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Induced recharge at new dam sites—Sana'a Basin, Yemen

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Abstract In approaching the task of developing recharge estimates for dam sites, several constraints are apparent, including the scarcity of site-specific data for the selected new sites and the availability of simple yet robust analysis techniques. Combined, these constraints require an approach which involves best use of available data, adoption of relatively simple analytical approximations of reality, and the adoption of several key assumptions. In arid country with limited resources, two simple techniques have been used for recharge estimation: (1) a simple water balance model in spreadsheet and (2) a more refined Darcian approach involving an analytical approximation of a flow-net solution. By applying the two models at three new dam sites, the amount of recharge rates calculated over the period 2007–2026 was close. This is because, despite Darcian approach that should have affected the recharge rate as other parameters were introduced in the calculation of q_t, e.g., groundwater table mound, reservoir water height, etc., the results show general agreement between the two methods which seem to validate the assumptions made in both methods. A general conclusion of this comparison is that the hydraulic conductivity (K) is the main determining factor in recharge calculations in these situations. The water balance model was used to estimate recharge at Wadi Bahaman, under gravity and cascade dams' scenarios. Using gravity dam at Wadi Bahaman for groundwater recharge proved not suitable based on the relatively small predicted runoff from a small catchment area and geological concerns in the abutment areas. Instead, a series of three low check dams (2 to 4 m high) was proposed. These check dams will slow down the runoff flow, form small reservoirs, and enhance recharge along the valley, without requiring expensive foundations. Estimated groundwater recharge under cascade dams (141,407 m^3/year) is greater than recharge estimated for gravity dam (103,853 m^3/year) by at least 36%.

Keywords Dams · Artificial recharge · Water supply · Yemen · Arid

Introduction

Water resources management issues in Sana'a Basin is a complex issue, straddling the needs of supplying a growing population in an arid region, within a diverse and complex physiographic environment. Over the last two decades, groundwater aquifers in Sana'a have been severely over-exploited as demonstrated by the continued decline of the water levels in Sana'a basin. The impact of this problem is already felt in the capital city Sana'a. As water scarcity increases, the inhabitants of outlying areas around major cities have become less willing to permit public access into what they consider "their" ground water, Alderwish and Al Eryani (1999). Enhanced aquifer recharge is one alternative to the water sustainability crisis occurring in Sana'a Basin. Intermittent and intense rainfall events over the Sana'a basin watershed can lead to short-term surface water availability (Alderwish 1995). Without proper management of this water resource, excess precipitation can be quickly lost to the highly 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 (World Bank 2001).

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In the Sana'a basin (Fig. 1), the World Bank (2001) is planning to help finance the construction of a series of small dams for groundwater recharge in a number of secondary (tributary) wadis. These wadis cut more or less deeply into the bedrock which makes up the surrounding mountains. During significant rainfall events, the floods which produce surface flow in the wadis originate exclusively from these mountains. Selection of the proposed new dam site at the uppermost part of wadis made to avoid poor quality runoff water, however, means small catchment and relatively small runoff that may not justify the cost of classic big gravity dam. Moreover, wadi gradient is commonly steeper towards the upstream direction. The gradient is critical to assess if any piping out (spring outlet) will develop downstream to the proposed dam site. This dilemma led to the thinking of constructing cascade (check) dams on minor wadis of the Sana'a basin, which is presently the more appropriate option to enhance aquifer recharge.

This paper describes the approach and methodology applied to assess the potential recharge of four new proposed dam sites and suitability of cascade (check) dams on minor wadis of the Sana'a basin.

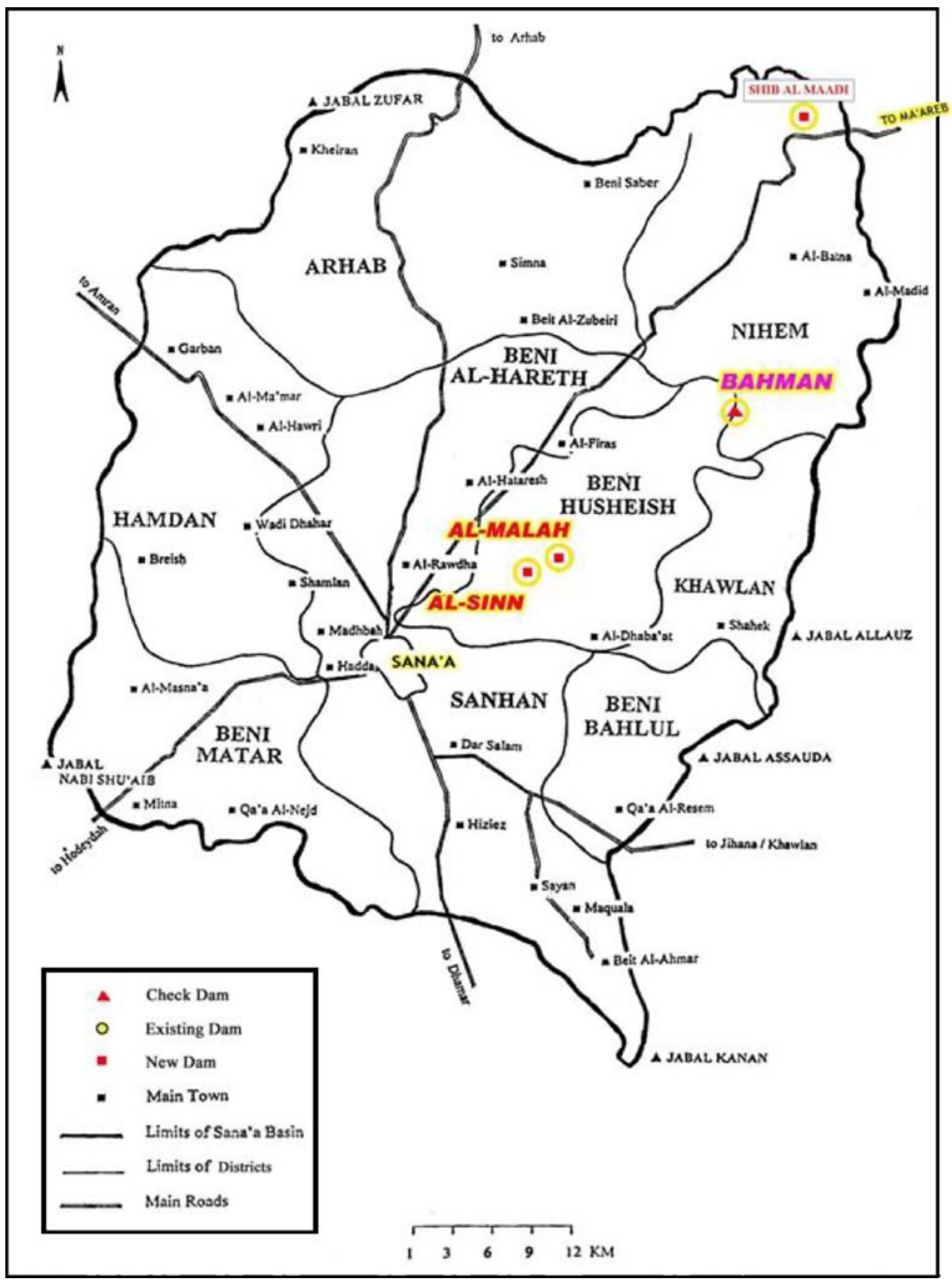

Fig. 1 Location of the studied new dam sites—Sana'a Basin, Yemen

The methodology

The conceptual model of wadi bed

The wadis in the study area are remote ephemeral streams. They are normally dry, with infrequent floods generated by rainfall of high intensity and short duration. When runoff occurs, the streams will often carry large volumes of water during a flood lasting a few hours and a large proportion of the flow is observed to infiltrate the bed and banks, causing the stream to disappear before reaching its outlet. However, under the right condition of a high intensity rainfall event over a relatively large part of the catchment with steep impervious slopes, the runoff can reach the lower recharge zone (Alderwish 1995).

The upper reaches of the wadis are usually devoid of fine sediments as these are commonly washed out by flow and deposited in the downstream part as a result of the decrease in flood flow velocity. The wadi deposits normally are poorly sorted with a large variation in grain size, but are predominantly coarse grained. The sediments are generally permeable; however, this permeability decreases in the downstream direction. Sediments formed within or close to the stream channel are much more coarse grained and permeable than those deposited on the flood plain. According to a schematic concept of depositional history, coarser-grained materials should prevail in the upstream part of the wadi and in older, deeper layers that were deposited during earlier, more vigorously erosive phases (Alderwish 1995). Along most of the wadi, there are distinctive channel banks, and channel area increases in the downstream direction. The effective channel area, however, varies depending upon the magnitude of the flood.

The thickness of the vadose zone varies between 10 and 40 m. The vadose zone thickness increases in the downstream direction where the channel bed is well above the groundwater table. Naturally, in wadi recharge, a saturated continuity between the stream and aquifer does not commonly exist, so accuracy in the description of the shallow aquifer may not be required in recharge estimation. However, under reservoir conditions, saturated continuity between the reservoir and aquifer does exist and accuracy in the description of the shallow aquifer is required in recharge estimation.

Hydrology and reservoir conditions

Three new dam sites were investigated during this study. These are Malah, Al Sinn, and Shib Al Maadi dam sites. Hydrology, geomorphology, and reservoir condition of each site are summarized in Table 1 and described briefly below.

The catchment area at Malah dam site has an elongated shape and is mainly constituted of steep slope hills, which covered more than 80% of the total catchment's area. Hillside slopes average 29%, and are covered with weathered rocks and bare soil. The catchment area has an intensive surface drainage network. Farmers reported that the wadi flows four to eight times per year. Floods may last 3 h and may reach 1 m height in the wadi (of 80 m width). This location is a narrow pass (about 70 m wide) between two low rolling hills. Upstream, the valley widens into a gently sloping rolling surface with a house built on a knob in the middle of the reservoir. Downstream, the valley widens again and, at about 400 m, flows down a steep narrow canyon. The profile of the dam axis is a compromise between a V- and a U-shaped valley. The reservoir area is about 70% located within the porous Tawilah sandstones and 30% in basaltic material. Fortunately, the less porous basalt is located at the head of the reservoir, where water will remain only for a short period after the floods. In any case, the permeable alluvial deposits provide a substantial recharge surface area and a good storage thickness everywhere in the reservoir. Even though most of the construction material will be taken from the upstream alluvial deposits, this should have only a marginal effect on the recharge and storage capacity of the reservoir (Hydosult-Komex-Darwish 2002).

The catchment area at Al Sinn dam site has an elongated shape and is mainly constituted of steep slope hills, which cover more than 60% of the total catchment's area. Hillside slope averages 26%, and are covered with weathered rocks and bare soil. The catchment area possesses an intensive surface drainage network. Farmers reported that the wadi flows four to eight times per year. Floods may last 2 h and may reach 1.5 m height in the wadi (of 50 m width). The profile of the dam axis at this location is a U-shaped gorge forming a narrow pass between moderate to steeply inclined high hills. Upstream and downstream of this pass, the valley widens. The wadi comes from high mountains not too far away. The area is barren and supports no cultivated lands upstream. The reservoir takes the form of a long winding scar. The short, little stubby tributaries will be flooded. The valley walls are all sandstone outcrops; hence, the surface of the recharge interface with the porous Tawilah sandstones is quite extensive and should benefit the recharge of the deep bedrock aquifer. Even though most of the construction material will be taken from the alluvial deposits in the reservoir, this should have only a marginal effect on the recharge and storage capacity of the reservoir (Hydosult-Komex-Darwish 2002).

The catchment at Shib Al Maadi dam site has an elongated shape; the upper part of it is mainly constituted of hilly area which forms approximately 50% of the total catchment area. The hilly area is covered by weathered and fractured rocks and bare soil and possesses high slopes, which average 21%. The remaining part of the catchment is constituted of an uncultivated flat plain. The main channel

Table 1 Summary of hydrology and catchment area at the new dam locations

Characteristics	Malah	Al Sinn	Shib Al Maadi
Total area	3.87 km^2	2.65 km^2	31.7 km^2
Length of main water course	2.800 km	2.100 km	9.5 km
Slope of main water course	12.22%	5.71%	2.53%
Total length of drainage network	6.2	5.1 km	42.9 km
Surface drainage network density	1.85 km/km^2	2 km/km^2	1.41 km/km^2
Percentage of generating hilly area to catchment area	80%	60%	50%
Slope of hilly area	29%	26%	21%
Average annual rainfall for catchment area	192.5 mm	192.5 m	160 mm

water course has 9.5 km length with gentle slopes which averages 2.5%. Shib Al Maadi dam, located upstream of the proposed site, affects the volume of runoff flowing in the wadi at the proposed site and reduce the siltation volume that may deposit at the proposed dam. Farmers reported that the wadi flows six to ten times per year, and floods may reach 2.5 to 3 m height at the proposed dam site where the water course is about 25 m wide. The water course bed is covered with calcareous gravel and coarse sand. From the point of view of geomorphology, this north central limit of the Sana'a basin is a resurgent mountain plain cut through by large and small wadis which usually follow zones of weaknesses in the massive Amran Limestone. Major wadis are depositional (early maturity or late youth). Most secondary tributaries are still in the erosional stage of development (youth). Most of the recharge water should find its way through the limestone fractures of the reservoir and to the bedrock aquifer. This should be vertical (wadi and reservoir bottom) and lateral at least for a short distance before it will continue downward to the bedrock aquifer (Hydosult-Komex-Darwish 2002).

Quantitative assessment methodology

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 and 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). Nevertheless, for this study, based in large part on sparse existing data and limited resources, relatively simple estimation techniques are required. Accordingly, two techniques have been used for recharge estimation:

1. a simple water balance model, and
2. a more refined Darcian approach involving an analytical approximation of a flow-net solution.

Hydrometeorological approach

The proposed enhancement of groundwater recharge in Sana'a Basin is to be conducted through storage of flood-waters in reservoirs constructed over a part of the minor wadi bed "permeable area". The conventional method to estimate reservoir subsurface seepage (recharge) is the water balance equation. A water budget determination of reservoir subsurface seepage (Q_s) may be expressed as (Linsley et al. 1975):

$$Q_s = (S_1 - S_2) + I + P - O - E$$

where S=storage (S_1 and S_2 are storage at time 1 and time 2, respectively), I=surface inflow, O=surface outflow, E=evaporation, and P=precipitation over the reservoir area (usually negligible on the scale being considered).

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 runoff, and the evaporation.

The estimation of runoff volume (daily, monthly, and annual) generated in the catchment area at the dam's location based on the SCS–RRM developed by the TSHWC (1992) and as modified by Alderwish (1995) for measured floods over Sana'a Basin was then used to estimate daily runoff volume generated over the proposed new dam's catchment. The model aimed to estimate daily runoff volume from synthetic daily rainfall for the next 20 years (2007–2026). The model is a distributed one, with rainfall inputs applied to a number of distinct rainfall zones throughout the catchment area and with different "runoff characteristic zones" being separately treated within each rainfall zone. This distributed approach provides the best estimation of runoff in a given watershed as it considered the watershed composed of number of hydrological cells possessing the same physical characteristics. Inundated surface area required for evaporation and infiltration calculations was estimated based on stage–volume relationships developed for each dam site. A numerical model was developed to simulate reservoir operation at the proposed new dam sites. The reservoir simulation was used to: determine the storage capacity and therefore the height of the dam; decide on the "vocation" of the reservoir between surface utilization and/or groundwater recharge; determine the yield or the mean volume that could be released from the reservoir to fulfill its purposes; and estimate the average hydrological variables of the reservoir, e.g., precipitation, evaporation, and infiltration.

Importantly, however, without direct measurement of the change in storage in the reservoir, recharge cannot be estimated by direct subtraction from the other values. Thus, a computed value of recharge must be provided for the water balance calculation. Average measured K at the dam site was used to compute average infiltration through reservoir bottom using simple Darcy flow. As all new dam sites examined as part of this study have deep water tables (21.5–45 m), vertical infiltration processes are assumed to be the controlling factor due to the considerable head put on the subsurface system by the presence of water in the reservoir. This results in a system in which the vertical component of flow is more dominant (Abdul Razzak et al. 1989). This means that the component of flow in the z direction is significant (Freeze and Cherry 1979). On this basis, a vertical hydraulic gradient of near unity was selected for preliminary estimation of recharge in the water balance model.

A simple spreadsheet model was used to calculate daily recharge rate from the reservoir. This 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.

The model calculates recharge as follows;

(A) The rainfall (P_i) and/or surface inflow (I_i) on the ith day is added to S_i, the reservoir storage at the start of the ith day. Thus, the revised uniform storage in the reservoir (S_i-1) will be;

$$S_i - 1 = S_i + I_i + P_i \tag{1}$$

(B) The daily surface outflow is checked and calculated as the difference between the maximum reservoir storage MAXS (the amount of water over the water spillway over the dam) and S_i-1.

$$\text{Surface outflow} = S_i - 1 - \text{MAXST} \qquad \text{if } S_i - 1 > \text{MAXST} \tag{2}$$

And so reservoir storage S_i-2 becomes equal to MAXST for the same day

Or

$$S_i - 2 = S_i - 1 \qquad \text{if } S_i - 1 \leq \text{MAXST} \tag{3}$$

(C) The daily potential evaporation on the ith day ($\mathrm{Et_o}$) is calculated from average monthly meteorological data and the Penman equation and deducted from the reservoir storage. By multiplying $\mathrm{Et_o}$ by the surface area of water in the reservoir, the actual evaporation is determined (if dry $\mathrm{Et_o}=0$)

$$\text{Revised storage } S_i - 3 = S_i - 2 - \mathrm{Et_o} \tag{4}$$

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

$$S_i - 3 = S_i - 2 - Q_t \qquad \text{if } S_i - 2 > Q_t \tag{5}$$

And the calculation is repeated for the subsequent day.

At each new dam site studied, 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 curves established from the topographical survey for each new dam site. 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. Daily potential evaporation is calculated using available monthly average meteorological data (SAWAS 1996) and has been subtracted from the reservoir storage in a daily basis. A daily infiltration rate is estimated; using the average recorded saturated K in the dam vicinity. 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, assuming that there is continuous maintenance of the reservoir and removal of accumulated silt.

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

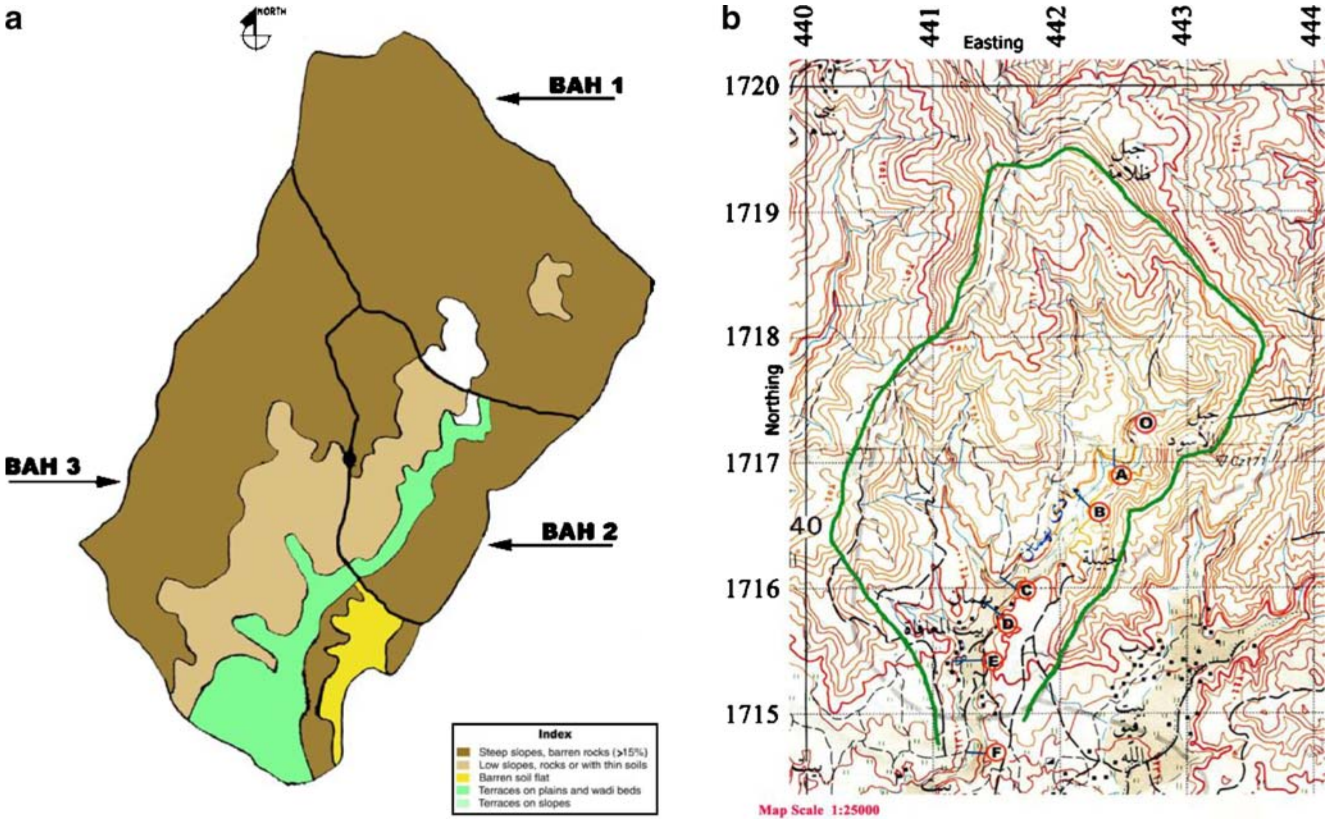

Fig. 2 **a** Hydrological catchment of Bahaman check dams, **b** hydrological sections for Bahaman main water course

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 an originally dry reservoir bed can be predicted using classical one-dimensional vertical infiltration equations such as Green and Ampt (Besbes et al. 1978) when floodwater enters the reservoir bed. However, once the wetting front reaches the water table, the flow becomes primarily horizontal and the Green and Ampt method no longer applies. Two phase studies (e.g., Bouwer 1978, etc.) have indicated that the Green and Ampt model of infiltration rates is an adequate representation of reality as far as infiltration rates are concerned and particularly so when the depth of ponding over the wadi bed is significant, which is typically the case for reservoirs of the type is being considered. The infiltration discharge per unit length of the wadi also has been obtained using the Green and Ampt

Fig. 3 Malah dam site main wadi channel

Fig. 4 Abutment of Al Sinn dam site

equation at the very moment the wetting front hits the saturated zone:

$$q_o = KW\left\{\frac{\mathrm{H}+D}{D}\right\}$$

Where q_o is infiltration discharge per unit length of wadi, K is the hydraulic conductivity, D is the depth of soil profile between the initial water table location and the bottom of the river bed, H is the depth of water above the wadi bed, and W is the wadi bed width (approximate of the width of infiltration zone). However, once the wetting front reaches the water table, the flow becomes primarily horizontal and the Green and Ampt method no longer applies (Alderwish 1995). 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 expressed by Darcy's law as:

$$q(t) = K\,A'\Delta h/L' \tag{6}$$

Where $q(t)$ is the seepage rate (m^2/day), K is the hydraulic conductivity (m/day), 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:

$$A' = {}^1\!/_2(W + [e + h(0,t)] \tag{7}$$

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,

$$L' = (2D + e + W - h(0,t))/2 \tag{8}$$

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

$$\Delta h = H + D - h(0,t) \tag{9}$$

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

$$Q(t) = K[e + W + h(0,t)/2D + e + w - h(0,t)] \times [H + D - h(0,t)] \tag{10}$$

At time zero, this formula should reduce to q_0, the discharge prevailing at the moment the wetting front merges with the initial water table. Equation (10) does not (as a result of the crude flow-net approximation), but a

Fig. 5 Bahaman dam site main wadi channel

Table 2 Summary of recharge estimates at three new dam sites for study period (2007–2026)

New dam sites	Al Malah dam site			Al Sinn dam site			Shib al Maadi dam site		
years	Recharge by Darcian	Recharge by water balance	Induced recharge	Recharge by Darcian	Recharge by water balance	Induced recharge	Recharge by Darcian	Recharge by water balance	Induced recharge
2007	107,568	125,751	57,993	66,661	72,283	42,770	598,075	565,307	301,760
2008	180,407	217,471	81,746	115,288	129,086	66,841	390,313	371,247	189,944
2009	122,314	135,993	59,597	72,091	74,309	52,078	910,287	846,148	545,361
2010	126,369	125,773	64,948	67,553	68,601	48,259	216,332	204,672	99,035
2011	231,003	293,793	72,466	151,275	170,050	34,618	770,820	702,761	411,143
2012	129,700	146,829	69,579	77,182	88,990	46,310	891,301	820,153	400,623
2013	51,871	53,791	32,242	28,211	28,533	28,211	684,510	627,148	315,592
2014	113,018	120,753	20,475	64,331	65,757	64,331	362,564	345,515	192,279
2015	129,952	165,473	67,255	85,006	100,514	36,030	364,945	346,942	221,086
2016	62,806	65,062	43,221	34,045	34,370	34,045	137,358	134,487	64,328
2017	132,164	162,962	70,454	85,281	98,053	37,206	459,003	436,233	285,753
2018	116,379	133,351	45,189	70,997	77,704	29,269	397,674	374,551	220,355
2019	60,467	63,304	19,978	33,999	34,556	16,415	243,961	237,495	140,865
2020	6,751	6,880	6,751	3,500	3,519	3,500	165,070	161,492	57,385
2021	9,573	9,759	9,573	4,974	5,000	4,974	167,504	160,442	79,128
2022	140,729	180,539	56,853	89,212	106,913	22,971	71,361	46,383	13,220
2023	127,219	169,146	57,377	93,920	111,791	40,455	480,118	482,927	358,768
2024	18,448	18,866	18,448	9,627	9,689	9,627	65,722	65,413	8,579
2025	51,139	53,544	32,019	27,906	28,238	27,906	394,629	374,955	241,603
2026	68,368	72,866	25,918	39,578	40,448	20,587	85,814	83,818	40,356
Total	1,986,246	2,321,906	912,083	1,220,635	1,348,403	666,402	7,857,360	7,388,089	4,160,721
Average annual	99,312	116,095	45,604	61,032	67,420	33,320	392,868	369,404	208,036
STD	48,215	62,022	21,922	32,429	39,007	16,213	236,855	220,145	125,777

slightly corrected form of it does, namely (Parissopoulos and Wheater 1995)

$$q(t) = q_0\left[(1 + h(0,t)/e + W)(1 - h(0,t)/2D + e + W)^{-1}\right] \quad (11)$$
$$[1 - h(0,t)/D + H]$$

Equation (11) has the proper limits for small and large times. Also, it does not depend upon the manner in which q_0 is estimated. For this reason, it is preferred to Eq. (10), which is already approximate and in addition does not have the proper limit at time zero (Wheater et al. 1995). Using Eq. (11) does not require that q_0 be evaluated by a Green and Ampt infiltration formula such as Eq. (6), although Eq. (6) is particularly simple, convenient, and quite accurate (Reeder et al. 1980).

An additional check on method accuracy was provided by a series of numerical model test runs using Groundwater Vistas, based on the MODFLOW code (Alderwish and Dottridge 1995). 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 Abdul Razzak et al. (1989), Wheater et al. (1995), and Hydosult-Komex-Darwish (2002). Vertical hydraulic gradients in situations with relatively deep initial water tables were found to be relatively high, depending on input parameters, generally supporting the assumptions used in the estimations above.

Clearly, 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, described adequately by the Green and Ampt model. 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. At this point, the flow becomes primarily horizontal (two-dimensional) and one-dimensional equation no longer

Table 3 Predicted recharge (m^3) 2007 to 2026 Bahaman new gravity and check dam sites

Year	Annul recharge from a gravity dam	Recharge check dam 1	Recharge check dam 2	Recharge check dam 3	Annual recharge from 3 check dams
2007	246,807	124,720	12,019	108,386	245,125
2008	426,595	211,928	3,382	188,943	404,253
2009	265,081	133,516	26,559	115,042	275,117
2010	250,557	126,221	22,582	108,947	257,750
2011	573,481	284,914	64,789	250,387	600,090
2012	284,792	140,600	96,084	127,847	364,531
2013	107,029	55,220	19,775	46,121	121,116
2014	236,788	120,056	22,529	102,753	245,338
2015	324,991	158,275	45,907	144,157	348,339
2016	129,633	66,365	5,971	57,052	129,388
2017	317,056	157,009	20,125	139,853	316,987
2018	260,391	129,998	6,529	112,918	249,444
2019	123,901	63,559	3,917	54,153	121,628
2020	13,806	7,220	234	5,870	13,324
2021	19,981	10,244	14,710	8,901	33,855
2022	352,852	173,202	26,130	153,971	353,303
2023	346,356	165,999	103,495	153,982	423,477
2024	37,808	19,501	7,599	16,624	43,723
2025	105,807	53,792	180,181	45,778	279,752
2026	143,280	71,823	17,046	62,878	151,746
Total recharge	4,566,992	2,274,161	699,563	2,004,562	4,978,286
Annual average recharge	228,350	113,708	34,978	100,228	248,914
Total natural wadi recharge	2,489,922	1,035,573	246,452	868,130	2,150,155
Induced recharge	2,077,070	1,238,588	453,111	1,136,433	2,828,132
% of induced recharge	55	54	65	57	59
Annual average induced	103,853	61,929	22,656	56,822	141,407

applies. In addition, there will follow various periods of increasing and decreasing water levels in the reservoir and, periodically, drying and re-wetting cycles.

Suitable type of recharge dam

A suitable type of dam in Sana’a basin minor wadis has been tested at Wadi Bahaman. Induced groundwater recharge was estimated using water balance approach under a gravity dam and under a series of three low check dams (2 to 4 m high). The section of the wadi considered for site of check dams is downstream of the UTM coordinates E: 0442463 and N: 1716973. The last proposed potential site can be considered as the ultimate downstream location below which the construction of a check dam is considered impractical (i.e., overall extension is 4.2 km along the wadi bottom). Available area for recharge (m^2) for check dams were: 27,449 for check dam (1), 13,933 for check dam (2), and 60,000 m^2 for check dam (3). For gravity dam, the available area is 75,600 m^2. Water balance approach was used to estimate induced groundwater recharge under gravity dam and check dams (Fig. 2a and b; see also Figs. 3, 4, and 5). The results are given in Table 3.

Results and conclusions

To assess the actual benefit of the proposed 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. Natural indirect recharge was assessed using regression relation developed by Alderwish (1995), between generated runoff and wadi recharge.

The modified SCS–RRM model (Alderwish 1995) was used to estimate daily runoff volume generated over the proposed new dam's catchment. The model aimed to estimate daily runoff volume from synthetic daily rainfall for next 20 years (2007–2026). Inundated surface area required for evaporation and infiltration calculations was estimated based on stage–volume relationships developed for each dam site. For Darcy approach, the daily recharge rate $q(t)$ has been estimated by an approximate two-dimensional recharge expression based on Darcy's law, and developed from simple flow-net theory. This approach was developed by Abdul Razzak et al. (1989). Calculation inputs for each site: K (average hydraulic conductivity of layers underlying the reservoir). The depth of soil profile between the initial water table location and the bottom of the reservoir bed was set to be 37, 45, and 22 m at Malah, Al Sinn, and Shib al Maadi dam sites, respectively, based on vertical electrical soundings results at the sites. The initial aquifer average saturated thickness is approximated at 31, 50.1, and 26 m at Malah, Al Sinn, and Shib Al Maadi dam sites, respectively, from well logging and geophysical results.

Table 2 summarizes the results of recharge estimation at the three new sites investigated within Sana'a Basin by the two approaches. The total calculated recharge rate over the 20-year period (2007–2026) using the Darcian approach is close to that calculated by the water balance method. Despite Darcian approach that should have affected the recharge rate as other parameters were introduced in the calculation of q_t, e.g., groundwater table mound, reservoir water height, etc., the results showing a general agreement between the two methods would seem to validate the assumptions made in both methods. A general conclusion of this comparison is that the hydraulic conductivity (K) is the main determining factor in recharge calculations in these situations.

Total predicted groundwater recharge for a single gravity dam as well as for the three proposed new check dams over 20 years is shown in Table 3.

The annual average induced recharge from check dams are 61,929, 22,656, and 56,822 m^3, totaling 141,407 m^3. This amount is higher than the annual average induced recharge under gravity dam scenario which is 103,853 m^3. This means that there is an increase of about 36% of induced recharge under check dams than gravity dam. For dam types, additional benefits of check dams over gravity dam are to regulate the flood flow in the wadi by reducing its velocity through these dams. It delays (extends) the duration of flow over the wadi and hence increases infiltration opportunity. Check dams also remove fine suspended materials through settlement, providing clear water to the downstream part, which infiltrates more readily.

As has been seen from the above that despite the scarcity of site-specific data which limited the use of sophisticated analysis technique, a simple approach developed carefully can provide acceptable results for estimation of induced recharge. Using data of less quality and quantity with sophisticated techniques will provide results of same or less quality than simple techniques do with their approximation and assumptions. This seems true in subsurface analysis as the medium is modeled in all cases as a uniform, homogeneous, and essentially isotropic medium characterized by a single value of hydraulic conductivity. The documented presence of fractures, joints, and fault zones, layers of varying mineralogical composition and hydraulic conductivity, and other structural features will almost certainly cause infiltrating water to migrate laterally, in some cases creating small isolated perched zones and trapped water bodies unavailable for exploitation, and not contributing to recharge of the target formation. These considerations would seem to suggest that the recharge values provided by the two simple methods described herein are reasonable and encourage use of simple method in areas with least data and resources.

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