Integrated Watershed Management for Small Catchments Within Sana'a Basin, Yemen

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LIST OF ABBREVIATIONS

GDI	General Directorate of Irrigation
GIS	Geographic Information System
GRS	Global Position System
GSMRB	Geological Survey and Minerals Resources Board
IWRM	Integrated Water Resources
JICA	Japan International cooperation Agency
MCM	Million Cubic Meter
MWE	Ministry of water and Environment
NWRA	National Eater Resources Authority
NWSA	National Water Supply and Sanitation Authority
NWSSIP	National Water Sector Strategy and Investment Program
SBWMP	Sana'a Basin Water Management Project
SCS	Soil Conservation Service
TNO-DGV	Institute of Applied Geoscince- Delft, The Netherlands
VES	Vertical Electric Sounding
YOMINCO	Yemen Oil and Mineral Resources Corporation
WEC	Water and Environment center
HKD	Hydrosult-Komex-Alderwish
TS-HWC	Technical Secretariat of the High Water Council
SAWAS	Sources for Sana’a Water Supply Project
MAF	the Ministry of Agriculture and Fisheries
SWSLC	Sana’a Water and Sanitation Local Corporation
GARWSP	General Authority of Rural Water Supply Projects

ABSTRACT

The study apply an integrated water resources management (IWRM) approach to assess the effectiveness of the supply management applied in the Sana'a basin by the Sana’a Basin Water Resources Management Project (SBWMP) to slow down the depletion of aquifers in the Sana'a basin and to procure transferable findings that would be applicable to other regions. The study covered 10 selected constructed dam and their catchments.

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 four 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. 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.

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

1.1. Background

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, Hydrosult, Komex, Darwish, (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 underground 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.

1.2. Objectives of the Study

Against the above background, the present study applying an integrated water resources management (IWRM) approach to assess the effectiveness of the supply management applied in the Sana'a basin by the SBWMP to slow down the depletion of aquifer in the Sana'a basin and to procure transferable findings that would be applicable to other regions.

Integrated Water Resources Management (IWRM) is for a long time considered to be able to cope with complex water management problems. In many cases the different goals are in conflict and the notion “integrated” indicates clearly that water resources management should be approached from a broad perspective taking all potential trade-offs and different scales in space and time into account and has been considered to be able to cope with complex water management problems. The study discusses water management to be applied in 10 rehabilited/constructed dams' sites including a cascade dam site within the Sana'a basin. The study included two tasks that address:

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.

1.2.1 Main objective

To measure two essential parameters in the field, which are required for the recharge calculations: the height of water in the reservoir (inundated area), which controls the opportunity for infiltration in space, and the duration of inundation representing the infiltration opportunity in time.

1.2.2 Sub objectives

As choice of methods should be guided by the objectives of the study, available data and the possibilities to get supplementary data, as well as time available and economy are important factors; three techniques are proposed for current recharge assessment, being also the sub-objectives:

1. to develop a simple water balance model;
2. to estimate a more refined Darcian approach involving an analytical approximation of a flow-net solution.
3. Numerical modelling using MODFLOW to simulate groundwater flow and recharge mechanisms from dams lake. , at least, for 4 dam sites.

Despite the complicated set of data required, water balance methods are considered by some to be the most accurate way to estimate recharge (Lerner et al, 1990). Accordingly, a reservoir water balance approach will be used to estimate both the evaporation and the deeply percolating part of the reservoir losses. This is will be undertaken through a simple spreadsheet model which describe both the evaporation and deep percolation, based on a simple daily water balance equation over the reservoir area.

The more refined Darcian approach can be used as a check on the water balance method, and also in an attempt to provide a more refined recharge estimate. The Darcian approach method, described in detail below, describes not only the saturated flow from the reservoir to the aquifer, but the vertical infiltration of water into the unsaturated zone beneath the reservoir bottom. These techniques were used recently in calculation of induced recharge for new recharge dam sites in Sana'a basin, Alderwish (2009).

More sophisticated recharge models using unsaturated-saturated zone codes and calibrated using recent collected data from recharge dams will be worthwhile at this stage of Sana'a Basin Project. However, that approach is computationally exhaustive.

2. Previous studies on the study area

Several groundwater studies have been undertaken in Sana'a basin since 1972. The first study that focused on water and geology of Sana'a basin was done by Italconsult in 1972. The only scientifically based with proper field study covered the whole basin are those of Mosgiprovodkhoz (1986), and Alderwish (1996). All other studies with variable accuracy as they either used adopted percentage of annual rainfall method which depends on the area. The Darcy method used by most is not expected to be very reliable, since it is normally only suitable for steady state, isotropic conditions and uses head gradients based on poorly defined water level contours and uncertain transmissivity values TSHWC, (1992). Example of these studies include Italoconsult (1973), Howard Humphreys (1977 and 1979), Charlmbous (1982). The Water and Environment Center (WEC) conducted a study in 2001, Japan International Cooperation Agency (JICA) in 2007 and in 2008. For the Sana'a Basin Water Management Project (SBWMP), Hydrosult Inc, conducted a detailed study on the Sana'a basin, using the results of previous studies and filling the information gaps to get a more complete picture of Sana'a basin hydrogeological system. Wells inventory studies were carried several times; the most recent one was performed by WEC in 2003.

All previous estimates of recharge in the Sana'a basin relate to different areas, based on an inadequate conceptualisation of the systems, and use different methods and inadequate data. While the rest are based on these original studies undertaken by Mosgiprovodkhoz (1986) and Alderwish (1996). Recharge estimates made by some of these studies are given in *Table 2.1.*

Table 2.1 Estimated Groundwater Recharge in Sub-Basins

No	Sub Basin	Recharge (Mm^3)	No	Sub Basin	Recharge (Mm^3)
1	Wadi al Mashamini	0.86	12	Wadi al Furs	0.79
2	Wadi al Madini	2.73	13	Wadi al Iqbal	2.31
3	Wadi al Kharid	1.76	14	Wadi Zahr & al Ghayl	7.11
4	Wadi al Ma'adi	1.71	15	Wadi Hamdan	0.82
5	Wadi A'sir	4.27	16	Wadi al Mawrid	1.54
6	Wadi Khulaqah	1.54	17	Wadi Sa'Wan	1.41
7	Wadi Qasabah	0.83	18	Wadi Shahik	4.12
8	Wadi al Huqqah	1.36	19	Wadi Ghayman	1.24
9	Wadi Bani Hwat	5.58	20	Wadi al Mulakhy	1.66
10	Wadi Thumah	1.00	21	Wadi Hizyaz	1.92
11	Wadi as Sirr	3.81	22	Wadi Akhwar	2.32
Total			**50.7**		

Source; Dr. A.Noaman and Eng. W. Mulat (2007), Water Balance and Hydrological Monitoring

A reconnaissance isotope study was carried out to identify areas of groundwater recharge by Jungfer (1984). Water samples were analyzed for tritium, O-18, deuterium and C-14. The results showed that except for isolated areas in the southern and western portions of the basin, the Tawilah aquifer has received little or no recent recharge. Other studies investigated the groundwater hydrochemical quality in the basin. Between 1987 and 1996 the Project Sources for Sana'a Water Supply (SAWAS) conducted a long term study including hydrological measurements, rainfall records, groundwater levels observations, chemical and microbiological analyses of water 'samples, well inventories, geophysical surveys, and the drilling of exploratory boreholes, SAWAS, (1996).

In 2002 a modeling study was conducted by Foppen based on hydrochemical analyses of samples taken in 1995 and 2000 from the alluvium, volcanic and sandstone aquifers below the urban area of Sana'a. Some of the samples were taken from outside the urban area, FOPPEN, (2002). The recent existing MODFLOW numerical aquifer model developed by Hydrosult/TNO-NITG / WEC (2009) assumes K and Sy for the Cretaceous Sandstone Aquifer of 0.3-1.0 m/d (higher in known fracture zones) and 0.02-0.08 respectively, NWSA/TNO-NITG,(1996). It was calibrated using 2003 survey data, using Sy and I (recharge) as variables, and then verified (with variable success) to observation well data Specific previous studies for dam sites under consideration in the present study were undertaken first by Hydrosult, Komex, Darwish (HKD) (2002). This study was feasibility studies for new and rehabilited dams. It followed by detailed design/rehabilitation studies undertaken by Stanely (2006) covering Al-jaef, and Al-Lujma, while Holcrow (2007) studied AlHyathem, Bahman, Bani Naji, Beryan and Mahalli. GDI studied Thoma and Tozan dams.

The studies on groundwater recharge (artificial or natural) have takes many different approaches to estimate or evaluate the groundwater recharge. Some use hydrological and hydro-geological modeling, others measure soil moisture and subsurface temperature, while again others use geo-electric measurements to determine subsurface geological and hydro-geological structures required for artificial groundwater recharge and also to suggest the best locations for injection wells to enhance artificial groundwater recharge. For example, Alawneh (2003) studied groundwater recharge modeling using Wadi Bayer as case study. He addressed the natural recharge and the effectiveness of the currently constructed dike by using:

(1) Hydrological analysis and models and collection of climatic data (daily, monthly, annual rainfall, temperature and evaporation). He used different techniques and models, such as HEC-HMS, and the SCS method-curve number method for an evaluation of the collected data. In order to make runoff estimations, he studied soil type, other exposed rock formations and catchment characteristics.

(2) Hydrogeological conditions. Alawneh (2003) used a Processing Modflow model in order to determine the suitability of aquifers for natural recharge and to quantify the infiltration rate. He also made permeability tests for 15 m top soil. Some of his results revealed that the permeability of the upper 2 meters, which form the floor of the reservoir, is 11.82×10-2 cm/sec and for other depths (5-15m) the permeability ranges between 1.805×10-3 and 7.331×10-6 cm/sec. From the ground water model it was found that the natural recharge in the area is due to the flood water runoff filling the reservoir. For a 30 day and 15 day retention period it was found that the groundwater table will rise in the range of 0.33 to 1.5 m and 0.11 to 0.90 m for the two retention periods respectively.

3. Methods

Applying IWRM to assess the various aspects of sustainable water resources through evaluating the role of dams constructed for the purpose of groundwater recharge (which, if successful, is a way of contributing to the sustainability of water resources by balancing the amount of water extracted with the amount recharged to the aquifer). Also to assess of the possibility of using other methods of water harvesting, their effectiveness and find ways of improving their performance to the maximum efficiency. Applying IWRM principles in assessment of artificial groundwater recharge through these structures would avoid compromising the sustainability of vital eco-systems. Also with regard to aspects of tectonic structure, for example, the decline of earth layers and the collapse of rock masses can occur as a result of overexploitation of water without maintaining the balance between extraction and recharge, which leads to resource depletion and increased risk of landslides in the affected areas, which in turn can result in the destruction of buildings and vital infrastructure.

The present study focuses on both technical and socio-economic aspects. In the technical aspects, Hydrological and hydrogeological studies include monitoring of water levels in the dams' reservoirs and in dug wells near the dams, comparing the amount of vaporized water with the amount that is supposed to infiltrate to recharge the aquifers. While the socioeconomic aspect tried to fill the gap between the knowledge of and the practical application on the ground of the principles of IWRM. Through interviewing people up- and downstream of dams, the possibility and the acceptance of the application of those solutions are studied, as well as the social and economic impact of the dams. For example, dams for artificial recharge is one of the solutions implemented in the study area, but its efficiency on the ground in terms of scientific, economic and social aspects was largely unknown. Analysis of data collected by questionnaires which were distributed to three groups of people: those directly downstream of the dams, those a middle distance away from dams and those far from the dams provide insight in regard to social effect to the constructed dam.

The results from the scientific field study and the socio-economic study will then be used to reach to the third link in IWRM, which is the role of concerned institutions that can contribute to improving the situation through legislation by seeking to implement IWRM principles as well as by strengthening the infrastructure required in the region.

For selected studied 10 structures in Sana'a Basin, the following methods/assessment were undertaken:

1. Runoff estimation using SCS method to model runoff for period 2002-2009.
2. Reservoir simulation model developed to determine the variability of reservoir's storage, water level height and area of inundation all are required for groundwater recharge estimate.
3. 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.
4. Groundwater Modeling for simulations of groundwater flow beneath dam site using MODFLOW and reservoir simulation package.
5. Hydro-Socio-Economic Dam Benefit Analysis including:
   5.1. Dams Cost Effectiveness

5.2. Environmental and Social Benefit
5.3. Recharged Water Chemistry Aspects

Detailed steps of methods applied are described below:

3.1 Selected studied dams and their conceptual model

The list of dams considered in the present study is shown in *Table 3.1*

Table 3.1 : list of dams considered in the present study

NO.	Dam Name	Type	Location	Storage of Reservoir (m^3)
1	Al-Haythem	Embankment, 17m	Nahim	220,000
2	Al-Jaef	Masory,17m	Bani Al-Harieth	60,000
3	Al-Lujma	CFRD, 18m	Bani Bahlool	85,800
4	Arisha	Embankment, 11m	Nahim	350,000
5	Bahman	27- Check Dam	Bani Al-Harieth	N/A
6	Bani Naji	Embankment, 18m	Nahim	170,000
7	Beryan	Masory,11m	Bani Hashaish	90,000
8	Mahilli	CFRD, 12m	Nahim	220,000
9	Thoma	CFRD, 18m	Nahim	130,000
10	Tozan	CFRD, 15m	Hamdan	220,000

The study discusses water management to be applied in 10 rehabilited/constructed dams' sites including a cascade dam site within the Sana'a basin *Figure 3.1.*

3.2. Catchment Characteristic and reservoir condition

Table 3.2 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 3.2: Dams' catchment characteristics

Parameters	Catchment Area	Reservoir volume	Main stream length	Top water level	Max elevation	Slope S
Dam Sites	Area Km2	Volume Mm3	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

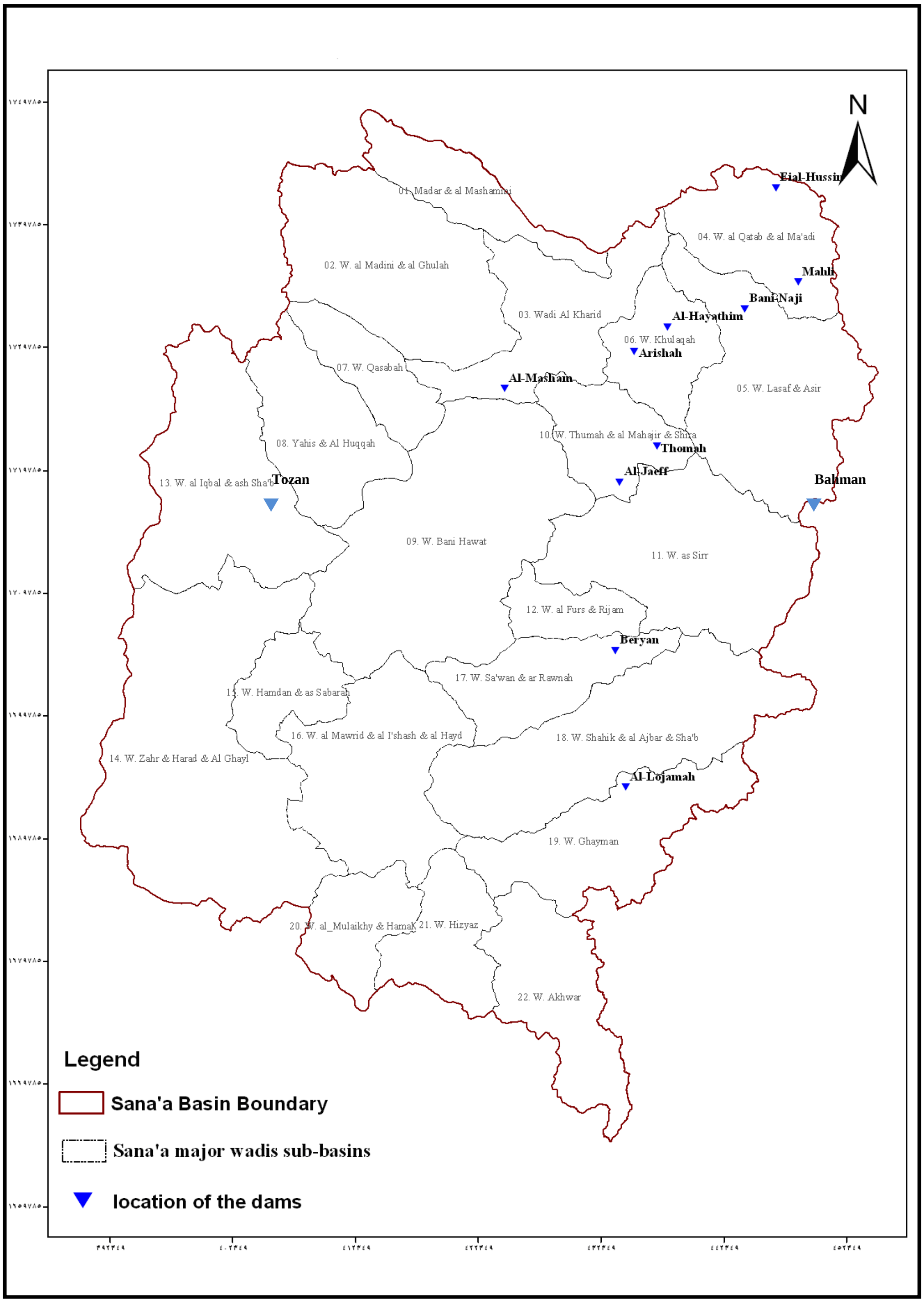


FIGURE 3.1 : DAMS LOCATION

3.3. 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 3.3.*

Table 3.3 : 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

3.4. Runoff estimation for studied dam sites

3.4.1. Model description

The method used is that developed by the U.S. Soil Conservation Service (1972) to estimate runoff from storm rainfall for small watersheds. The method assumes that for any storm rainfall there will be an initial loss, Ia, which is the initial quantity of interception-depression storage and initial infiltration that must be satisfied by any rainfall before runoff occurs, "the threshold value", so the potential runoff is P-Ia. After runoff begins, the additional depth of water retained in the watershed, Fa, is less than or equal to some potential maximum retention, S. The hypothesis of the SCS method is that the ratios of the two actual to the two potential quantities are equal, that is,

$$Fa/S = Qe/(P-Ia) \qquad (1)$$

From the continuity principle,

$$P = Qe + Ia + Fa \qquad (2)$$

Combining (1) and (2) and solving for Qe, direct runoff, gives,

$$Qe = \frac{(\mathrm{P} - \mathrm{Ia})^2}{\mathrm{P} - \mathrm{Ia} + \mathrm{S}} \qquad (3)$$

This is the basic equation for computing the depth of direct runoff from a storm by the SCS-method. The estimation procedure for each parameter for the Sana'a basin is described below.

Estimation of the soil storage potential for any wadi, S, is accomplished through use of a series of empirical curve numbers, CN, (SCS, 1972), where the storage is,

$$S = (1000/CN - 10)*25.4 \qquad (4)$$

25.4 is the conversion for S in millimeters.

The curve number, CN, is a function of land use, agricultural practices, crop cover, infiltration, depression storage and antecedent condition of the soil and must be estimated subjectively for each soil type. The SCS publications provide a series of tables to assist in estimation of the appropriate curve number. The curve number values reported by TSHWC (1992) were used as initial estimates of the curve number of each runoff zone. Improved values were derived through selection of small fairly homogeneous catchment areas, with a minimum number of runoff characteristic zones, where peak flood discharges were measured in a previous study, Mosgiprovodkhoz (1986) and/or Alderwish (1996). By comparing the computed and measured floods for a succession of catchments with an increasing number of ROCs, appropriate curve numbers for all zones were derived. The adopted values of CN values are given in *Table 3.4*

An empirical relation between initial loss Ia and maximum water storage potential of the soil, S, was proposed by the SCS (1972), on the basis of measured runoff from over 70 catchments in United States of America;

$$Ia = K_f * S \qquad \text{where } K_f = 0.2 \qquad (5)$$

TSHWC (1992), however, suggested slightly different initial loss scaling factors, (K_f) for Yemen, between 0.15 and 0.30, for each runoff characteristic zone. They argued this variation was necessary, to emphasise the hydrological differences between different ROCs. However, the S parameter in equation (5) which is inversely related to the curve number (CN), was originally proposed by SCS to allow for the variability of different soil types, through the fact that a higher CN value means less initial storage to be satisfied before runoff occurs. During the calibration of the model it was found that use of different initial loss scaling factors (K_f) is required, at least for the steep rocky slopes (0.15) and for undeveloped wadi bottom (0.3).

The runoff response is strongly affected by the antecedent state of the catchment. To allow for this, SCS (1972) suggested revised CN values for "wet", "dry" and "normal" antecedent conditions;

For wet conditions, $$CN(1) = 4.2CN(2)/(10 - 0.058CN(2)) \qquad (6)$$

For dry conditions $$CN(3) = 23CN(2)/(10 + 0.13CN(2)) \qquad (7)$$

Where CN(2) is the average value for normal conditions (SCS, 1964).

Table 3.4: Adopted USSCS Curve Numbers, (dimensionless)

ROC type	CN(2) Normal catchment state	CN(1) Dry antecedent condition	CN(3) wet antecedent condition
P1	94	87	97
P2	88	74	95
P3	70	60	89
P4	70	60	89
A1	55	35	74
A2	65	45	82

3.4.2. Runoff volume estimate for dams sites

The model classified the area of the watershed in "runoff characteristics zones" (ROCs), which have similar physical characteristics and land. The different ROCs represent different response patterns of the soils in transforming rainfall into direct runoff. The model attempts to simulate the effect of daily rainfall on different types of land surface occurring in each catchment through the use of the identified ROCs prevailing in the watershed. In general, the model distinguished between two main runoff zones: runoff creating zones and runoff absorbing zones.

-. In the runoff-producing zone:
P1: steep, barren rock
P2: low slope, rock
P3: steep natural vegetation
P4: barren soils

- In the runoff absorbing zone
A1: flat and sandy
A2: terraces on plain
A3: low slope, vegetation

The characteristics of each zone as estimated by HKD (2002) is similar to the present study, since HKD had used similar values for the Curve Numbers suggested by Alderwish (1996), and that based on calibration of flow measurements.

4. 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 as all are 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.

4.1. Reservoir Simulation

4.1.1. Objectives of the Reservoir Simulation

The main objective of the reservoir simulation is to determine the variability of reservoir’s storage, water level height and area of inundation required for groundwater recharge study. In the present case of this project, the main purpose of the reservoir is to store the water for recharging the shallow ground aquifers. Therefore the numerical model that is presented only considers the groundwater recharge through the reservoir flow section, the evaporation losses and the spills as outflows/releases or losses from the reservoir.

In dam sites were surface irrigation or other demands such as water supply are present, the above assumption will be valid through applying black box concept using monitoring data of reservoir water level height.

4.1.2. Numerical Model

The numerical model used in the present study 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 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):

$$Si = Si-1 + Qi + Pi - Ei - Ii - Ri$$

Si : storage at the end of the day i
Si – 1 : Storage at the end of the dayi-1
Qi : inflow during the day i
Pi : precipitation over the reservoir during day i
Ei : Evaporation from the reservoir during the day i
Ii : Infiltration under reservoir during the day i
Ri : 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. At the present study, reasonable accuracy was achieved due to availability of real field measured data.

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 consultants (e.g. HKD, Stanely, GDI).

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) for measured floods over Sana'a Basin. The model estimate daily runoff volume for the period between Jan 2002 to Dec 2009, using daily rainfall of NWRA A station*)* (daily runoff*)* – spilled away water, if any).

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>

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 under de-siltation condition were estimated by calibrating measurements during period of monitoring and these shown in *Table 4.1* While under de-siltation condition an average K was calculated from the measured reservoir water level during the period of monitoring.
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.

Table 4.1: Average hydraulic conductivity of reservoir bottom

Dam sites		Calculated during the period between	average hydraulic conductivity of reservoir bottom K m/d
Al-hyatjem	Silted	3/11/2008-17/12/2008	0.02
	de-silted	6/9/2009-13/10/2009	0.2
Aljaef	normal	9-12/2009	0.09
Al-lujma	Normal	2008-2009	0.14
Arisha	Normal	2008-2009	0.035
Bannaji	de-silted	2/11/2008-23/12/2009	0.07
Beryan	normal	2008-2009	0.13
Bahman	normal	-	-
Mahalli	Silted	2/11/2008-3/2/2009	0.03
	de-silted	7/9/2009-22/12/2009	0.075
Thoma	Silted	-	-
	de-silted	4/7/2009-6/10/2009	0.056
Tozan	Silted	-	-
	de-silted	6/9/2009-13/10/2009	0.1

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 the “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 due to the structure. Although the two main prominent processes responsible for reservoir depletion are evaporation and infiltration to shallow aquifer, spilled water/outlet discharge etc. were considered in calculation of infiltrated water during simulation of reservoir operation. The reservoir storage levels are considered on everyday and the corresponding areas used for the calculations of the recharge and evaporation volumes.

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 due to the structure.

4.1.3. Model calculation:

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 (Si-1) will be;

$$\text{Si-1} = \text{Si} + \text{Ii} + \text{Pi} \qquad (1)$$

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 Si-1.

$$\text{Surface outflow} = \text{Si-1} - \text{MAXST} \qquad \text{if Si-1} > \text{MAXST} \qquad (2)$$

And so reservoir storage Si-2 become equal to MAXST for the same day

Or

$$\text{Si-2} = \text{Si-1} \qquad \text{if Si-1} <= \text{MAXST} \qquad (3)$$

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) is calculated from average monthly meteorological data (CAMA weather station) and the Penman equation and 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 Eto=0))

$$\text{Revised storage Si-3} = \text{Si-2} - \text{Eto} \qquad (4)$$

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

$$S_{i-3} = S_{i-2} - Qt \qquad \text{if } S_{i-2} > qt \qquad (5)$$

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. It has been estimated for silted reservoir condition and de-silted reservoir condition. 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 silted period and normal condition.

4.2. 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:

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

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:

$$A' = \tfrac{1}{2}\left(W + [e + h(0,t)\,]\right) \qquad (8)$$

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,

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

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

$$\Delta h = H + D - h(o,t) \tag{10}$$

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

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

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),

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

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).

4.3. 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 and achieving realistic estimations of the impacts of water saving and aquifer recharge investments in the site. The studies were based on the results of investigations undertaken by HKD (2002), WEC (2002), Halcrow (2006) and Stanley (2006).

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. 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.

A Simulation System for Modelling Groundwater Flow and Pollution, is a processing program for MODFLOW. It is a Windows-version of Processing MODFLOW with the goal of bringing various codes together in a complete simulation system. The size of the program code grew, as Windows-based adjective transport model PMPATH was added together with options and features for supporting the solute transport models MT3D, MT3DMS and MOC3D and the inverse models PEST and UCODE.

The applications of MODFLOW, a modular three-dimensional finite-difference groundwater model of the U. S. Geological Survey, to the description and prediction of the behaviour of groundwater systems have increased significantly over the last few years. The "original" version of MODFLOW-88 can simulate the effects of wells, rivers, drains, head-dependent boundaries, recharge and evapotranspiration.

At present, PMWIN supports seven additional packages, which are integrated with the "original" MODFLOW. The Reservoir package (Fenske et al., 1996) simulates leakage between a reservoir and an underlying ground-water system as the reservoir area expands and contracts in response to changes in reservoir stage.

5. 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, 1996). 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

5.1. 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

5.2. 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).

5.3. 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),

6.Ruslts and Discussion

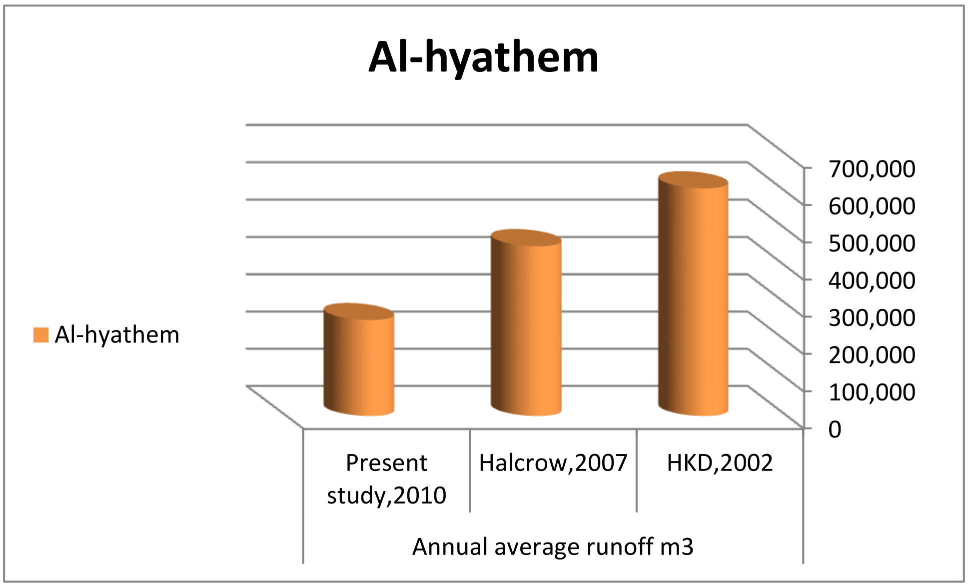
6.1 Runoff estimation for studied dam sites

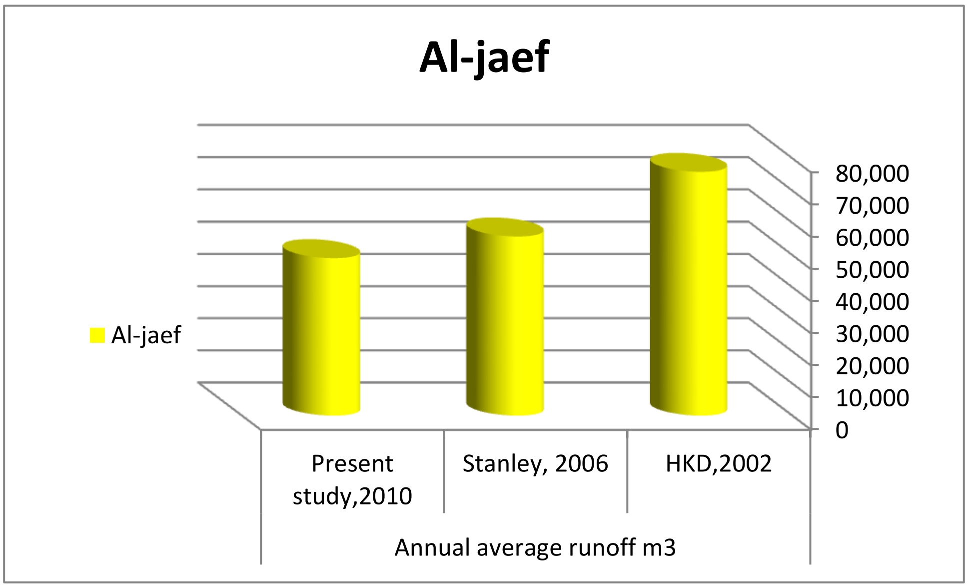
The estimated daily runoff volume for all dam site catchments do not match with the reservoir water level measured during August 2008 – Dec 2009. As has been described above the model has been capable of estimation of daily runoff, and has been calibrated for wadis of Sana'a basin with measured floods (Alderwish, 1996). This indicates the differences are probably contributed to the distribution of the rainfall over the watershed.

Annual average runoffs estimated by various consultants for studied dams are shown in *Table 6.1.*

Table 6.1 : Annual average runoffs estimated by various consultants for studied dams.

Dam site	Annual average runoff m^3					
	GDI,2001	HKD,2002	AEC,2002	Stanley, 2006	Halcrow,2007	Present study,2010
Al-hyathem	-	611,319	-	-	456,200	258,000
Al-jaef	-	75,815	-	55,756	-	49,043
Arisha	-	154,000	113,000	-	102,700	121,871
Al-lujma	-	28,680	-	31,723	-	14,750
Bahman	-	236,000	-	407,421	-	130,875
Baninaji	-	133,464	96,000	-	86,500	135,875
Beryan	-	101,952	-	122,201	-	62,186
Mahalli	-	198,200	208,000	-	197,200	209,563
Thoma	174,000	-	-	-	-	116,857
Tozan	368,000	-	-	-	-	129,286





The differences on the annual average runoff by various consultants are due the use of various rainfall stations and different record period over the study area. Present project used NWRA HQ with mean annual rainfall of 131.6 mm. HKD's runoff estimation was based on Birbasil and Sana'a Airport rainfall stations with mean annual rainfall of 186.5mm while Halcrow adopted values from AEC study in which they used an annual average of 158 mm for 1000-year rainfall data sets generated by AEC (2006). While *GDI estimate reported in GDI report 2001, based on rational equation (R=C*P*A/1000).*

The differences on the annual average runoff by various consultants are due to the use of various rainfall stations and different record period.

The over estimation of runoff volume by Stanley is related to the fact that they changed the CN values and parameters based on verbal information from local people. They neither used CN values suggested by the High Water Council for surface water hydrology, nor used CN values proposed by Alderwish (1996) which originally developed for Sana'a basin wadis using actual measured flows. Other reason for observed high differences in annual runoff is due to use of different rainfall stations and/or over different period of record by various consultant.

The result of the model in agreement with what has been previously reported (HKD, 2002 – Halcrow 2007), that the reservoir has never filled to spillway level and it is understood that the maximum observed water level in the reservoir is about 1.5m above the pipe or about 2098.5 masl.

Volume of daily runoff for the period 2002-2009 for all dam sites. These were used in the daily simulation of dam reservoir together with the monitoring reservoir water level 2008/2009. The flood volume during 2002-2009 for all dam sites during present study is given in *Table 6.2*.

Table *6.2 : The flood volume during 2002-2009 for all dam sites*

Dam site	Total flood volume of the catchment m^3	Total volume of flood spilled away or pumped out of reservoir m^3	Total inflow water to reservoir m^3
Al-hyathem	2,650,000	807,194	1,257,806
Al-jaef	343,300	121,208	222,092
Arisha	853,100	220,468	632,632
Al-lujma	118,000	0	118,000
Bahman	1,047,000	96,321	950,679
Baninaji	1,087,000	0	1,087,000
Beryan	435,300	5,242	430,058
Mahalli	1,676,500	267,808	1,408,692
Thoma	811,000	349,017	461,983
Tozan	905,000	106,800	798,200

6.2 Reservoir simulation results

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 (6.1).*

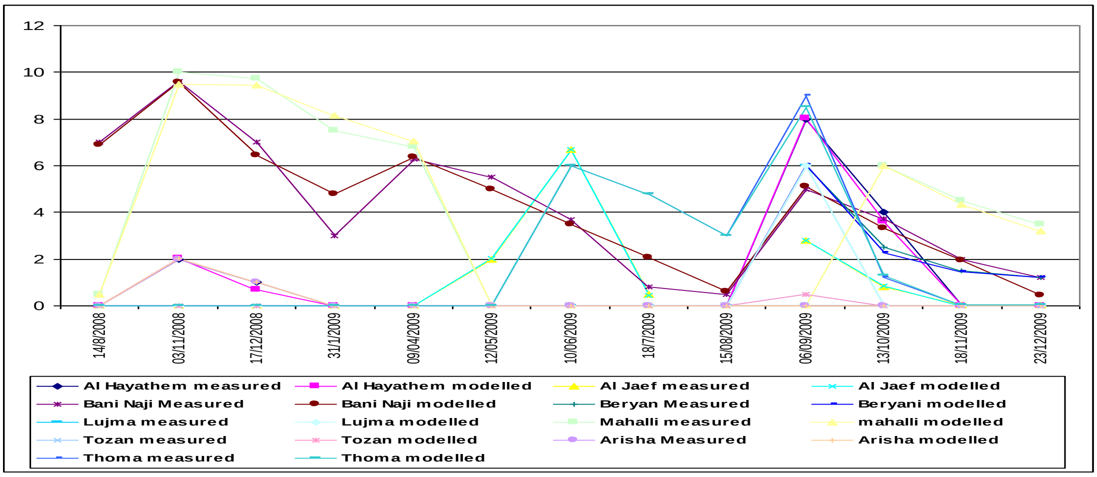


Figure (6.1) Measured and modeled reservoir water levels for studied dams' sites

Al Hyathem

With the reservoir capacity of 250,000 m^3, the reservoir has spilled 3 times in the 8 years simulations (during 2003). Also it has emptied and remained in that condition during the period of silt removal process (28/1/2009 and 28/2/2009). The emptied water from the reservoir was taken as spilled water.

The total infiltration of water during the period 2002-2008 was calculated as 745,498m^3, that's about 68% of inflow water under silted reservoir (k=0.01m/d). While during 2009, under de-silted reservoir, the infiltrated water was 149,897m^3, that's about 93% of inflow water (k=0.2 m/d). The high increase of percentage (93%) of infiltrated water indicates full recovery of clean reservoir bottom can be achieved back through effective silt removal process and consequently excellent recharge through reservoir bottom. The results also refers to that if the reservoir bottom kept clear of sediments, there will be no need to enhance dam's recharge through regulating outlet discharge downstream of wadi channel.

Table 6.3 : Results of simulation of reservoir at Al Haythem dam site.

Parameters	HKD (2002) m3	Halcrow (2006) M3	Present study (2009) m3
Runoff	611,319	456,200*	258,125
Precipitation	186.5mm	158 mm	146.9 mm
Groundwater recharge	413,941	340,000	136,037
Evaporation	213,860	116,200	58,016

*For 1000- year wadi flow data sets as generated by AEC for the dam site.

In the present study, the percent of recharge due to dam construction is estimated as 53% of the runoff during 2002-2009. This figure is less than those estimated by HKD 67% and Halcrow 75%. As reported by Halcrow (2006), the figure estimated is only indicative as it was difficult to determine the actual figure during their study of existing dams. HKD estimation assumed de-silted reservoir condition. During the present study, the daily dynamic recharge was calculated based on actual field measurements of reservoir water levels.

Al Jaef

With the reservoir capacity of 60,000 m^3, the reservoir has spilled over three times in the eight years simulations (during 2003). Also it has emptied several times and it remained in that condition during the period of construction (5/12/2007 and 4/5/2009). Runoff during this period considered as if spilled away water.
During calibration using observed data and information, it was possible to quantify the water discharged from the reservoir through the outlet. An average K of the reservoir bottom was estimated by calibrating measurements between 5/9/2009 and 12/10/2009. It was understood that the dam outlet was open during June/July 2009. This confirmed by the drop of the reservoir water level between 9/6/2009 and 14/7/2009 by about 5 meters. The released water through outlet was quantified as 19,500 m^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 (19,500/36). Compare this figure with no-water discharged through outlet, the calculated infiltrated water through reservoir bottom would have been 16821m^3 (86%) of runoff. **This means that no additional recharge would have been gained, if the outlet left open to discharge water freely along wadi channel.**
The total infiltration of water during the period 2002-2009 was calculated as 192,373 m^3, that's about 87% of inflow water under normal condition of reservoir. No de-siltation was carried out for this site. Runoff, precipitation, groundwater recharge and evaporation as estimated by various studies are shown in *Table 6.4*

Table 6.4 : Results of simulation of reservoir at Al Jaef dam site.

Parameters	HKD (2002)	Stanley (2006)	Present study (2009)
Runoff	75,815	142,974	49,043
Precipitation	186.5 mm	172.43 mm	146.9 mm
Groundwater recharge	65,431	48,245	32,684
Evaporation	9,626	8,175	4,232

HKD (2002) estimated the highest recharge of 65,431m^3 (86%). However, under reservoir siltation, they estimated recharge as 36,960 m^3. Stanly (2006) estimated annual average recharge as 34% of annual runoff. While the present estimate of annual recharge is 49,043m^3 that's (66%).

Al lujma

With the reservoir capacity of 28,000 m3, the reservoir has not overflow of spill away in the 8 years simulations.

The total infiltration of water during the period 2002-2009 was calculated as 106,306 m^3, that's about 90% of inflow water under normal condition of reservoir. No monitoring information available for reservoir under silt condition.

Table 6.5 : Results of simulation of reservoir at Al Lujma dam site.

Parameters	HKD (2002)	Stanley (2006)	Present study (2009)
Runoff m3	28,680	75,049	14,750
Precipitation	192.5 mm	170.14 mm	170.1 mm
Groundwater recharge m3	21,069	36,221	13,447
Evaporation m3	7,931	44,036	1,462

The main problem of the inaccuracy observed on the daily runoff volume estimation was due to the representation and distribution of rainfall over the wadis within Sana'a Basin. In the present study, this was overcome through applying black box model using available monitoring data.

The present study estimated the highest percent of annual recharge as 91% of annual runoff, followed by HKD (2002) as 74% and the least percentage of annual recharge was that of Stanley (2006) 48%. The over-estimate of the recharge during present study is evident as recharge was estimated under de-silted condition of the reservoir. However, this is acceptable as the benefit cost for these dams will cover the future recharge under assumed regularly de-silted reservoir. No doubt the estimate of recharge using daily time interval provide accurate recharge figures in arid areas. Stanley (2006) and HKD (2002) both were used monthly interval time for reservoir simulation and hence their figures are not assumed to be accurate. Moreover, during the present study, the daily dynamic recharge was calculated based on actual field measurement of reservoir water levels.

Arisha

With the reservoir capacity of 180,000 m^3, the reservoir has overflow of spill away eight times during the 8 years simulations.

The total infiltration of water during the period 2002-2009 was calculated as 418,894 m^3, that's 49% of total runoff and 66% of inflow water under normal condition of reservoir.

Table 6.6 : Results of simulation of reservoir at Arisha dam site.

Parameters	HKD (2002)	Halcrow (2006)	Present study (2009)
Runoff m3	154,000	102,700	121,871
Precipitation	186.5 mm	166 mm	176.1
Groundwater recharge m3	128,144	75,000	59,842
Evaporation m3	25,856	27,000	34,349

There is general agreement between annual average runoff to the dam location by previous studies. HKD reported the highest percentage of recharge to runoff (83%) and the lowest 46% under silted reservoir. Halcrow (2006) percentage was (73%) while the present study percent was 49% of annual runoff. As no de-siltation carried out for this reservoir, the 49% represent silted reservoir annual average. During the present study, the daily dynamic recharge was calculated based on actual field measurement of reservoir water level.

Bannaji

With the reservoir capacity of 250,000m^3, the reservoir has not spilled during the 8 years period of simulations.

The total infiltration of water during the period 2002-2009 was calculated as 886015 m^3, that's about 82% of inflow water under de-silted reservoir (k=.07). Additional calculation of infiltration was made for siltation conditions (2002-2007) as 212702

m^3, which represents 37% of total inflow water. While for 2008-2009, under de-silted condition, the amount of recharge estimated as 423517 m^3, that 84% of inflow water.

Table 6.7 : Results of simulation of reservoir at Bani Naji dam site.

Parameters	HKD (2002) m3	Halcrow (2006) m3	Present study (2009) M3
Runoff	133,464	86,500	135,800
Precipitation	168.5mm	142 mm	146.9 mm
Groundwater recharge	122,790	65,000	79,000
Evaporation	10,210	21,500	57,967

There is general agreement on the annual average runoff by previous studies. However, average annual recharge estimated by HKD was 92% of runoff (de-silted reservoir) and 36% (silted-reservoir). Halcrow estimated recharge as 75%, while the present study 58% of annual average runoff (or 78% if assumed de-silted reservoir).

Beryan

With the reservoir capacity of 145,000m^3, the reservoir has spilled over three times in the eight years simulations (during 2003). Also it has emptied several times and it remained in that condition during the period of construction (1/1/2008 and 1/5/2009). Occurred runoff during this period was considered as spilled over water along wadi channel.

The total infiltration of water during the period 2002-2009 was calculated as 385,241m^3, that's about 89% of total runoff. Clearly this value overestimate the actual recharge because the calibrated K value used after construction of the new dam, using monitoring data between 1st Sep and 11 Oct 2009. No monitoring data for silted bottom reservoir.

Table 6.8 : Results of simulation of reservoir at Beryan dam site.

Parameters	HKD (2002)	Stanley (2006)	Present study (2009)
Runoff	101 967	122,201	62,186
Precipitation	190 mm	170.14 mm	146.9 mm
Groundwater recharge	41,217	98,494	55,034
Evaporation	59,954	11,983	6,579

The highest percentage of recharge to runoff is estimated by present study (88%). It followed by the percent estimated by Stanley (80%). HKD estimated recharge as only 40% of annual runoff. During the present study, the daily dynamic recharge was calculated based on actual field measurement of reservoir water levels and black box model. This overcome inaccuracy observed on the daily runoff volume estimation was due to the representation and distribution of rainfall over the wadis within Sana'a Basin and other parameters.

Mahalli

With the reservoir capacity of 315,422 m^3, the reservoir has spilled over three times in the 8 years simulations (during 2003). Also it has emptied and remained in that condition during the period of de-siltation (1/3/2009 and 1/6/2009). The emptied water considered as spilled away water.

The total infiltration of water during the period 2002-2008 was calculated as 934,364 m^3, that's about 71% of inflow water under silted reservoir (k=.03). While during 2009, the infiltrated water is 68,263 m^3, about 76% of inflow water under de-silted reservoir (k=.075). Interestingly, the de-siltation of reservoir bottom led to increase of infiltration through reservoir bottom by only 5%.

Table 6.9 : Results of simulation of reservoir at Mahalli dam site.

Parameters	HKD (2002) m3	Halcrow (2007) m3	Present study (2009) m3
Runoff	198,180	197,200	209,563
Precipitation	161.2 mm	136 mm	146.9 mm
Groundwater recharge	149,868	125,000	137,457
Evaporation	48,132	72,200	50,622

There is general agreement on the annual average runoff by previous studies. Similar approximately in annual recharge estimation for all three studies 75% for HKD, 63% by Halcrow and 66% by present study.

Thoma

With the reservoir capacity of 170,000m^3, the reservoir has spilled over for three times during the simulation period of eight years during August 2003.

The total infiltration of water during the period 2002-2009 was calculated as 403,972 m^3, that's about 87% of inflow water under de-silted reservoir (k=.056), using water balance approach. Also it has emptied several times and it remained in that condition during the period of rehabilitation/de-siltation (13/1/2008 – 31/8/2008) then (1/1/2009 – 28/2/2009). Dewatering of the reservoir and runoff during this period considered as spilled away water.

During calibration using observed data and information, it was possible to quantify the water discharged from the reservoir through the outlet. An average K of the reservoir bottom was estimated by calibrating measurements between 6/10/2009 and 14/7/2009. It was understood that the dam outlet was open starting August and up to Dec 2009. This confirmed by the drop of the reservoir water level between 5/9/2009 and 12/10/2009 by more than 8 meters. The release of water through outlet during 5/9/2009 and 12/10/2009 was quantified as 110,000m^3. As this water flow along wadi channel, 88470m^3 has been infiltrated to underground (86%) using K=0.056 and an area covered by daily discharge from outlet equal to 2702m^3 (110,000/37 days). Evaporation for same period (same area) estimated as 14,163 m^3. Compare this figure with no-water discharged through outlet (over the same period), the calculated infiltrated water through reservoir bottom would have been 32,102m^3 (86% of available water) and evaporation 5,166m^3. However, leaving the water in the reservoir, to either infiltrate or evaporate, (after a complete year), the recharge would have been 95,013m^3 (88%) through reservoir bottom while evaporation is only 12,626 m^3.

This makes sense as volume of recharge and evaporation for the same area, would be controlled by the rate of K and evaporation depth. As K for reservoir bottom is .06m/d, and average daily evaporation rate is 0.008 m/d, the infiltration would be a folder higher than evaporation.

Tozan

With the reservoir capacity of 200,000m^3, the reservoir has overflow four times during the 8 years period of simulations. The total infiltration of water during the period 2002-2009 was calculated as 690,656 m^3, that's about 87% of inflow water under de-silted reservoir (k=0.1), using water balance approach. Also it has emptied several times and it remained in that condition during the period of rehabilitation/de-siltation.

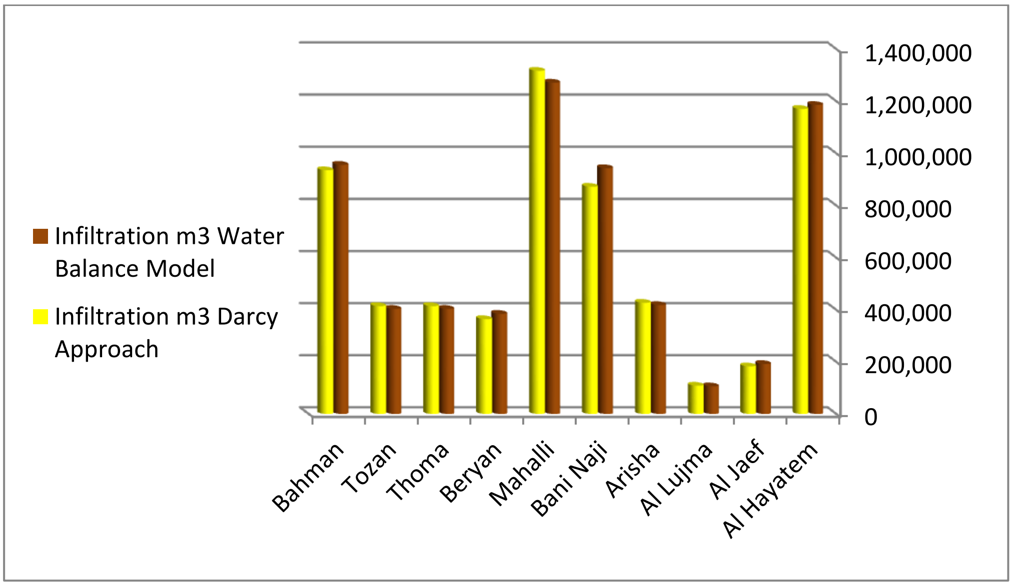
6.3 Darcian Approach

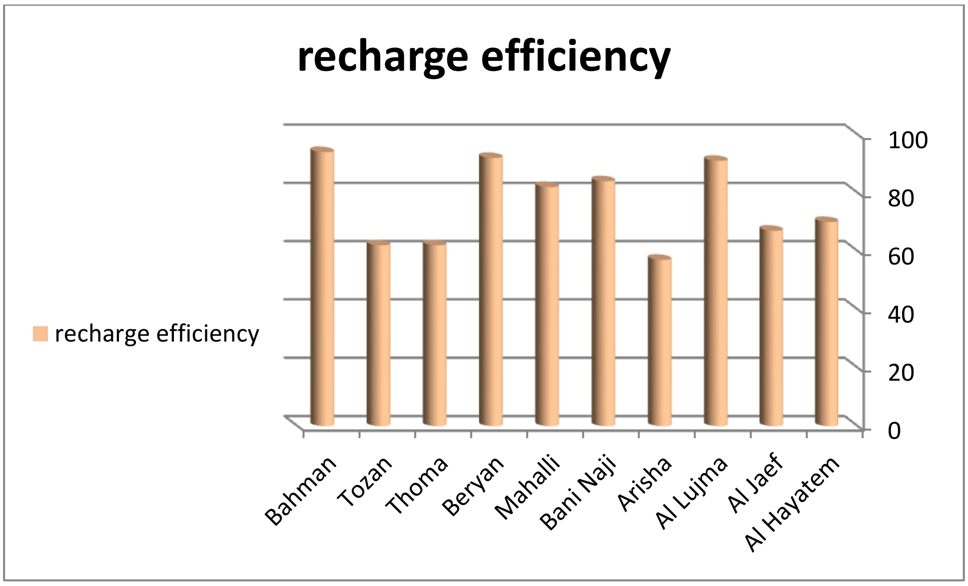
Dynamic daily recharge to shallow aquifer during 2002-2009 was estimated using the developed model of reservoir simulation (water balance, section 3.1) combined with a more refined Darcian approach involving an analytical approximation of a flow-net solution. Summary of the results of total recharge volumes by the two methods are given in *Table (6.10).*

Table (6.10) 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%.

6.4 Numerical Simulation (Modflow)

he use of groundwater numerical simulation (MODFLOW) provides better understanding and quantification of dam sites surface and groundwater resources availability. The influence of the interaction of all manageable recharge parameters as it occurs in the field on the recharge percentage is calculated and these are summarized in *Table (6.11)*

Table (6.11) : Summary of groundwater modeling

Dam site	Mahalli	bannaji	Al-jaef	Al-hyathem
Aquifer type	Sandstone (L.S.)	Limestone	Sandstone	limestone with dykes
horizontal hydraulic conductivity m/d	1.2	10.71	1	18
vertical hydraulic conductivity m/d	0.02	0.032	0.011	0.015
Total leakage during simulation m^3	409,774	433,697	25,453	231,953
Total groundwater abstraction during simulation m^3	1,557,243	54,969	111,741	94,477
difference between leakage and abstraction m3	1,147,469	378,728	86,288	137,476
Time steps (days)	1096	731	235	1096
Average daily leakage rate m^3	374	593	108	212
depth to groundwater table under reservoir mbgs	1	10	2	13.5
number of cells over modeled area	245	194	234	613
Total inflow water m^3	611,500	507,000	27,300	306,000
An average reservoir area m^2	15,625	7,800	5,000	15,625
Total reservoir water elevation mags	39.14	65.00	5.46	19.58
An average water depth in the reservoir	0.036	0.089	0.023	0.018
Daily leakage/kv	18,694	18,540	9,846	14,109

The groundwater modeling 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

6.5 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, 1996). 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.

6.5.1. 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 6.12.*

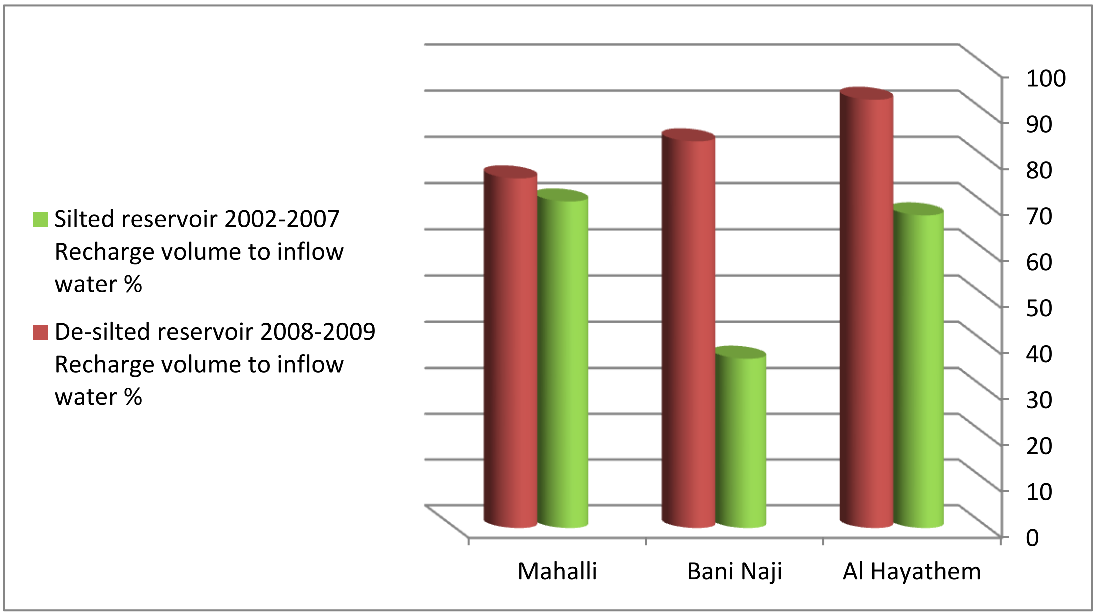
Table 6.12: Annual Average of incremental recharge under silted reservoir conditions

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 (6.13).*

Table 6.13 : 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.

6.5.2. Incremental Recharge under De-Silted Reservoir Condition

Table 6.14 : 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.

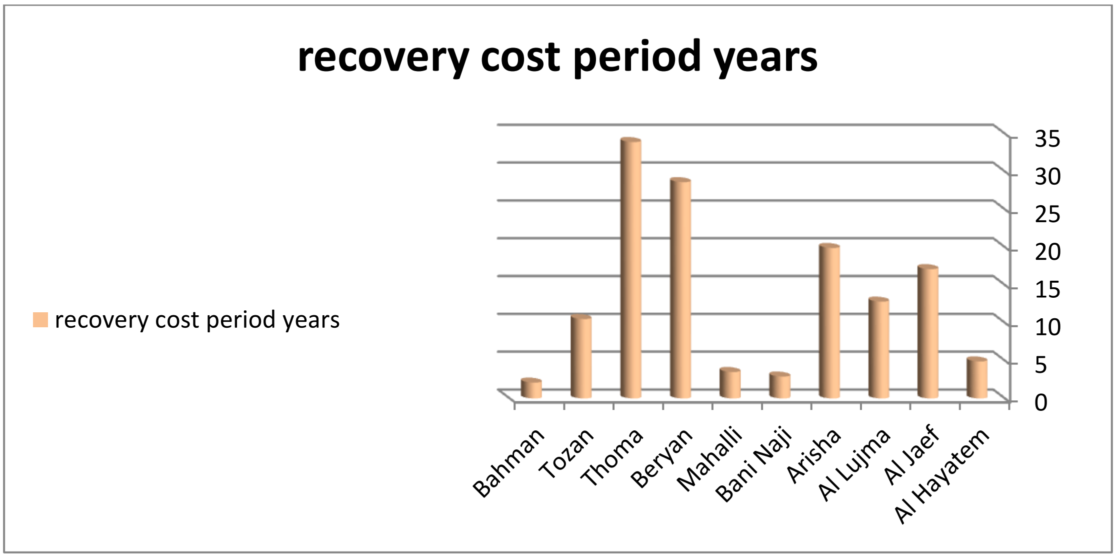
6.5.3 Dams Cost Effectiveness

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 (6.15).*

Table 6.15 : . 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

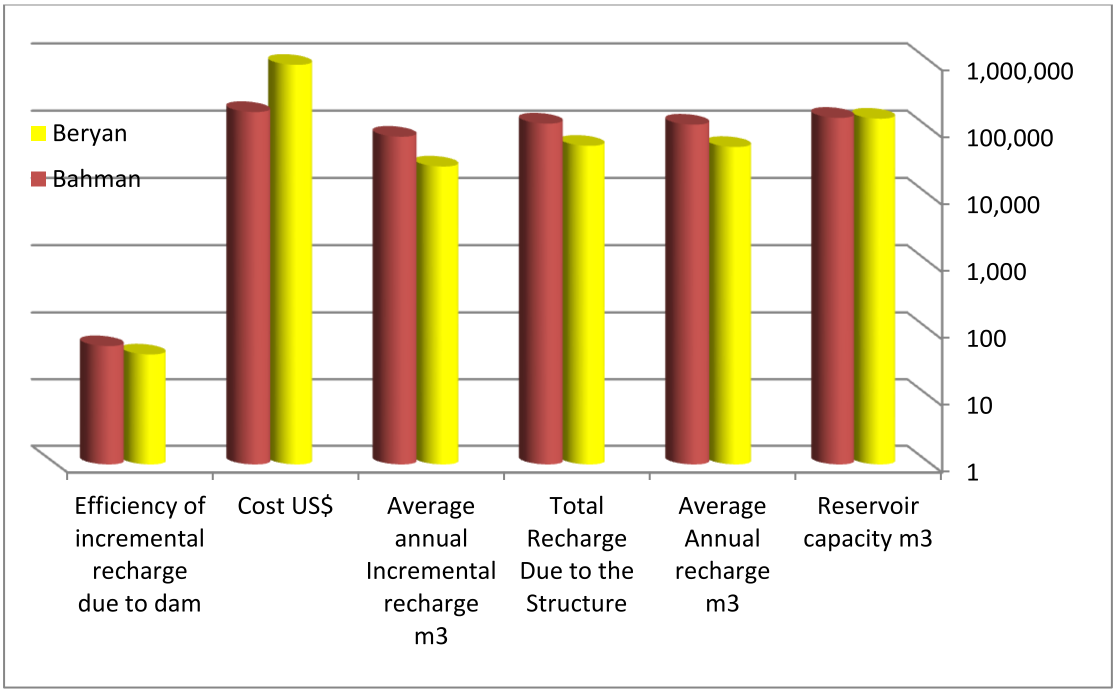


The value of recharged water assessed as 250 YER ($ 1.1) for a cubic meter following the cost estimate of cubic meter of de-salineated water taken to Sana’a (TREC, 2006). SBWMP rehabilitated 8 existing dam sites and constructed two new dam sites. The new dams built by the project were Beryan (gravity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

Table 6.16: 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).



6.6. 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.

6.7. 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 6.17*

Table 6.17 : 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.

7.conclusion and recommendations

- 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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