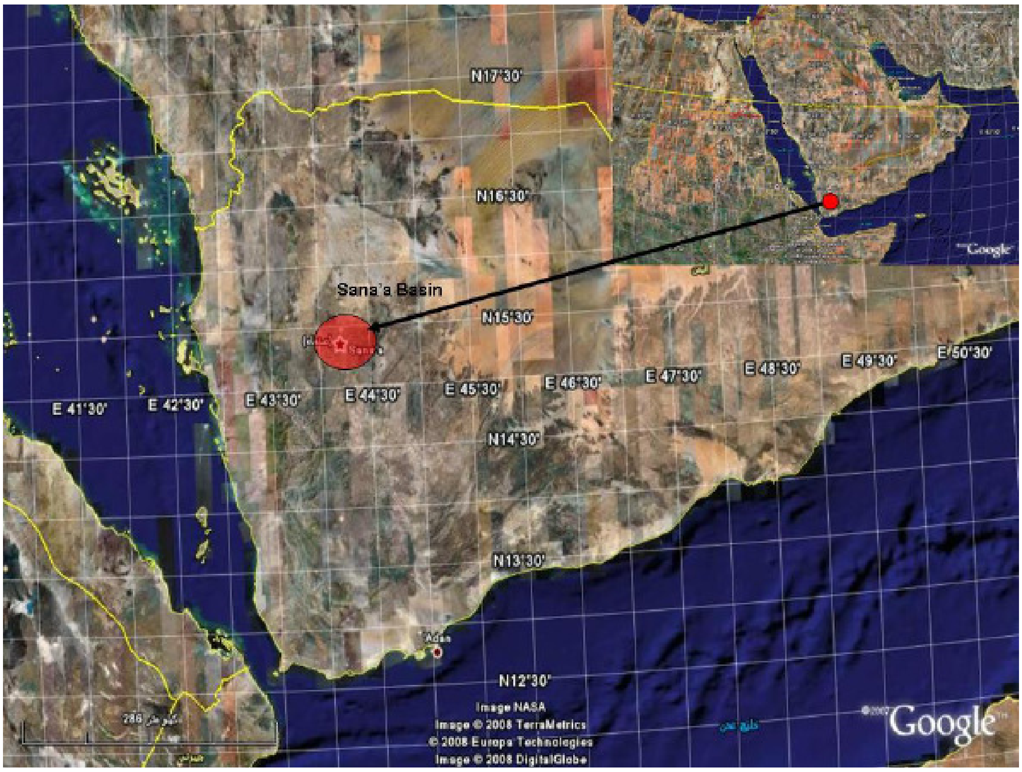

Figure 1(a). A map shows Sana'a Basin Location within Yemen Boundary

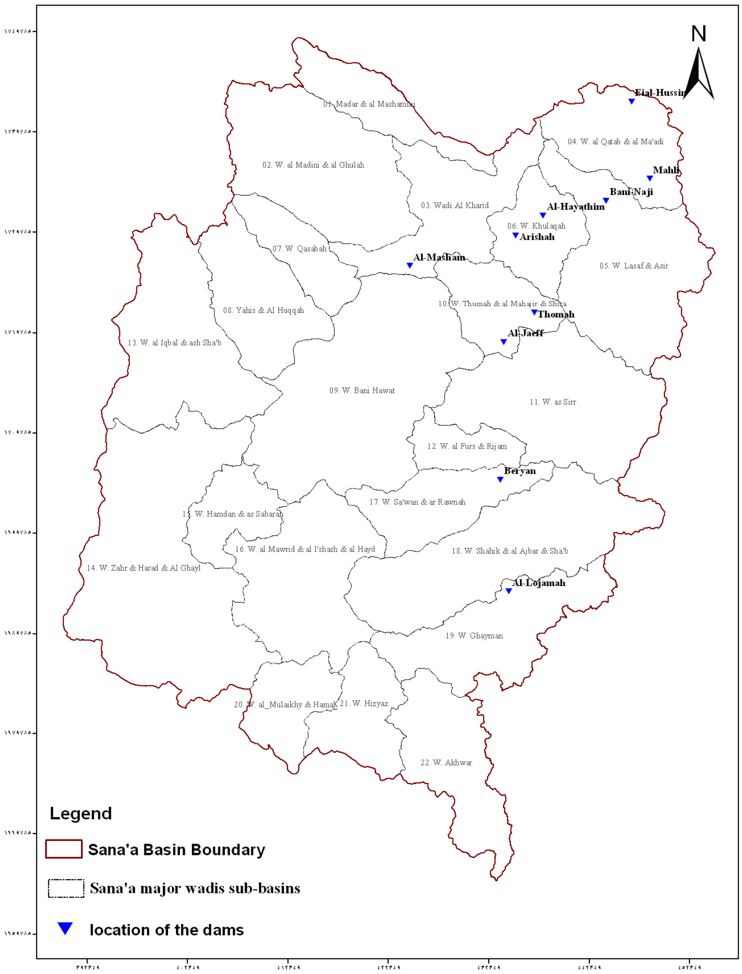

Figure 1(b). Studied Dams Locations within sub-catchments in Sana'a Basin

2. METHODOLOGY

2.1 The Conceptual Model of Dam Sites

The wadis in the study area are remote ephemeral streams. They are normally dry, with infrequent floods generated by rainfall of high intensity and short duration. When runoff occurs, the streams will often carry large volumes of water during a flood lasting a few hours.

The groundwater recharge thus is limited to the infiltration during intermittent flood flow in dry wadi channels. The flood water is used for recharge, irrigation and domestic purposes through surface dams. Most of dams (small-scale reservoirs) are constructed to recharge groundwater, some dams are also used for irrigation and only few are used for domestic purpose. Total volume of the annual flow through wadi in the study area is calculated to range between 24 and 41 MCM (JICA 2007).

The upper reach of the wadis are usually devoid of fine sediments as these are commonly washed out by flow and deposited in the downstream part, as a result of the decrease of the flood flow velocity. The wadi deposits are normally poorly sorted with a large variation in grain size, but are predominantly coarse grained. The sediments are generally permeable in the upper and middle reaches and are widely favorable for groundwater recharge. However, this permeability decreases in the downstream direction, Alderwish (1996), Foster (2003). The thickness of the vadose zone varies between 10-30m. The vadose zone thickness increases in the downstream direction where the channel bed is well above the ground water table. Naturally in wadi recharge a saturated continuity between the stream and aquifer does not commonly exist, so accuracy in the description of the shallow aquifer may not be required in recharge estimation. However, under reservoir conditions, saturated continuity between the reservoir and aquifer does exist and accuracy in the description of the shallow aquifer is required in recharge estimation.

The main purpose of check dams is to regulate the flood flow in the wadi by reducing its velocity through these dams. It delays (extends) the duration of flow over the wadi and hence increases infiltration. Check dams also remove fine suspended materials through settlement, providing clear water to the downstream part, which infiltrates more readily.

2.2. Hydrology

Sana'a Basin has an area of around 3,200km^2 and varies in elevation of 1900m to 3700m with an average of 2,200m above sea level. It is a hydro-geologically mostly self-contained highland plateau surrounded by mountains. The Basin is divided into 22 sub-basins reflecting surface water drainage systems and topography.

Catchment Characteristics

Table (1) presents a list of catchment characteristics for the 10 dams falling within the remit of the present study area. It shows the latest estimates of catchment areas. In addition, the Table presents information on the slopes of the catchments, which are key inputs for the floods volume and computed inflows.

Table 1. Dam catchment characteristics

Parameters	Catchment Area	Reservoir volume	Main stream length	Top water level	Max elevation	Slope S
Dam Sites	Area Km^2	Volume Mm^3	Length m	Level m	m	m/m
Al Hayathem	32.77	0.22	9170	2002.5	2610	0.066
Al Jaef	2.7	0.06	1750	2250	2400	0.086
Bani Naji	6.59	0.17	2900	2099.2	2390	0.1
Beryan	10.35	0.145	5500	2530	2880	0.0636
Lujma	1.30	0.028	1250	2575	2765	0.010
Mahalli	13.46	0.22	4200	2177.7	2670	0.117
Tozan	23	0.20	5,500	2320	2740	0.042
Arisha	6.66	0.351	3500	2113.5	2390	0.079

Thoma	7.25	0.130	3250	2230	2720	0.15
Bahman	10.16	0.145	4500	2335	2750	0.092

Catchment Rainfall and Runoff

In arid areas, daily rainfall data is required for computation. It is unlike seasonal and annual rainfall usually represents a measure of individual storm (cell) rainfall which might have limited areal extent. The results of the regression analysis attempted to relate the daily data from different rainfall gauges indicate poor relation (i.e very low coefficient of determination and high standard error of estimate).

Increasing of the time of span to 2 or 3 days, would provide better relation than the daily. This is probably because increasing of the time scale result in more events to occur, and hence represent a summation of a number of individual events (cells) that took place. This means that if it was possible to shift the rainy day up or down for one or two days, strong relations between the rain gauge records would become evident. The spatial variation of the daily rainfall is important in the choice of rainfall series to be used as input to a rainfall-runoff model. An input of areal rainfall over the basin estimated from several rainfall stations has produced runoff estimate that are insufficiently variable. (In other words, the rainy days are not the same for the all stations and a shift of one or two days is common). So instead, the study area has been divided into two rainfall zones; the first covers the north-east part and represented by NWRA HQ rain gauge. The second covers south-east part of the basin, and represented by Dar Salem rain gauge.

With respect to flow data for the Sana'a Basin, no data at all have been collected as yet. However, measurements of reservoir water level have been covered during last two years (2008-2009) by Sana'a Basin Water Management Project (SBWMP). For earlier period (2002-2007) the US Soil Conservation Service approach to flow generation with curve numbers (CNs) was used with CN values estimated from measurement of minor wadis flood in Sana'a Basin. The details of the methodology are presented in Alderwish (1995), Alderwish (2009). Compiled daily runoff volumes during 2002-2009 for each dam sites were used as input to the reservoir simulation model.

Catchment Climate

The climate of the Basin is subtropical, mild and moderately continental. Evaporation exceeds precipitation. The average annual precipitation of the basin is about 250 mm. The hottest month is July, with average temperatures of the order of 22 to 24 degree Celsius. The average annual temperature ranges from between 12 to 20 degrees Celsius. Average monthly relative humidity varies from 35% to 55%. Mean annual duration of sunshine hours is 9 hours per day. The average maximum wind velocity is 11 - 13 meters per second in winter, and 13 – 15 m/sec in summer. The rainy days are spread mainly from March to August. Annually, the number of rainy days range from 25 days (maximum) to 6 to 10 days (minimum).

Evaporation is basically a physical process, which transforms a liquid medium into vapour phase. The development of evaporation is basically determined by the energy needed to change the phase of a given amount of liquid which important for evaporation from free water surface. Due to the different type of soil, absence of vegetation, and infrequent floods in wadi channel bed, the actual evaporation was estimated from the assumed relationship between the ratio of Ea/Ep (the actual/potential evaporation) and the soil moisture content. The rate of fall at which actual evaporation falls beneath the level of potential evaporation as the soil moisture deficit increases is a controversial issue and a number of models have been proposed (TSHWC, 1992). This is might be true for a vegetated soil. However, for the wadi channel, a relation between the accumulated evaporation and square roots of time has been found, and hence a simple exponential decline was used to estimate the actual evaporation as the soil moisture content fall beneath the field capacity. This approach was required and imbedded in the calculation of daily runoff volume from catchments using the SCS method. For reservoir operation studies, open water evaporation (Eo) has been estimated using Penman-Monteith equation Monteith (1981) with rc equal zero. The actual evaporation rate from open surface water is given by:

$$\lambda E = \Delta\ (Rn\text{-}G) + \rho aCp/ra(es - ea) \qquad (1)$$

$$\Delta + \gamma$$

Where: E is rate of Evapotranspiration ($kg/m^2/s$), Δ is rate of change of saturated vapour pressure with temperature ($mb/^oC$), Rn is the net radiation (W/m2), G is soil heat flux density (W/m2), ρa is air density (Kg/m^3), Cp is specific heat of air at constant pressure (1005 J/Kg), es is saturated vapour pressure at screen temperature (mb), ea is screen vapour pressure (mb), γ is psychromatic constant, λ is latent heat of vaporization (= 2465 KJ/Kg), and ra is aerodynamic resistance s/m. Parameterization of various variables of the above equation for Sana'a basin is discussed, under two terms which contribute to the evaporation in the Penman-Monteith model; the aerodynamic term and the energy term (Aldewish 1995).

A combined daily series for meteorological elements for Sana'a airport station between 1983-1990 was completed from daily data from Al-Irra weather station which is located about 300 m from it. However, adjustment was not required, not only due to the closeness; Mos. (1986) proved that a synchronous daily variation of temperature, sunshine, relative humidity, and wind speed at all weather stations in and around Sana'a basin. As these elements are less variable than rainfall, the combined series for Sana'a airport weather station was used for the analysis.

Table 2. Meteorological Statistics (means over the period 1983 – 1990) and Computation Potential Evaporation at MET station of CAMA (Sana'a Airport).

Months	Temp ^oC	Relative humidity (%)	Sunshine duration (hrs/DAY)	Wind speed (m/s)	Monthly Eo mm	daily Eo mm
JAN	12.9	64.3	10.4	2.8	187.5	6.05
FEB	16.8	49.9	4.6	2.7	167.5	5.98
MAR	19.1	49.4	4.2	3.2	217.5	7.02
APR	19.6	57.8	7.7	4.4	256.25	8.54
MAY	21.9	43.8	10.1	3.8	318.75	10.28
JUN	23.5	41	9.6	4.8	351.25	11.71
JUL	23.5	41	9.6	4.8	360	11.61
AUG	23.5	47.7	7.6	4.3	311.25	10.04
SEP	21.4	39.4	9.5	3.2	278.75	9.29
OCT	18.5	38.7	10.6	2.9	256.25	8.27
NOV	15.7	39.5	10.2	2.4	197.5	6.58
DEC	13	39.4	9.6	2.8	190	6.13

MEAN	17.2	42.5	7.8	3.1	228	8.44

2.3. Hydrogeology and Reservoir Characteristics

The main aquifers of Sana'a comprise the Tawilah Sandstone, Tertiary volcanic, Amran Limestone and Quaternary deposits. Connections typically exist between various aquifers via fractures, faults and dykes. Local aquifers can also exist in fractured parts of otherwise poor aquifer formations. As can be seen from the list below, all dams, save perhaps for Arisha dam site, are located in rocks with good aquifer potential. Significant water storage within the underlying rocks is therefore available.

The locations of the 10 dam sites are situated in various geological formations. A brief overview of the hydrogeological characteristics encountered at each of dams' sites is given in Table (3).

Table 3. Summary of hydrogeological characteristics for studied sites

Dam site	The main aquifer underlying dam	Average Hydraulic conductivity (K) m/d	Average depth to groundwater table meter bgs.
Al Hayathem	Limestone with weathered igneous material as dykes	0.09	15
Al Jaef	Cretaceous Sandstone	0.09	10
Al Lujma	Tertiary Volcanic aquifer.	0.14	11
Arisha	Ahjur Formation shale and sandstone	0.035	18
Bani Naji	Jurassic Amran limestone	0.07	13
Mahalli	Cretaceous Sandstone	0.045	18
Beryan	Weathered Tertiary basalt	0.13	15
Thoma	Cretaceous Sandstone	0.056	11
Tozan	Cretaceous Sandstone	0.1	33
Bahman	Cretaceous Sandstone	1.29	19

Each of the above sites has different hydrogeological characteristics related to reservoir condition and potential for recharge from the dam. In addition each dam site contains variable thicknesses of alluvial wadi deposits that can act as aquifer. Brief description of reservoir conditions at each dam site is given below:

Al Hayathem

The wadi at the dam site consists of flat area (Qa'a like). The reservoir takes the form of a small, elongated lake surrounded by low but steep limestone valley walls, Figure (2). According to the GDI Report (2002) the estimated reservoir capacity is 250,000 m^3. There is high propensity for heavy siltation. Estimated volume of sediments was 32,000 m^3 in 10 years period i.e. about 3200 m^3/year, Halcrow (2006).

Figure 2. Looking upstream from dam crest (Halcrow, 2006)

Al Jaef

The existing reservoir is spread over a sandstone formation. The reservoir forms a small basin with steep rock slopes on either side, Figure (3). The reservoir occupies a wide channel measuring about 90 m wide when full. Downstream of the dam, the wadi channel begins to widen and ends in a wide cultivated area. Reservoir capacity is 60,000 m^3. Even though the dam has been in existence since 1998, very small amount of siltation is noted.

Figure 3. Rim of Al-Jaef Reservoir Lake within Sandstone Strata (Stanley 2006).

Al Lujma

The existing reservoir is spread over a highly weathered basaltic formation. The width of the reservoir is very narrow. The upstream part of the reservoir is filled with alluvial deposits to a reasonable thickness. The reservoir takes the form of small-elongated lake surrounded by steep basaltic valley walls. Reservoir capacity is 28,000 m^3. Average sediment rate was estimated at this site as 477m^3/year HKD (2002) to 553 m^3/year, Stanley, (2006).

Arisha

The reservoir area just upstream of the dam is basically a large flat shallow bowl. When full with water, the resulting large lake would present a scenic view, with a background of high rocky peaks. The entire bed of the reservoir consists of fine-grained soils. Siltation brought in the raising season is used by local people in farm development. The reservoir appears to be regarded by the local people as storage, not a recharge reservoir. In view of the surrounding geology and the high rate of siltation, this may be understandable, Figure (4). No wells observed within 1 km along the wadi, downstream of the dam. In addition the 'angry' frustrated locals did not allow continuous measuring of reservoir water level. Estimated rate of silt deposit in the reservoir averaged 3000 m^3/year.

Figure 4. View upstream of Arisha dam (Halcrow, 2007)

Bani Naji

The reservoir is a small, elongated lake surrounded by low, sometime steep valley walls of limestone and intermediate igneous rocks providing good containment. The reservoir survey has indicated a reservoir area at spillway invert level to be 32,678m^2 with a reservoir volume to this level of 170,000m^3. Vortex, every about 30 seconds, an air bubble rises from the reservoir and pops out of the water surface. As it breaks, the sound of "bump" is heard. It appears this may be an indication of a seepage conduit in the floor of the reservoir, but that the conduit is not entirely open or possibly partially obstructed, Figure (5).

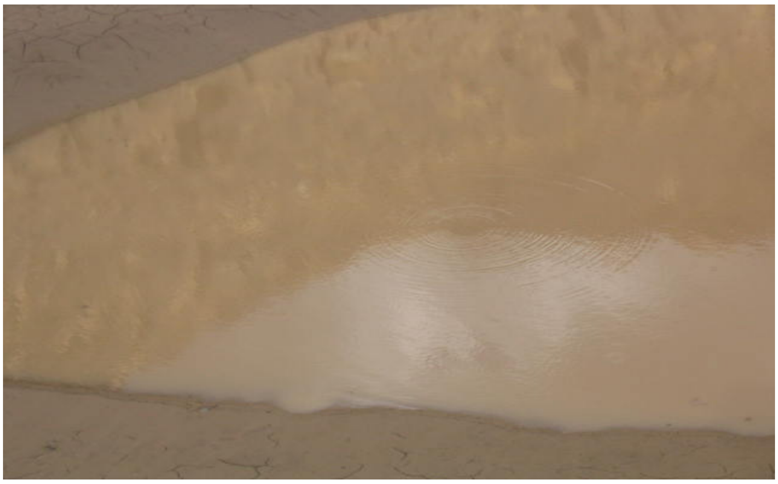

Figure 5. Vortex at End of Bani Naji Reservoir (Stanley, 2006)

Mahalli

The reservoir area is located within a porous intersection of shear zones. Even with a huge amount of silt and fine sand behind the dam, covering the whole impounding area, the reservoir still functions as a recharge reservoir. Actual reservoir capacity is around of 200,000 m^3. Silt rates accumulation was estimated at rate of 4500 m^3/yr.

Beryan

The existing reservoir is roughly square in shape measuring approximately 180mx180m. It is surrounded with high hills, which provide good containment. The existing reservoir is spread over a highly weathered basaltic formation. The upstream part of the reservoir is filled with alluvial deposits to a considerable thickness. The reservoir created by the existing dam has high banks around the entire perimeter. The reservoir capacity is determined at about 145,000 m^3. This corresponds to a reservoir level of 2,554.05 m according to the area capacity curves of Beryan reservoir. Reservoir spread area is about 51,800 m^2.

Thoma

The village of Thoma lies upstream of the dam and the cultivated area mainly lies between the village and the reservoir. The cultivated area extends over about 20ha but not all the land is farmed concurrently and continuously. Reservoir capacity reported as 130,000m^3.

Tozan

The built reservoir capacity is 200,000m^3. During 2002 the accumulated sediments depth is 5 m. Reading this height from the Depth-Area-Capacity curve that was used for the design of the dam. This height of sediments yields an area of 8,920 m^2 and a volume of 41,000 m^3. As the dam constructed in 1989, the annual average of silts accumulation estimated as 3400 m^3. With maximum height of the intake pipe is at 9 meters, this left the reservoir capacity to be 90,000 m^3. This makes the life of the dam (without de-siltation) be 14 years.

Bahman

The main channel is located in a narrow U-shaped valley. The remaining part of the water course, where the construction of series of check dams is carried out, crosses a relatively wide valley. The locations of these check dams are most favourable in the middle to the lower lengths of the wadi, where alluvial deposits are found over sandstone. Construction of check dams in the lower region of the wadi is likely to be more economical and effective for aquifer recharge, and it would be an excellent vehicle to engage local communities in practical action for water resources conservation.

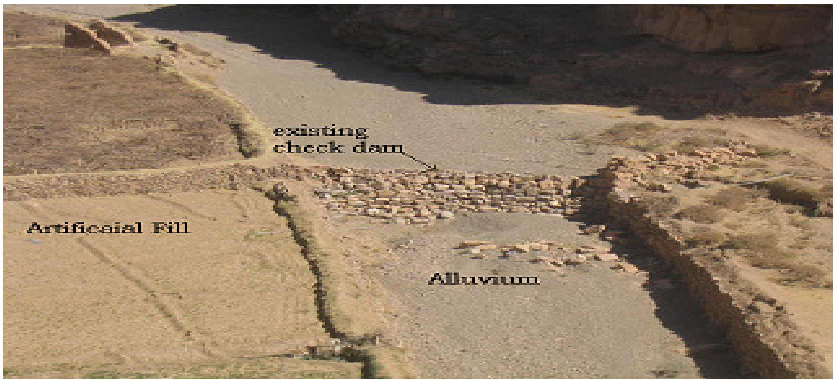

Figure 6. Downstream of Check Dam Area (Stanley, 2006).

3. Dynamic Recharge Assessment

Recharge from dam reservoirs in arid areas, which results from periodic flood inflows, is inherently not a steady-state phenomenon. At the outset, as the reservoir fills during a flood event, infiltration of the unsaturated zone begins as a vertical flow process. If the pre-existing groundwater surface is deep, this infiltration process may continue for some time, until the wetting front reaches the groundwater surface, and a saturated continuity is established. Only at this point in time can standard Darcian saturated flow methods be said to apply, in the strictest sense. In addition, there will follow various periods of increasing and decreasing water levels in the reservoir, and periodically, drying and re-wetting cycles, Alderwish & Dottridge (1995). Accurate and fully realistic descriptions of these processes require complex mathematical models, and in general can be said to be beyond any simple analytical solutions, Wheater, (1988). Assessment of dynamic daily recharge volume for 10 studied structures in Sana'a Basin was undertaken by applying the following:

1. Reservoir simulation model developed to determine the variability of reservoir's storage, water level height and area of inundation required for groundwater recharge estimate.
2. The developed model of reservoir simulation combined with a more refined Darcian approach involving an analytical approximation of a flow-net solution to estimate dynamic daily recharge to shallow aquifer.
3. Groundwater Modeling for simulations of groundwater flow beneath dam site using MODFLOW and reservoir simulation package.

3.1. Reservoir Simulation Model

Numerical Model

The numerical model used here is simple natural process taking place from a reservoir. It is presented on daily time unit. This is because the marginal additional outputs would be much different on the monthly time basis. In arid regions, using time span of more than a day to represent a hydrological event (process) would jeopardize the output of the simulation of that event (Alderwish, 1996). All the flood events get presented in the simulations and its utilization on the daily basis can be watched through the daily simulations. This approach in estimation of daily reservoir operation is more accurate than that based on the total volume of monthly runoff, or even approach uses daily runoff for simulation of monthly reservoir operation.

The conventional method to estimate reservoir subsurface seepage (recharge) is the water balance equation. A water budget determination of reservoir subsurface seepage (Qs) may be expressed as (Linsley et al, 1975):

$$Si = Si\text{-}1 + Qi + Pi - Ei - Ii - Ri \quad (1)$$

Si : storage at the end of the day i

S_{i-1} : Storage at the end of the dayi-1
Q_i : inflow during the day i
P_i : precipitation over the reservoir during day i
E_i : Evaporation from the reservoir during the day i
I_i : Infiltration under reservoir during the day i
R_i : spills from the reservoir during the day i

This approach is simple in theory, but application rarely produces reliable results since all errors measuring outflow, inflow, evaporation and change in storage are reflected directly in the computed recharge (Linsley et al, 1975). The accuracy of this method of calculation obviously depends on the accuracy of the initial data, the amount of the runoff and the evaporation. Model input, include:

1. Area and Storage Curve, Inundated surface area required for evaporation and infiltration calculations was estimated based on reservoir surface area and storage versus elevation curves developed previously for each dam site from topographic surveys by previous studies e.g. HKD (2002), Stanley (2006), and GDI (2002).
2. Inflow, the estimation of the daily runoff volume generated in the catchment area at the dam location was based on the SCS-RRM developed by the TSHWC (1992), and modified by Alderwish (1996) and calibrated for measured floods over Sana'a Basin. The model estimated daily runoff volume for the period Jan 2002 to Dec 2007, using daily rainfall from station of respected rainfall zone.
3. Precipitation, the direct precipitation over the reservoir was considered to have the same value as the used rainfall station for runoff calculation.
4. Evaporation, the evaporation from the reservoir surface was considered as given in table (2).
5. Other inputs, necessary for reservoir simulation is an average hydraulic conductivity of reservoir bottom. An average K of the reservoir bottom under silted and de-silted reservoir condition was estimated by calibrating available lake water level measurements. As in any normal reservoir operation, surface irrigation, water supply, water tankers, open of outlet.. etc is normally utilized simultaneously as the inflow enter the reservoir. Consequently, there is need to find the mean reservoir level as these would contribute to the depletion of the reservoir. The need of daily information on these parameters has been overcome through availability of daily information of reservoir levels during the period 2008/2009. This information allows calibration of "black box" model and parameterization of model parameters. The groundwater recharge expected from water spills from the reservoir was estimated using regression equation developed for natural indirect recharge through wadis of Sana'a Basin, Alderwish, (1996). This allows more accurate estimation of the induced recharge volume due to the structure.

The model proceeds by adding daily rainfall and runoff over the reservoir bottom while removing potential evaporation from reservoir storage. If the incoming runoff is higher than the height of the reservoir (spillway), surface outflow discharges.

(A) The rainfall (Pi) or/and surface inflow (Ii) on the ith day is added to (Si), the reservoir storage at the start of the ith day. Thus the revised uniform storage in the reservoir (S_{i-1}) will be;

$$S_{i-1} = S_i + I_i + P_i \quad (2)$$

At the dam site, after the daily runoff volume (surface inflow) is added to the storage of the reservoir, the new height of water at the reservoir and the inundated area of the reservoir is calculated using the developed height-area curve established from topographical survey at the dam site.

(B) The daily surface outflow, is checked and calculated as the difference between the maximum reservoir storage MAXS (=the amount of water over which water spillway over the dam) and S_{i-1}.

$$\text{Surface outflow} = S_{i-1} - \text{MAXST if } S_{i-1} > \text{MAXST} \quad (3)$$

And so reservoir storage S_{i-2} become equal to MAXST for the same day
Or

$$S_{i-2} = S_{i-1} \text{ if } S_{i-1} <= \text{MAXST} \quad (4)$$

Daily surface outflow to be discharged from the reservoir is calculated as a difference between the height of the water in the reservoir and height of the spillway.

(C) The daily potential evaporation on the ith day (Et_o) deducted from the reservoir storage in a daily basis. (By multiplying Et_o by the surface area of water in the reservoir, the actual evaporation is determined, (if dry Et_o=0))

$$\text{Revised storage } S_{i-3} = S_{i-2} - Et_o \quad (5)$$

(D) The reservoir storage S_{i-3}, after deducting the amount of subsurface seepage (Qt) will be.

$$S_{i-3} = S_{i-2} - Qt \text{ if } S_{i-2} > qt \quad (6)$$

And, the calculation is repeated for the subsequent day.

A daily infiltration rate (Qt) is estimated; using the average estimated K during calibration of the model for each dam site. It is assumed that no groundwater table mound is created, and that the rate of recharge from the reservoir bed equals the horizontal flow of groundwater in the shallow aquifer. The saturated K value is held constant over calculation period.

Reservoir simulation results include day to day values of main items of the daily simulation and presents; the runoff, the inflows, groundwater recharge, evaporation losses and the spilled away water. Measured and modeled reservoir water levels for studied dams' sites are depicted in Figure (7).

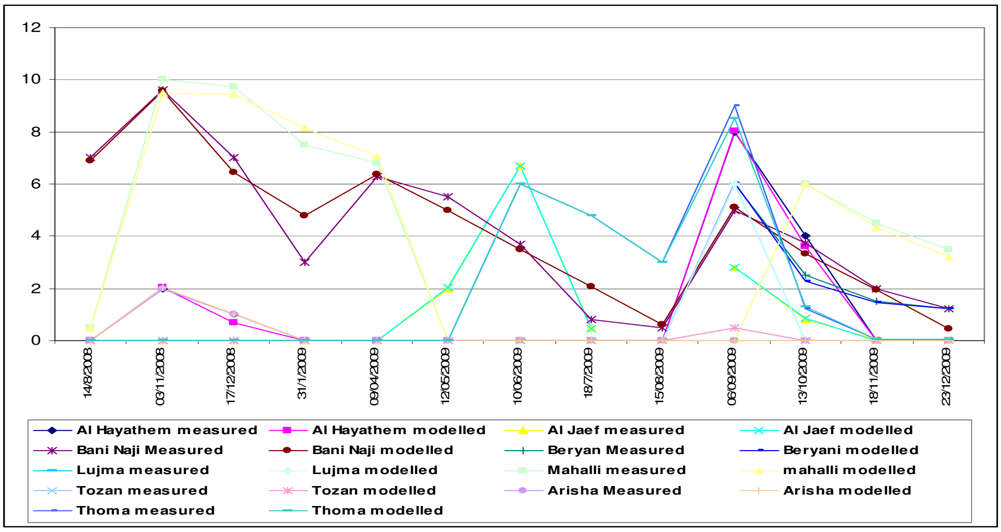

Figure 7. Measured and modeled reservoir water levels for studied dams' sites

3.2. Darcian Approach

For artificial recharge of groundwater, water is ponded to a considerable depth over limited areas for long periods of time. The aim of recharge operations is to saturate the soil down to the water table. Under these conditions the time variation of infiltration is complex, with temporary increases in rate superimposed on a gradually declining trend. Escape of soil air around the infiltration basin, bacterial action, changes in water temperature, changes in soil structure, and other factors influence these variations. Using Darcian approach, the subsurface seepage from the reservoir must be estimated indirectly from measurement of groundwater levels, permeability, water depth at the reservoir and other factors. The infiltration rate over originally dry reservoir bed can be predicted using classical one-dimensional vertical infiltration equations such as Green and Ampt, Besbes et al (1978) when a flood (water) inters the reservoir bed. However, once the wetting front reaches the water table, the flow becomes primarily horizontal and the Green Ampt method no longer applies. Another equation (method) should be applied following the beginning of the aquifer recharge. (i.e. the time of arrival of wetting front at initial water table position). Using flow net approach, the approximate two-dimensional recharge rate q (t) may be quantified using Darcy's law as:

$$q(t) = K\,A'\,\Delta h/L' \tag{7}$$

Where q (t) is the seepage rate m^2/d, K is the hydraulic conductivity m/d, A' is the average cross-sectional area of the flow tubes, Δh= is the piezometric head drop, and L' is the average length of the flow tubes which carry water away from the river bed to the lateral boundary, x=0. The average area of the flow per unit of reservoir length:

$$A' = ½ (W + [e + h(0,t)] \quad (8)$$

Where e is the initial aquifer average saturated thickness and h (0,t) is the groundwater recharge mound height deviation from the initial water table elevation at the boundary. Similarly the average length of the flow lines is obtained by the arithmetic mean of the boundary flow lines, namely,

$$L' = (2D + e + W – h(0,t))/2 \quad (9)$$

The head drop between the reservoir bed and the vertical lateral boundary (x=0) is:

$$\Delta h = H + D – h(o,t) \quad (10)$$

Substituting A' and L' in (1), an approximate formula for the recharge rate:

$$Q(t) = K [e + W + h(0,t)/2D + e + w - h(0,t)] [H + D – h(o,t)] \quad (11)$$

At time zero, this formula should reduce to q0, the discharge prevailing at the moment the wetting front merges with the initial water table. Equation (11) does not (as a result of the crude flow net approximation), but a slightly corrected form of it does, namely: Parissopoulos, et al (1995),

$$q(t) = q0 [(1 + h(0,t)/e+W)(1- h(0,t)/2D+e+W)-1][1 – h(0,t)/D+H] \quad (12)$$

Equation (12) has the proper limits for small and large times. Also it does not depend upon the manner in which q0 is estimated. For this reason it is preferred to (11), which is already approximate and in addition does not have the proper limit at time zero Wheater, et al (1995). Using (12) does not require that q0 be evaluated by a Green and Ampt infiltration formula such as (7), although (7) is particularly simple, convenient, and quite accurate, Reeder et al, (1980).

Dynamic daily recharge to shallow aquifer during 2002-2009 was estimated using the developed model of reservoir simulation (water balance, section 3.1) combined with a more refined Darcian approach involving an analytical approximation of a flow-net solution. Summary of the results of total recharge volumes by the two methods are given in Table (4).

Table 4. Total recharge volume at all dam sites during 2002-2009 under normal reservoir conditions

Assessed Parameters Dam sites	Total Runoff m^3	Spill Away water m^3	Total Inflow m^3	Evaporation m^3	Infiltration m^3 Water Balance Model	Infiltration m^3 Darcy Approach	Indirect recharge Downstream of the Dam (spill away water) m^3	Total Recharge Due to Dam Structure m^3	recharge efficiency
Al Hayatem	2,065,000	807,194	1,257,806	71,738	1,186,069	1,170,697	261,539	1,439,922	0.70
Al Jaef	343,300	121,207	222,092	29,623	192,373	183,000	41,104	228,791	0.67
Al Lujma	118,000	-	118,000	11,694	106,306	108,844	-	107,575	0.91
Arisha	853,100	220,468	632,632	240,440	418,894	427,646	63,068	486,338	0.57

Bani Naji	1,087,000	-	1,087,000	222,648	943,653	872,373	-	908,013	0.84
Mahalli	1,676,500	267,808	176,087	358,616	1,271,580	1,317,019	77,716	1,372,015	0.82
Beryan	435,300	5,242	430,058	46,055	385,241	364,674	26,286	401,243	0.92
Thoma	811,000	349,017	461,983	124,535	403,972	414,635	91,514	500,817	0.62
Tozan	811,000	349,017	461,983	124,535	403,972	414,635	91,514	500,817	0.62
Bahman	1,047,000	96,321	950,679	8,408	956,498	935,526	35,597	981,609	0.94

Figures of recharge estimated by two methods are in agreement for the 10 dams sites. This is in agreement of earlier conclusion, Alderwish, (2009), that simple approach developed carefully can provide acceptable results for estimation of induced recharge under dams' sites.

Recharge efficiency for studied gravity dams' sites varies between 57% for Arisha and 92% for Beryan dams. Check dams of Bahman shows recharge efficiency of 94%.

3.3. Numerical Simulation (Modflow)

Four dam sites with sufficient data availability allow use of groundwater numerical simulation (MODFLOW) to provide better understanding and quantification of dam sites surface and groundwater resources availability. The reservoir package (Fenske et al 1996) simulates leakage between a reservoir and an underlying ground-water system which allow assessing the effect of different dam/groundwater recharge (interactions) i.e. direct sub-reservoir recharge. These simulations involved using all available information including monitoring data for reservoir and groundwater levels available for the period 2008/2009. The groundwater divide and surface water divide of catchments are the same. The groundwater flow follows the topography of the area. After infiltration in lowland areas, the water flows downwards. Used parameters and results for the four dam sites studied are summarized in Table (5). The numerical study of the recharge process is carried out with regard to four site-specific and existing management practices. Detailed site specific are discussed in Alderwish, 2010. The influence of the interaction of all manageable recharge parameters as it occurs in the field on the recharge percentage is calculated.

Table 5. Results of groundwater modeling at four dam sites

Dam sites	Al Hayathem	Al Jaef	Bani Naji	Mahalli
Aquifer type	limestone with dykes	Sandstone	Limestone	Sandstone (L.S.)
horizontal hydraulic conductivity m/d	18	1	10.71	1.2
vertical hydraulic conductivity m/d	0.015	0.011	0.032	0.02
Total leakage during simulation m^3	231,953	25,453	433,697	409,774
Total groundwater abstraction during simualation m^3	94,477	111,741	54,969	1,557,243
difference between leakage and abstraction m^3	137,476	86,288	378,728	1,147,469
Time steps (days)	1096	235	731	1096
Average daily leakage rate m^3	212	108	593	374
depth to groundwater table under reservoir mbgs	13.5	2	10	1
number of cells over modeled area	613	234	194	245

Total inflow water m^3	306,000	27,300	507,000	611,500
An average reservoir area m^2	15,625	5,000	7,800	15,625
Total reservoir water elevation mags	19.58	5.46	65.00	39.14
An average water depth in the reservoir	0.018	0.023	0.089	0.036
Daily leakage/kv	14,109	9,846	18,540	18,694

The analysis resulted in the following conclusions:

1. There is general agreement between recharge figures estimated by analytical solutions (Water balance and Darcian approach) and groundwater numerical simulation results. Indicative recharge rates, behavior of the groundwater mound in response to induced infiltration after accumulation of water in the reservoir, and vertical hydraulic gradients established in situations where D is large, all confirmed the validity of the analytical approaches, within the bounds of the assumptions and limitation discussed in Alderwish (2009).
2. There is a high positive correlation between vertical conductivity and leakage rate for all dam sites (R2=0.985). The high the Kv the more leakage amount. Similar correlation established with horizontal aquifer hydraulic conductivity for three sites. Al Hayathem dam site is exceptional. The groundwater flow in this site controlled by igneous intrusions. There is clear delay of surface recharge water to reach wells in the downstream side of the dam. This has been explained by presence of the reservoir on an area forming Qa'a like (graben). Along 8km of the wadi channel, the area is surrounded by a contour line of 2200 masL. Distribution of groundwater mound under the reservoir is dissipating toward upstream part more than toward downstream direction, causing delay of recharged water to reach the downstream wells. The groundwater table at this site is the deepest between all sites, and an increasing groundwater depth reduces the vertical percolation rate as has been shown by Haimerl (2001).
3. Al Hayathem and Bani Naji sites show positive (enhanced) recharge over groundwater abstraction during simulation period. Mahalli has highest groundwater abstraction comparing to other sites, while Al Jaef dam reservoir remained empty for rehabilitation over long period of simulation.
4. The affect of the water level of the reservoir shows leakage rate is increasing with an increase of surface water level at all dams' sites. The high leakage amount observed at Bani Naji site despite its relatively smaller reservoir area than Mahalli and Al Hayathem imply that reservoir water depth is more significant for an effective recharge than the area of the reservoir.
5. Groundwater occurrence and flow in the study area is controlled by structural geology. Fracture aperture, density, length and orientation, as well as the presence of dykes and faults, appear to play prominent roles in groundwater flow at these dam sites and consequently the leakage volume and its destination. Dams constructed over limestone aquifer, shows highest leakage amount as it is permeability is originated from the crushed/faulted, fissures, fractures rocks (e.g. Bani Naji). However, presences of igneous intrusions reduce the amount of leakage as observed at

Al Hayathem dam. For this site, the intruded bodies cause infiltrating water to migrate away and not contributing to recharge of target formation (site).

6. Daily leakage rate/Kv shows positive correlation with inflow water

4. HYDRO-SOCIO-ECONOMIC DAM BENEFIT ANALYSIS

The rigorous technical and economic evaluation of the effectiveness of recharge enhancement structures is far from straightforward. Several factors are involved. The key requirement is to estimate the additional runoff that is recharged over-and-above that which would have occurred naturally (i.e. the difference between 'with project' and 'without project' conditions). Therefore, to assess the actual benefit of the structure, only induced recharge caused by structure should be estimated. This means that natural indirect recharge through the wadi channel should be evaluated and deducted from the total recharge caused by the construction of the structure. The natural indirect recharge was assessed using regression relation developed between generated runoff and wadi recharge in Sana'a Basin (Alderwish, 1995).

For three dams' sites, the incremental recharge due to construction of the dam has been assessed under two different conditions of the reservoir (silted and de-silted), using generated runoff volumes during 2002-2009.

Incremental Recharge under Silted Reservoir

For three dam sites, measurement of reservoir water level when reservoir was silted and after de-siltation allows assessment of the effect of de-siltation process of the reservoir bottom. Summary results of incremental recharge during 2002-2007 are given in Table (6).

Table 6. Annual Average of incremental recharge under silted reservoir conditions

Assessed Parameters	Total Runoff m^3	Evaporation m^3	Total Recharge Due to Dam Structure m^3	Natural indirect recharge (without dam) m^3	Incremental Recharge m^3
Al Hayathem	258,125	65,164	139,461	83,365	23,402
Bani Naji	135,875	84,310	49,829	68,174	- 18,345
Mahalli	209,563	50,951	136,077	79,326	56,751

The efficiency of incremental recharge to inflow water of Mahalli dam under silted reservoir is 32% and for Al Hayathem is 15%. While for Bani Naji dam negative (less) recharge gained from the silted reservoir than natural indirect recharge. Therefore, an essential aspect of the maintenance of all such structures should be the periodic removal of alluvial sediment (fine sand, silt and clay) and organic material (bacterial slimes and algae) that tend to accumulate, so as to restore the infiltration capacity of the reservoir and/or wadi floor. It is important that the materials removed are recycled as a top dressing for agricultural soils. This can further be followed as shown in Table (7).

Table 7. Recharge under silted and de-silted reservoir bottom at three dams' sites

Reservoir condition	Silted reservoir 2002-2007			De-silted reservoir 2008-2009		
Dam site	Total recharge volume m^3	Recharge volume to inflow water %	Average K- of reservoir bottom m/d	Total recharge volume m^3	Recharge volume to inflow water %	Average K- of reservoir bottom m/d
Al Hayathem	745,498	68	0.01	149,897	93	0.20
Bani Naji	212,702	37	0.01	423,517	84	0.07
Mahalli	934,364	71	0.04	68,263	76	0.075

At Al Hayathem dam site, the high percentage of increase of total infiltrated water to total runoff (93%) after the reservoir was de-silted indicates full recovery of clean reservoir bottom. Consequently excellent recharge through reservoir bottom can be attained through effective silt removal process. This further, supported by results of recharge volume after de-siltation at Bani Naji dam reservoir. The results refers sustainability to enhance dams' recharge can be attained through regular reservoir sediments removal. Exception, noticed at Mahalli site, where only 5% increase of recharge volume has been achieved after de-siltation process. Structures (fissures, factures, faults) apparently is the controlling factor of the amount of infiltrated water. This implies that recharge takes place through the reservoir banks (via unclogged fractures), rather than through the highly silted bottom. Numerical study has confirmed the affect of the structural control on the amount of leakage.

Incremental Recharge under De-Silted Reservoir Condition

Table 8. Annual average of incremental recharge under-de-silted reservoir

Assessed Parameters	Total Runoff m^3	Evaporation m^3	Total Recharge Due to Dam Structure m^3	Natural indirect recharge (without dam) m^3	Incremental Recharge m^3	efficiency of indirect recharge m^3	efficiency of recharge due to dam construction m^3
Al Hayatem	258,125	8,967	179,990	83,366	96,624	0.32	0.70
Al Jaef	49,043	4,232	32,684	18,249	14,436	0.37	0.67
Al Lujma	14,750	1,462	13,447	2,200	11,247	0.15	0.91
Arisha	106,638	30,055	60,792	38,780	14,129	0.36	0.57
Bani Naji	135,875	27,831	113,502	60,511	52,990	0.45	0.84
Mahalli	209,563	44,827	171,502	79,630	91,872	0.38	0.82
Beryan	62,186	6,579	57,320	25,364	28,201	0.41	0.92
Thoma	115,857	17,791	71,545	53,177	18,368	0.46	0.62
Tozan	115,857	17,791	71,545	53,177	18,368	0.46	0.62
Bahman	130,875	1,051	122,701	44,541	78,160	0.34	0.94

*A 40% reduction in recharge volume under de-silted reservoir condition can be assumed to estimate recharge volume under silted reservoir (HKD, 2002).

Bahman checks dams show highest efficiency of recharge followed by smaller gravity dams. The least efficiency, in general, noticed for larger dams. For cases under study, depending on site-specific boundary conditions dams recharge varies between 57% and 94% of average annual runoff to the aquifer.

These results indicate induced infiltration through dams' reservoir bottom is an effective approach to enhance groundwater recharge at minor wadis in arid areas. For existing dams, regular de-siltation of sediments from reservoir bottom would keep this approach effective. Therefore, there will be no need to alternative policy to regulate slowly release of the stored floodwater downstream to infiltrate in the wadi bed downstream as had been suggested before e.g. Halcrow (2006). Although this policy try to optimize dams' recharge management to the best benefit for the aquifer, through spreading stored water spatially and temporally. It did not oversee the importance of silt removal not only to improve infiltration but as essential regular process to extend the life of the dam. The importance of silt removal was confirmed during simulation of reservoir operation at two dam sites. During calibration of reservoir of Al Jaef dam using observed data and information, it was possible to quantify the water discharged from the reservoir through the outlet. This is carried out as follows:

[1] an average K of the reservoir bottom was estimated by calibrating measurements between 5/9/2009 and 12/10/2009.
[2] the released amount of water through outlet during June/July 2009 was quantified as 19,500 m^3, using impeded stage-capacity-area curves in the reservoir model.
[3] as this water flow along wadi channel, 17,394m^3 (89%) has been infiltrated to groundwater aquifer using daily constant volume of outlet discharge of 541.66 m^3/d (19,500m^3 /36 days).
[4] with no outlet discharge, the infiltrated water through reservoir bottom would have been 16,821m^3 (86%) of inflow water.

This means that no additional recharge would have been gained, if the outlet left open to discharge water freely along wadi channel as long as the reservoir has been desilted. Similar results of equal infiltration percentage (86%) for recharge from regular outlet discharge and bottom of the reservoir.

It has been observed that the evaporation quantum has been LESS than the recharge quantum. This is because hydraulic conductivity values are greater than the evaporation depth value. The evaporation depths are known to be high in the Sana'a Basin, as shown in studies done by SAWAS (1998) based on Evapotranspiration studies which is average as 8.4 mm/day (i.e. 0.0084 m/d). This means unless Kv of reservoir bottom is equal or less than 0.0084 m/d the recharge would be greater than evaporation. Within the study sites, the infiltration rates are some ten to hundred times higher than the evaporation rates in the Sana'a Basin. As an example for Thoma dam, K for reservoir bottom is 0.06 m/d and average daily evaporation rate is 0.0084 m/d, this means the infiltration rate is ten times higher than evaporation.

Lujma dam site show highest increase in recharge efficiency due to dam construction. It has the smallest reservoir capacity and highest hydraulic conductivity due to weathered/fractured tertiary volcanic (basalt). This implies that when designing recharge structures increasing surface water level would increase infiltration rate. The least efficiency observed at Arisha and Thoma dam sites due to their small hydraulic conductivity due to lithology of the reservoir/aquifer. This means, sand, gravel, densely fractures are important to achieve reasonable effective recharge volume. The least efficiency of Tozan dam site may be related to the deep groundwater table (33mbgs). This is in agreement with study conducted by

Hameirl (2001) in Sultanate Oman, that increasing of groundwater depth reduces the vertical percolation rate.

The highest efficiency of recharge achieved for Bahman. Cascade dams proofed to be the most effective method of recharge enhancement in arid minor wadis. Mainly as this design allow an increase of opportunity for recharge in space and time.

Dams Cost Effectiveness

Cost effectiveness of 10 studied dam sites was assessed in terms of US$/$m^3$ of water harvested from dams. The results were compared with the cost incurred on dams construction/rehabilitation to determine the recovery cost period. Summary of the results for 10 dams are given in Table (9).

Table 9. Value of recharged water and period of cost recovery

Dam site	Annual Incremental Recharge m^3	cost of recharged water US$	cost of rehabilitation/construction US$	recovery cost period years
Al Hayatem	96,624	109,800	534,000	4.9
Al Jaef	14,436	16,405	280,649	17.1
Al Lujma	11,247	12,781	164,091	12.8
Arisha	14,129	16,056	319,664	19.9
Bani Naji	52,990	60,216	177,195	2.9
Mahalli	91,872	104,400	362,831	3.5
Beryan	28,201	32,047	915,663	28.6
Thoma	18,368	20,873	707,680	33.9
Tozan	18,368	20,873	218,170	10.5
Bahman	78,160	88,818	182,082	2.1

The value of recharged water assessed as 250 YER ($ 1.1) for a cubic meter following the cost estimate of cubic meter of de-salineated water taken to Sana'a (TREC, 2006). SBWMP rehabilitated 8 existing dam sites and constructed two new dam sites. The new dams built by the project were Beryan (gravity dam) and Bahman (cascade dams). The following is comparison between the newly constructed Bahman check dams and Beryan gravity dam.

Assessed parameters	Beryan	Bahman
Average annual runoff m^3	62,186	130,875
Reservoir capacity m^3	145,000	149,171
Average Annual recharge m^3	55,034	118,252
Total Recharge Due to the Structure	57,320	122,701
Average annual Incremental recharge m^3	28,201	78,160
Cost US$	915,663	182,082
Efficiency of incremental recharge due to dam	0.45	0.60

Comparing the incremental recharge, value of incremented recharge water and cost of construction for these two sites indicates the cascade dams of Bahman shows triple the amount of incremental recharged water than Beryan (gravity dam), with only about one fifth of the cost of construction of gravity dam (Beryan).

Environmental and Social Benefit

In this assessment special considerations are given on the water use and water management issues. The most significant factor in environmental and social terms is that the Sana'a Basin is suffering from rapid and severe depletion of groundwater as water from both aquifers is used for domestic, industrial and agricultural use. Rates of extraction far exceed both natural and artificial recharge (i.e through irrigation and wastewater return flow), its use is inefficient and water extraction is still not fully regulated (formally and informally) throughout the Basin. The rehabilitation of existing dams and construction of new dams within the Supply Management and Aquifer Recharge Study component of the SBWMP has been the subject of a comprehensive Environmental Impact Assessment (EIA) according to World Bank guidelines and Republic of Yemen's environmental assessment legal requirements. The key environment and social benefits of the 10 dams were assessed during design studies undertaken by Halcrow (2006), and Stanley (2006). Summary of those benefits are discussed below.

The main benefits emanating from that assessment were recharging of the shallow aquifers downstream of the dam providing additional water for irrigation and domestic use. Quicker drainage of the reservoir's water content could assist in lessening the hardness of the water with current problems likely to be associated with evaporation of water and build up of minerals in the silt remaining. The benefits could trigger social improvements such as reducing time for women and girls to fetch water helping them to stay in primary school longer, providing a more consistent water supply for agriculture and thus reducing buying costly tanker water in the drier months. With some additional sanitation and health programmes there could be health improvements particularly in relation to reducing the incidence of waterborne disease. The Water User Associations (WUA) should be established at each site to facilitate improved water management within the villages in close proximity to the dam and potentially effective local management of the dam. The operation of the outlet pipe will be a key function of the WUA currently being established to manage water, its use and to manage the every day operation of the dam. For Bahman check dams, the positive environmental impacts are additional water for domestic and agricultural use, increased employment of people living near the check dams, and improved flood control. The initial recommendation for maintenance of all the check dams would be to remove the alluvial sediment, fine sand, silt, clay and organic material that accumulate behind the check dams. Removal of this material would restore the infiltration capacity of the wadi floor. The material removed can be used as a top-dressing for agricultural soils. The use of drip irrigation as an alternative irrigation method is good option in managing demand side of water and should be applied conjunctively with dam construction. In Bahman, check dams system proves to be reasonable, economic and practical.

Some negative aspects include the potential decrease in water supply further downstream from the dam, and the potential to use the replenished shallow aquifers water supply for increased growing of qat and this could trigger increased use of pesticides and exacerbate groundwater extraction. With regard to downstream impacts the impact on ground water supplies are expected to be minimal. While two other programmes under the SBWMP include the preparation of pest management plans and irrigation improvement projects which will partly address cultivation of qat and excessive use of pesticides.

Recharged Water Chemistry Aspects

Evaluation of water quality aspects of Wadis on which the studied 10 dams exists were based on chemical analysis results during 1984 (83 samples) by Mos. (1986), 1994 (27 samples) by Alderwish (1996), 2005 (8 samples) by Halcrow (2006) and 2010 (63 samples) by SBWMB and Alderwish (2010), Table (10).

Table 10. of average TDS in mg/l of all samples for different wadis' dam sites

Dam site	MOS. 1986	Alderwish 1996	Halcrow 2006	SBWMP (2010
Maadi	844	NM	314	792
Al sirr	444	761	NM	776
ghyman	397	NM	NM	311
khulqa	1032	NM	707	919
mahajir	1580	NM	1304	924
Al Rawnah	346	469	NM	483
lafafa alsir	NM	NM	937	812
Zahar	NM	NM	NM	264

*NM= no measurements

The present water quality of the groundwater is a blend depending upon the history of quantity and quality of aquifer and recharged water. The potential sources of recharge are: reservoir (wadi flow) infiltration, irrigation return, and return flow through cess-pits within settlement areas and commonly share the same recharge areas, (i.e. wadi bottom). The main aspects of water quality at studied dam sites are;

Al Hayathem, Arisha and Bani Naji (Wadi Khulqah)

Slight reduction in TDS noticed between 1986 (1032mg/l) and 2010 (919mg/l). TDS of nearby dam sites shows lesser TDS of 707 mg/l and indicates active fresh recharge under reservoir site. 57% of all samples are brackish (TDS >1000 mg/l) dominated by Na and SO4 ions probably originate from gypsum dissolution, ion exchange and oxidation of pyrite. Solubility of aquifer material and its affect on water quality together with the effect of evapotranspiration and leaching has been manifested at these sites (wadi). The annual potential evaporation in Sana'a basin exceeds annual precipitation by a considerable amount. Thus, water that infiltrates in normal precipitation years evaporates and deposits small quantity of gypsum. Repeated rain events result in accumulation of gypsum in the upper part of the soil horizon. The rate of accumulation would increase significantly in the case of irrigated land.

Bani Naji (Wadi Al Hada'al)

20% of the samples has TDS >1000mg/l. The average TDS of the 10 samples from this sites show TDS at the edge of brackish water (800-900) with high Na and Cl constituents resulted from ion exchange process that actively through the limestone rocks of marine origin.

Mahalli (Wadi Al Maadi)

During 1986 TDS was 844 mg/l which is decreased during 2010 to 792mg/l. The two samples analyzed during 2006 near dam site show little TDS of 314 mg/l that resulted from dilution by fresh recharge water pulses. In general, 40% of samples analyzed have TDS of more than 1000 mg/l (brackish water) with main constituents of Ca, SO_4 resulted from dissolution of gypsum/anhydrite in the Amran Group. Samples with Ca, Na and Cl indicate affects of recycled water and associated with areas of high population and/or intense agricultural activities.

Al Jaef and Thoma (Wadi Al Mahajir)

Although general reduction in TDS values observed, 60% of samples are brackish dominated by Ca and SO_4 resulted from dissolution of gypsum. The reduction may indicate indirect natural recharge through wadi/reservoir is higher than irrigation return flow (recycled) along wadi bottom.

Beryan (Wadi Al Rawna)

100 mg/l in TDS values was the increase between 1986 and 2010. No brackish water has been recorded at any sample from this site. This reflects the least solubility of volcanic materials. Highest TDS is 739mg/l, with high nitrates and related to impacts of recycled domestic waste.

Al Lujma (Wadi Ghyman)

Slight reduction in TDS noticed between 1986 and 2010. All water samples are fresh and reflect hardly soluble volcanic materials. However, most of water is dominated by Na, and hence return flow percentage must be carefully guarded to prevent problems associated with sodification.

Bahman (Wadi Al-Sir)

In 1986 average TDS was 444mg/l which increased to be 761 in 1995 and 776mg/l in 2010.

9% of all samples analyzed are of brackish water (TDS>1000mg/l). These samples are either with high iron content (>2mg/l) indicating old water or with high nitrate level and reflects recycled water affect. Hydrochemical results at certain areas, suggests significant mixing of groundwater from the Quaternary deposits and the Cretaceous Sandstone is taking place, particularly where sandstone outcrops or is near to surface (i.e. hydraulic interconnection).

Tozan (Wadi Zahr, Iqbal)

4 samples during 2010 show an average TDS of 264mg/l and indicate fresh water of Ca-HCO_3 composition.

In summary, those dams where water does not easily drain through either an outlet pipe or via a geological fault beneath the dam there is a particular problem with total hardness, electrical conductivity, sulphate, nitrate and total dissolved solids. The high levels of evaporation occurring in these dams which feed the wells are likely to concentrate the minerals impacting on water quality. The need to ensure water quickly infiltrates the shallow aquifers after rainfall events via an outlet pipe or direct infiltration is thus apparent. This negative situation in particular noticed at Bani Naji dam site. The maintenance of the dam is in the hands of the local community, the majority of whom live upstream of the dam. Disputes between this community and another downstream to do with sharing water have been reported. It is believed that the local community would be reluctant to release water downstream because their farmland is upstream of the reservoir. Water is currently pumped from a well downstream of the dam back upstream to the fields. This forms a hydrological closed loop with some inflow from runoff and evaporation from the crops and the reservoir water surface. The runoff contains some dissolved minerals and the overall concentration of dissolved minerals can be progressively expected to increase in the long term. Already there is some evidence of salinity in the soil immediately downstream of the dam where limited seepage water emerges. The quality of water in the wells near this dam is poor compared to most other dam sites, Halcrow (2006). Well in Bani Naji site has evidence of either total coliforms or faecal coliforms which indicate sewage or waste contamination.

5. CONCLUSION

- The developed water balance model of reservoir simulation combined with a more refined Darcian approach involving an analytical approximation of a flow-net solution was used to estimate dynamic daily recharge to shallow aquifer. Figures of recharge estimated by two methods are in agreement for the 10 dams sites. This indicate that simple approach developed carefully can provide acceptable results for estimation of induced recharge under dam constructed in minor ephemeral wadis. Better understanding of the effect of different dam/groundwater recharge applied for certain dam sites provided through groundwater numerical simulation (MODFLOW) with reservoir package which simulates leakage between a reservoir and an underlying ground-water system.
- Full instrumentation at each dam site to hydrologically monitore at daily interval may not be justified for such very small dams with such a limited impact on the overall recharge scene in the Sana'a Basin. Such an effort would appear somewhat excessive in the context of so little other hydrological data being collected for far bigger and more critical Sana'a Basin catchments. Applying weekly/monthly monitored reservoir and groundwater table to black box model of daily time span to dam site can provide reasonably accurate daily dynamic recharge volume for these dams' sites. This approach is much better than using results of a single properly monitored catchment and transposed its results to the other small catchments of the dams.
- The affect of the water level of the reservoir shows leakage rate is increasing with an increase of surface water level at all dams' sites. Results also imply that reservoir

water depth is more significant for an effective recharge under lakes than the area of the reservoir.

- Although removal of silt of reservoir effectively increase recharge amount, at Mahalli, structures (fissures, factures, fault) are the controlling factor of the amount of infiltrated water, as little increase of infiltration amount under reservoir site was noticed after silt removal. The recharge was taking place through the reservoir banks (via unclogged fractures), rather than through the highly silted bottom.
- Groundwater occurrence and flow in the study area is controlled by structural geology. Fracture aperture, density, length and orientation, as well as the presence of dykes and faults, are play prominent roles in groundwater flow at these dam sites and consequently the leakage volume and its destination. Dams constructed over limestone aquifer, shows highest leakage amount as it is permeability is originated from the crushed/faulted, fissures, fractures rocks (Bani Naji). However, presences of igneous intrusions reduce the amount of leakage as observed at Al Hayathem dam. For this site, the intruded bodies cause infiltrating water to migrate away and not contributing to recharge of target formation (site).
- The average annual runoff volume available for recharge in the upper reaches of wadis (dam sites) varies between 15,000 and 258,000 m3/yr with an average of 116,000 m^3/yr. In six of the studied dams the volume is very small, so is the incremental recharge and consequently show cost ineffectiveness.
- Bahman checks dams show highest efficiency of recharge followed by smaller gravity dams. The least efficiency, in general, noticed for larger dams. Depending on site-specific boundary conditions, dams recharge of more than 57% of the stored water to the aquifer calculated. For cases under study, recharge percentages (efficiency) of even 94% has been achieved. Check dams along the upper-middle lengths of wadis, where Alluvial Deposits overlie Cretaceous Sandstone, as seen at Bahman site is found to be more economical and effective in aquifer recharge terms. Check dams prove to be an excellent vehicle to engage local communities in practical action for water resources conservation.
- The reservoir operation study shows no additional recharge was gained, when the outlet left open to discharge water freely along wadi channel as long as the reservoir bottom has been de-silted. De-siltation of reservoir bottom should be thought of as an essential management practice to extend dam life time, too. The periodic removal of alluvial sediment (fine sand, silt and clay) and organic material (bacterial slimes and algae) that tend to accumulate, should be removed to restore the infiltration capacity of reservoir and that should be an essential aspect of the maintenance of all such structures.
- The dam design does not need to entail an absolutely water-tight structure but only a totally safe structure. Seepage of stored flood water through a non-water-tight dam merely assists downstream recharge. Unless for other reasons, discharge of stored water through outlets to downstream channel are not needed to enhance recharge in the studied dams sites. An associated issue is that if the stored floodwater is successfully recharged locally, then farmers further downstream who would have benefited from partial recharge of their wadis would be disbenefited. Conflict is likely also as people upstream will not allow discharge of the outlet. Clearly these are

not the aim of any project. Therefore understanding and careful handling through community consultations and agreement should be reached during planning phase of any recharge enhancement project. The key mitigation measure is the need for the establishment of the WUA. Concerns over the current management of the dam and reservoir (i.e. disputes between the Sheik and the community on ownership of wells, the non removal of silt, the lack of input in doing routine maintenance on the dam wall, lack of maintenance of the outlet pipe) means WUA should be aware of and agree on the future management of the dam, the operation and maintenance of the outlet pipe, water quality and removal of silt. However it should be mentioned that WUA can not solve problem between upstream and downstream people.

- For dams e.g. Al Lujma, Arisha, and Beryan the area important challenge to any future intervention is water demand measures on water conservation and water use. This is true because the catchment area of dam is small and water availability in the area will not be improved even, if recharge of water takes place. The use of drip irrigation as an alternative irrigation method is good option in demand side of water and should be applied. Conjunctive use of surface and groundwater resources may improve water situation, save locals purchasing of the costly tanker water, reduce the amount of the O&M of their boreholes. Moreover, local people should be trained in matters that improve their capacity in managing water use, maintenance and operation of dams, conservation of water.
- Bahman check dams provide better chance for recharge through wadi bottom than gravity dam through increase infiltration opportunity. However, the number of the check dams should be evaluated accurately. One method to overcome limitation of data for these wadis, the implementation of the check dams in any wadi should be undertaken in more than one phase. This is will save money, especially as series of the check dams were originally proposed to slow down the runoff flow, form small reservoirs and enhance recharge along the valley, without requiring expensive foundations required for gravity dam. Check dams also remove fine suspended materials through settlement, providing clear water to the downstream part, which infiltrates more readily.
- The general recommendation for an optimised recharge management would be summarized in: the recharge flow should be adjusted in such a way that the available water can infiltrate in an area as small as possible for duration as long as possible. However, longer period can means deterioration of water quality and development of diseases caused by the availability of a surface water body.

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