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Longitudinally and laterally trench-supported subsurface dam innovative design procedures

Zekâi Şen[a,b,]

[a] Engineering and Natural Sciences Faculty, Istanbul Medipol University, Beykoz, 34815 Istanbul, Turkey
[b] Center of Excellence for Climate Change Research/Department of Meteorology, King Abdulaziz University, P.O. Box 80234, Jeddah 21589, Saudi Arabia
E-mail: zsen@medipol.edu.tr; zsen@kau.edu.sa

ABSTRACT

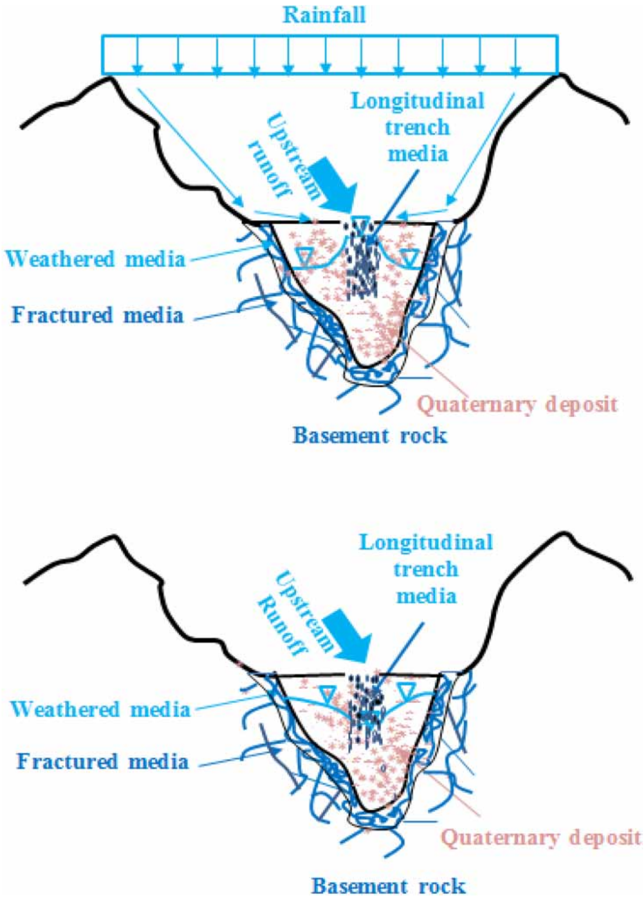
According to the Paris climate change agreement, temperature increases of around 1.5 or 2.0 °C by 2050 are bound to increase the amounts of evaporation and evapotranspiration, which are among the losses from surface water bodies, such as rivers, lakes, reservoirs and dams. In order to reduce these losses and support local water supply, subsurface dam construction projects are at the forefront in many countries, especially in arid and semi-arid regions, even in subtropical climate regions. In the literature, there are classical methodological explanations for underground dams with quite insufficient and restrictive interpretations. In this paper, two very similar but different new alternatives are proposed as longitudinally and laterally supported underground dams with inspirations from historical qanat groundwater subsurface structures. Both types are supported by artificial trenches with higher hydraulic conductivity than the surrounding Quaternary alluvial deposits to increase external and meanwhile to support internal areal recharge possibilities between the trenches and the surrounding natural porous, weathered and fractured layers. It is noticed that trench-supported subsurface dams are more effective, affordable, sustainable and manageable than classical alternatives available in the literature. It is recommended that a more refined subsurface groundwater movement mathematical formulation should be developed in the future.

Key words: dry, groundwater, lateral, longitudinal, recharge, subsurface dam

HIGHLIGHTS

- Subsurface dams play an important role against climate change impacts in many regions.
- Old qanat groundwater technology led to longitudinal and lateral trench-supported innovative subsurface dam designs.
- These innovative subsurface dam designs provide rainfall and runoff harvesting possibilities.
- Up-to-date literature review is presented and there is not enough subsurface dam information in the open literature.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The resilience of domestic, agricultural and industrial freshwater uses in the face of climate change and variability impacts can be increased by improving groundwater along with direct rainfall and indirect runoff recharge applications. As the world's largest reservoir of distributed freshwater, groundwater plays a central role in sustaining ecosystems and enabling human adaptation to climate variability and change (IPCC 2007; Taylor *et al.* 2013; United Nations 2015; Cotterman *et al.* 2017). As a result of the impact of climate change and population growth, groundwater-table levels and well productions are decreasing with quality deterioration. In many parts of the world, shallow wells are drying up due to excessive abstraction rates especially during dry periods. Projects of subsurface dams are gaining importance to increase the groundwater potential to harvest the runoff and thus to meet future water demand. One of the best solutions to overcome the aridity and drought problems in arid and semi-arid areas is subsurface dam construction (Ishida *et al.* 2003; Borst & de Haas 2006; Hoogmoed 2007; Şen 2008). Since the subsurface dam studies are quite inadequate, unfortunately, there is not enough literature review.

Groundwater storage improvements can be achieved by subsurface dam construction to capture groundwater flow and assist groundwater-table level raise, particularly in Quaternary alluvial depositional layers (Raju *et al.* 2006). These dams are preferred to surface dams because of almost no evaporation loss, higher efficiency and functionality, cheaper construction cost, less risk of pollution and land use even above the dam. They are economical, effective and sustainable for local water supply management. Not only suitable sites but also additional suitable construction designs of underground dams provide economic, effective and sustainable development in addition to the management of groundwater resources. A geographic information system (GIS) has been proposed to identify suitable sites for the construction of these dams (Jamali *et al.* 2013; Dehghani Bidgoli & Koohbanani 2021). Although there are different types of subsurface dams, many of them have not been as useful as expected due to insufficient scientific and technological evaluations. Site selection may be appropriate, but detailed groundwater arrangements may hinder useful functions. Appropriate sites should be determined after detailed topographical, geological, hydrogeological and engineering design procedures; otherwise, groundwater lateral water loss may result. Their use is widespread in various parts of the world such as the Arabian Peninsula, Africa, India and Brazil (Raju *et al.* 2006). Khairy *et al.* (2010) analyzed the possibility of a proposed subsurface dam construction in the Arabian Peninsula by applying a three-dimensional finite element (FE) numerical model to serve as strategic water resource storage.

Generally, subsurface dams are constructed along stream or wadi (valley) cross-sections (Şen 2008). For this purpose, a trench is dug along the cross-section so that the bottom of the trench ends in the bedrock. The trench is filled with permeable materials similar to the old-fashion qanat system (Lightfood 2000; Mostafaeipour 2010; Şen 2016). The scarcity of water in arid countries triggers many socio-economic activities and even a single drop of water must be used, reused, conserved and transferred from sources to places of consumption in the most efficient manner. The future management of water resources and the most efficient protection, allocation, transport and operation require not only a numerical data base but also a preliminary linguistic knowledge base as expert opinions and innovative motivations in the best research and technological design directions.

The total volume of good-quality water stored in subsurface dams is, in some cases, one or two times the long-term average annual runoff of the associated temporary waterways. Other benefits of subsurface dams include the absence of siltation problems, the absence of significant evaporation losses and the ability to easily refill from the bed of the wadi channels by direct or indirect (runoff) seepage (Şen 2019).

Climate change is leading to more erratic and extreme patterns of rainfall and drought in many countries around the world. Water buffering can reduce the effects of variable water supply. Decentralized rainwater harvesting techniques are available to provide safe water throughout the seasons, making a crucial difference for vulnerable rural and urban populations. In situations where climate change has resulted in a drier environment and the water balance has turned to scarcity, buffering water with a small rainwater harvesting facility can make a significant difference.

Increasing water storage capacity is a very efficient, simple and therefore promising adaptation strategy against climate changes. Increasing water collection and storage during scarce and unreliable rain showers can be achieved by harvesting rainwater in constructed tanks, increasing groundwater storage and installing small-scale subsurface dams on seasonal rivers and stream beds. In the dry subtropics, access to water for domestic uses such as drinking, sanitation, cooking and small-scale food production will increase if rainwater is collected, stored and used where it falls.

The main purpose of this paper is to propose two types of innovative subsurface dam design supports with longitudinal and lateral trench arrangements upstream of a subsurface dam. The trenches help to improve groundwater storage on the one hand and groundwater extraction on the other. Full-scale representative longitudinal and lateral trench-supported subsurface dams are explained with rather simple mathematical calculation methodology proposals.

2. GROUNDWATER RECHARGE POSSIBILITIES

It is possible to talk about direct and indirect recharge possibilities. Direct recharge is when excess rainfall seeps into suitable surface areas without converting to runoff. Indirect recharge is from runoff water which originates outside the precipitation impact area. The types of groundwater recharge in arid regions along with the mechanism are presented by Lloyd (1986), who stated that the most extensive, rich and important recharge in arid regions is due to indirect recharge that spreads floodwaters over thousands of square kilometres to both sides along the main wadi channel. In many places, from time to time, both direct and indirect recharges occur simultaneously. The soil surface area resulting in direct recharge is smaller and more homogeneous than in indirect recharge, and therefore estimates are more reliable.

Since the indirect recharge area is along the wadi channel and may extend from the upstream to the outlet, it is more difficult to calculate and requires additional maintenance and protection. Şen (2008) explained that through-layer flow runoff harvesting (RH) occurs through prominent fractures, cracks and voids in hard rocks (igneous and metamorphic) and solution cavities in limestone (soft rock). In addition, depressions over the drainage basin area occur as small lakes that partially recharge the aquifer and store surface water, the other part of which is lost as evaporation,

Apart from the above-mentioned types of recharging, there are also different causes and mechanisms involved in recharge processes. Such dominant mechanical factors include surface features (topography, morphology, depression dimensions and vegetation) meteorological processes (temperature, evaporation, humidity, solar irradiation and wind speed), land use (agriculture, transportation roads and urban areas), geology (soil type, rock type and fractures) and unsaturated zones (granular composition, thickness, effective porosity). The role of these factors varies from humid regions to arid regions, where the basic groundwater dynamisms are indirect recharge in wadi channels, depressions, limestones and sabkhas, volcanic rocks, sand dunes, and contact lines between different lithologies. All these factors affect the rainfall recharge collection location in arid regions along the wadi main channels.

Although RH is a very old technique, its use is reemerging in modern times as one of the simplest adaptation methodologies in arid and semi-arid regions because of water scarcity, stress and climate change (Shalamzari *et al.* 2019). Its use exists from time immemorial to collect and store from rainfall and runoff. Archeological evidence confirms that rainwater was retained as far back as 4,000 years, and the concept of rainwater harvesting in China can be traced back 6,000 years. The advantages and benefits of RH are many (Krishna 2003; Mahmoud & Alazba 2016). Water is almost free of charge and the only cost is for collection and use. RH provides a water source to augment limited groundwater resources. RH water is valued for its purity, softness, nearly neutral pH and being unaffected by disinfection byproducts, salts, minerals and other natural and man-made contaminants. Rainfall-fed agricultural products provide the best vegetables and crop quality.

In particular, the recharge point location in Quaternary alluvial land should have permeable material with enough porosity to retain substantial water. Occupying depressions along great wadis, the Quaternary terrain contains negligible primary porosity and hydraulic conductivity in places that partially act as subsurface dams, but elsewhere the porosity and permeability of the locations are well suited for rainfall and runoff groundwater recharge. Therefore, a detailed study should be undertaken to identify potential RH locations based on hydrological, hydrogeological and geophysical characteristics, including well inventory, landscape indicators, topographic features, geological setup, structural controls, drainage conditions and geoelectrical surveys. The choice of recharge points and trenches depends on the identification of permeable zones along the wadis.

3. CLASSICAL SUBSURFACE DAMS

Subsurface dams are quite simple, economical, locally efficient and safe solutions to store groundwater resources without evaporation losses. Classically, there are three commonly known types of subsurface dams, namely, fully subsurface, partial burial and similar surface dams, but the background is filled with porous material called sand-storage dams (Khairy *et al.* 2010; Barkhordari 2015). Any subsurface dam blocks the groundwater flow and tries to keep the groundwater-table level constant at the upstream. The two previous subsurface dams are described by Şen (2021) and their longitudinal sections are given in Figures 1 and 2.

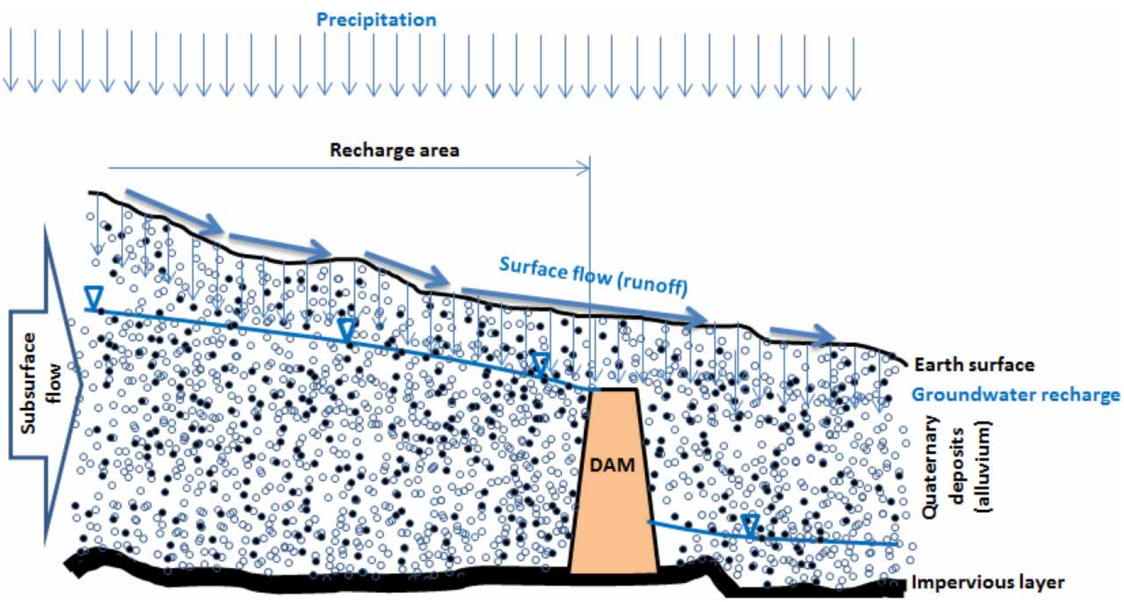


Figure 1 | Entirely buried subsurface dam (Şen 2021).

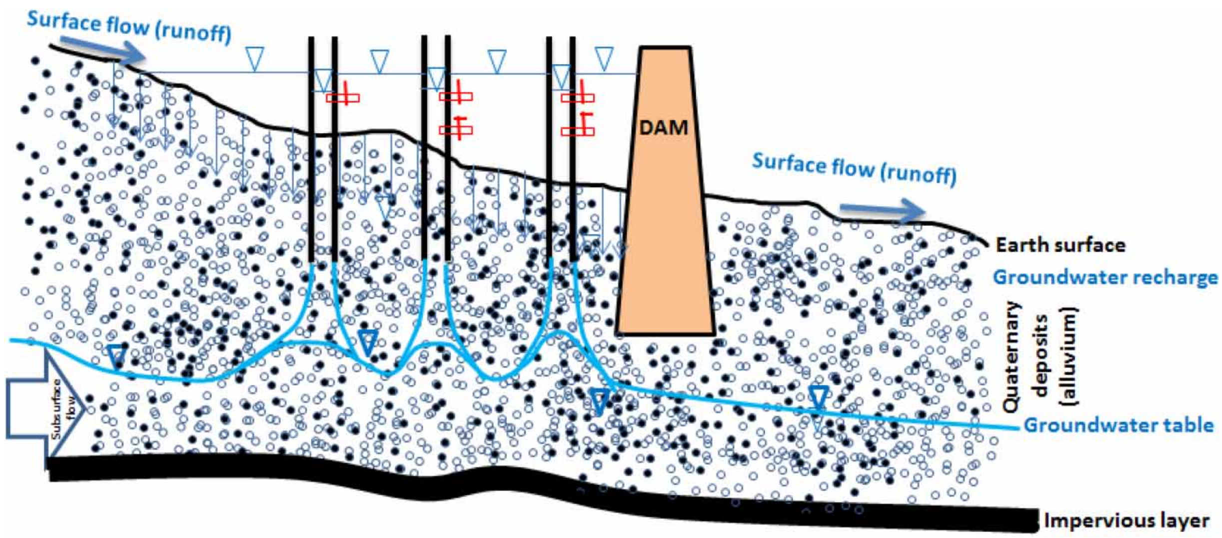


Figure 2 | Partially buried subsurface dam (Şen 2021).

The one in Figure 3 can be filled by sedimentation after erosion and transportation by sand, gravel and soil particles during periods of high flow. This is very similar to a retaining wall or fountains on the sides of foothills to provide drinking water socially and free of cost as a salvation service. Such subsurface dams are constructed in layers of sand deposition potential and finer material is washed downstream.

Transition zones between hills and plains with Quaternary deposits are the most suitable places for subsurface dams. As Nilsson (1988) stated, the topographical gradient of the construction sites is between 0.2% and 4%, but in extreme cases, the slopes reach 10%–16%. Another important consideration in choosing a suitable subsurface dam site is sand and gravel Quaternary sediments that can be recharged by occasional flooding from higher catchment elevations. Behind full penetration subsurface dams, the possibility of surveying fully saturated groundwater is not possible because flash floods pass over the dam without infiltration but fill the aquifers downstream of the subsurface dam. On the other hand, partially penetrating subsurface dams (Figure 2) allow for continuous groundwater recharge and allow groundwater to flow subsurface downstream. The groundwater extraction is provided by a series of shallow hand dug wells.

Subsurface dams protect groundwater with almost negligible evaporation losses and therefore their structures are preferred especially in arid, semi-arid and even in subtropical climates due to the effect of climate change. By taking preliminary precautions, the subsurface dam waters are kept away from the risk of pollution. In particular, the renewable capacity of subsurface reservoirs helps maintain groundwater quality for acceptable agricultural and domestic water supply purposes.

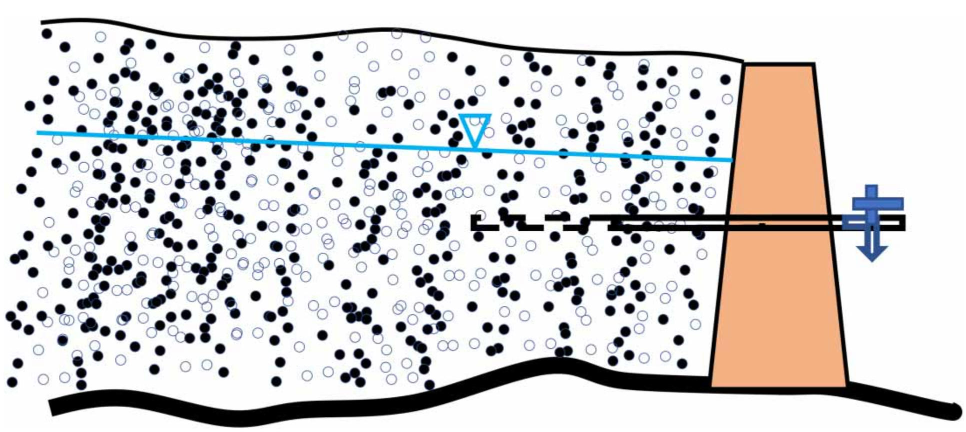


Figure 3 | Sand-storage subsurface dam.

There is no danger of infringement and the land being submerged under water. Social and eco-systematic impacts are minimal. Technology is preferred by society for various reasons. It increases the capacity of conventional wells, is simpler and cheaper to construct, is repeatable and is easily maintained by the community. Disadvantages are well-pumping and operation costs compared with the surface dams.

4. QANATS

As historical subsurface hydraulic structures, the invention of qanats was long thought to have taken place in Iran, but recent evidence suggests that the oldest examples are in south-east Arabia around 3100–3000 BC (Lightfood 2000). By 2300 BC, qanat technology had spread rapidly in the arid region from Pakistan to the Egyptian desert and later to China and Spain (Kobori 1980).

Şen (2014) explained the importance of these groundwater structures in terms of hydrogeology. The system of wells connected by a gallery that brings water from the foothills to the plains as shown in Figure 4 is called 'qanats'. The main groundwater-carrying part of the system is the deep-penetrating gallery with a small gradient. This gallery is filled with coarse hydraulic conductivity materials to allow easy groundwater flow.

The qanats consist of a long subsurface tunnel filled with a material with a relatively higher hydraulic conductivity than the surrounding subsurface, and there are shafts along this tunnel. Voudouris (2012) stated that the head well was constructed at the highest upstream point to find the groundwater. Qanats are among the oldest groundwater structures to meet both agricultural and domestic water demands. They are several kilometres long and provide groundwater with increased hydraulic conductivity from upstream to downstream. The water flows inside the tunnels with a slight slope, which ensures the gravitational flow of groundwater (Mostafaeipour 2010). Mahmoudian & Mahmoudian (2012) and English (1968) provide good documentation on initial application possibilities in northern Mesopotamia, Iran and eastern Turkey.

Qanats were built as gently sloping tunnels in the Quaternary alluvial fills or fans. The tunnel collects groundwater seepage and carries it downhill until it appears as surface water near the exploitation center above the water table. The widespread use of qanats in arid or semi-arid regions is due to the following points (Şen 2006):

(1) Groundwater flows with the force of gravity and therefore no extra power source is needed.
(2) Since the flow is completely in the subsurface, evaporation losses are minimal.
(3) It provides a reliable and sustainable water supply for local domestic and agricultural lands.
(4) Groundwater flow is reliably protected against pollution.

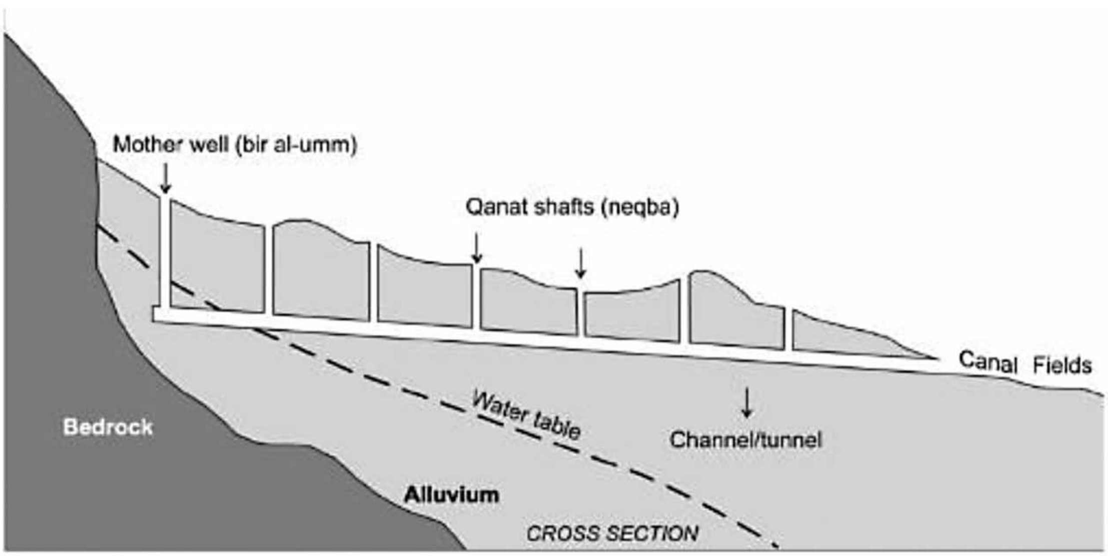


Figure 4 | Cross-section of a qanat (Lightfood 2000).

A detailed description of qanat construction in arid regions is given by Amin *et al.* (1983) in addition to its hydrologic importance, maintenance and specific features. In the following sections, combinations of qanat-type artificial groundwater transfer trenches are combined with different subsurface dams to improve groundwater recharge and subsurface dam efficiency and management.

5. LONGITUDINAL TRENCH-SUPPORTED SUBSURFACE DAMS

Generally, fully and partially penetrating subsurface dams are constructed along cross-sections at suitable locations for rainfall and runoff recharge increases to provide a static or flowing groundwater storage dam. In this paper, it is proposed to support these subsurface dams with artificial high hydraulic conductivity trenches in Quaternary deposits. To transport the recharge water upstream of these subsurface dams, several kilometres of artificial trenches almost along the natural alluvium deposit in the mid-flow channel are dug quite simply by excavators, large construction equipment that is versatile. The most common uses for an excavator include digging trenches, ditches and foundations. Figure 5 shows the longitudinal trench and subsurface dam locations within a wadi channel access. In order to reduce the inflow of sediment transport from the upstream runoff to the trench area, it is recommended to construct an artificial stilling basin at the upstream inlet location (see Figure 5).

The arrangement of wells along the longitudinal trench provides efficient groundwater abstraction for water supply. In these trenches, groundwater levels drop relatively faster than the surrounding alluvium groundwater level, and therefore groundwater flow into the wells is faster and much better than without trench construction.

In Figure 6, the A-A cross-section of the longitudinal trench-supported subsurface dam (see Figure 5) is presented for rainy (wet) (Figure 6(a)) and non-rainy (dry) (Figure 6(b)) periods. During the wet period, there is local precipitation, surface flow and upstream runoff, if any. Groundwater levels in high permeability trenches are higher than the surrounding Quaternary alluvial deposit groundwater tables. Accordingly, groundwater response in the trench is earlier than in the adjacent deposits, which helps faster and more extensive groundwater recharge, and hence, groundwater levels rise behind the subsurface dam. On the other hand, the dry period groundwater level in the trench is lower compared with the adjacent natural deposits, and

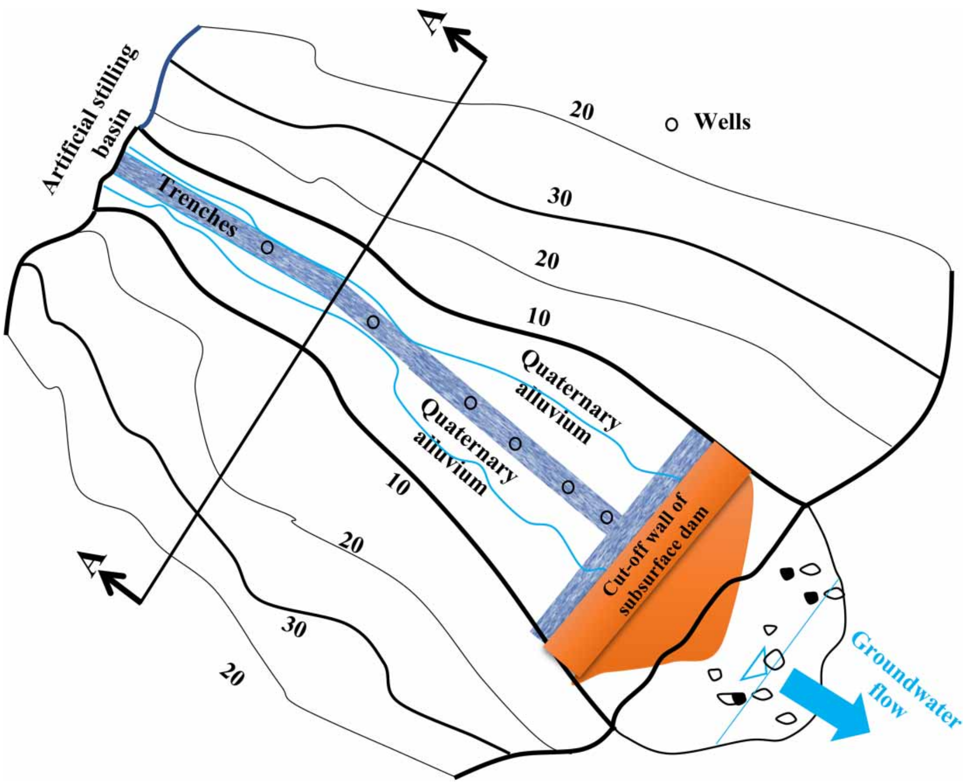


Figure 5 | Conceptual full penetration subsurface dam with longitudinal trench.

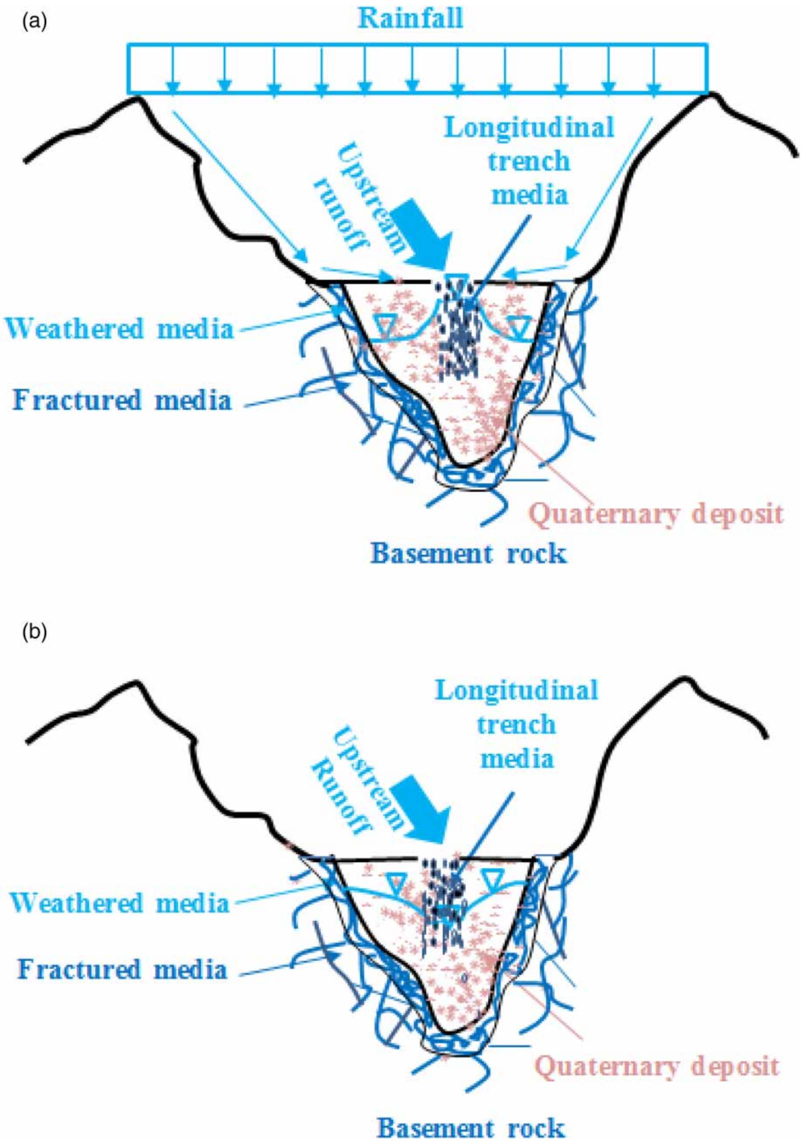


Figure 6 | (a) Longitudinal trench-supported subsurface dam, wet period groundwater recharge potential; (b) dry period groundwater abstraction.

therefore sensitive groundwater recharge takes place in the trench. In wet and dry periods, groundwater is present not only in the Quaternary alluvium deposits, but also in the weathered and fractured layers along the wadi floor. Compared with subsurface dam construction, the existence of a longitudinal trench provides dynamism to the external and internal groundwater recharge possibilities between the trench and the Quaternary deposits.

6. LATERAL TRENCH-SUPPORTED SUBSURFACE DAMS

Another trench-supported subsurface dam alternative is shown in Figure 7, where there are subsurface dam upstream lateral trenches with high hydraulic conductivities. The management dynamism of this alternative is completely different than the longitudinal trench case. The lateral trenches are constructed by means of excavation machine digging and then filling by coarse material to increase the hydraulic conductivity more than in the surrounding Quaternary deposits. Again a stilling basin should be placed in the water course channel prior to the trench area entrance.

Lateral trenches are positioned as permeable subsurface media with higher hydraulic conductivity, and therefore groundwater receives direct rainfall or runoff groundwater recharge opportunities. The wet and dry groundwater recharge and

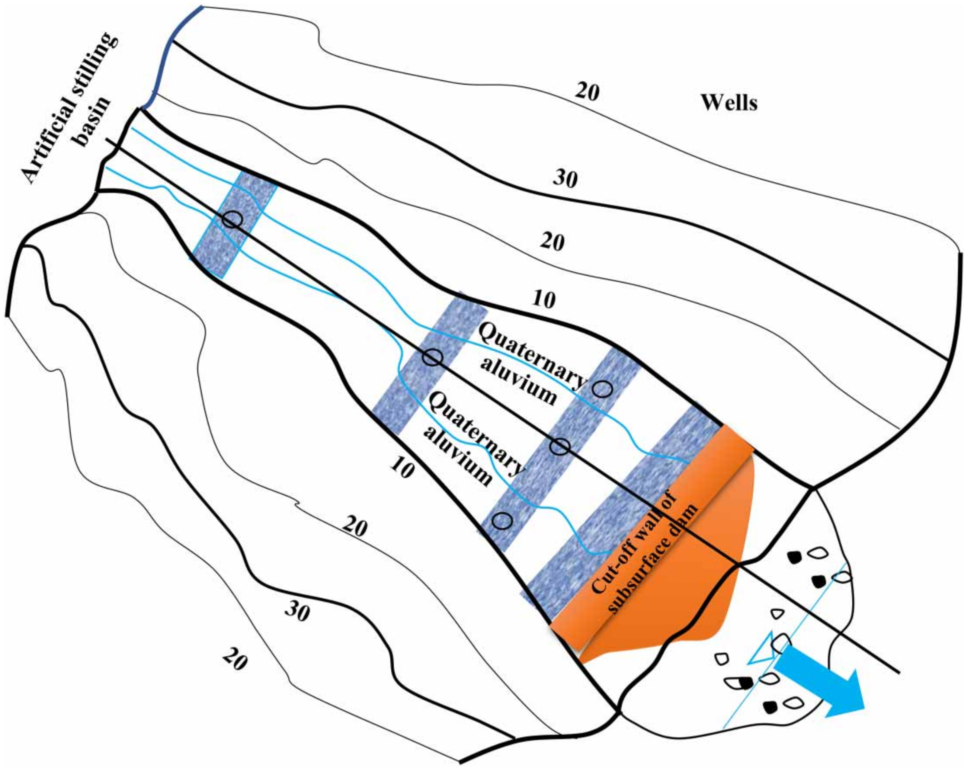


Figure 7 | Conceptual full penetration subsurface dam with a lateral trench.

interactions between the trenches and the Quaternary alluvial environment are shown representatively in Figure 8(a) and 8(b), respectively. In Figure 8(a), the possibilities of direct and indirect groundwater recharge cause groundwater table in the trenches to rise earlier and more easily than in surrounding Quaternary deposits. Therefore, internal recharge takes place from trenches to natural subsurface geological formations. However, during dry periods, the opposite occurs as internal groundwater recharge into trenches with high hydraulic conductivity (see Figure 8(b)).

During the wet period, the groundwater levels in the trenches are higher than the groundwater level in the Quaternary sediment. Lateral trenches act as extensive injection wells for faster groundwater recharge indirectly from direct precipitation and upstream runoff, and therefore internal groundwater recharge takes place between the lateral trenches and Quaternary deposit. Laterally supported subsurface dams are more efficient than longitudinal alternatives due to the possibility of recharge from two trenches over a certain area of the Quaternary deposit section.

7. DISCUSSION

Any conventional fully or partially penetrating subsurface dam construction has less efficiency compared with longitudinal and latitudinal trench-supported alternatives. This is due to the highly homogeneous composition of the subsurface groundwater movement flow, in addition to the external and internal recharge facilities and groundwater withdrawal for water supply. The following points are among the most important benefits from the longitudinally and laterally supported subsurface dams.

(1) Trench-supported subsurface dams provide more extensive recharges compared with classical subsurface dams.
(2) Trenches provide effective and easier groundwater recharge directly from the rainfall and upstream runoff.
(3) Abstraction well location within each trench provides longitudinally and laterally extensive well action along the trenches.
(4) The existence of trenches allows rather rapid groundwater recharge due to their higher hydraulic conductivity media than the surrounding natural Quaternary deposits.
(5) During wet periods, trenches intake rainfall and runoff waters rapidly leading to a higher groundwater table position than in the adjacent materials, and hence, internal recharge from the trenches helps to feed the Quaternary deposits extensively.

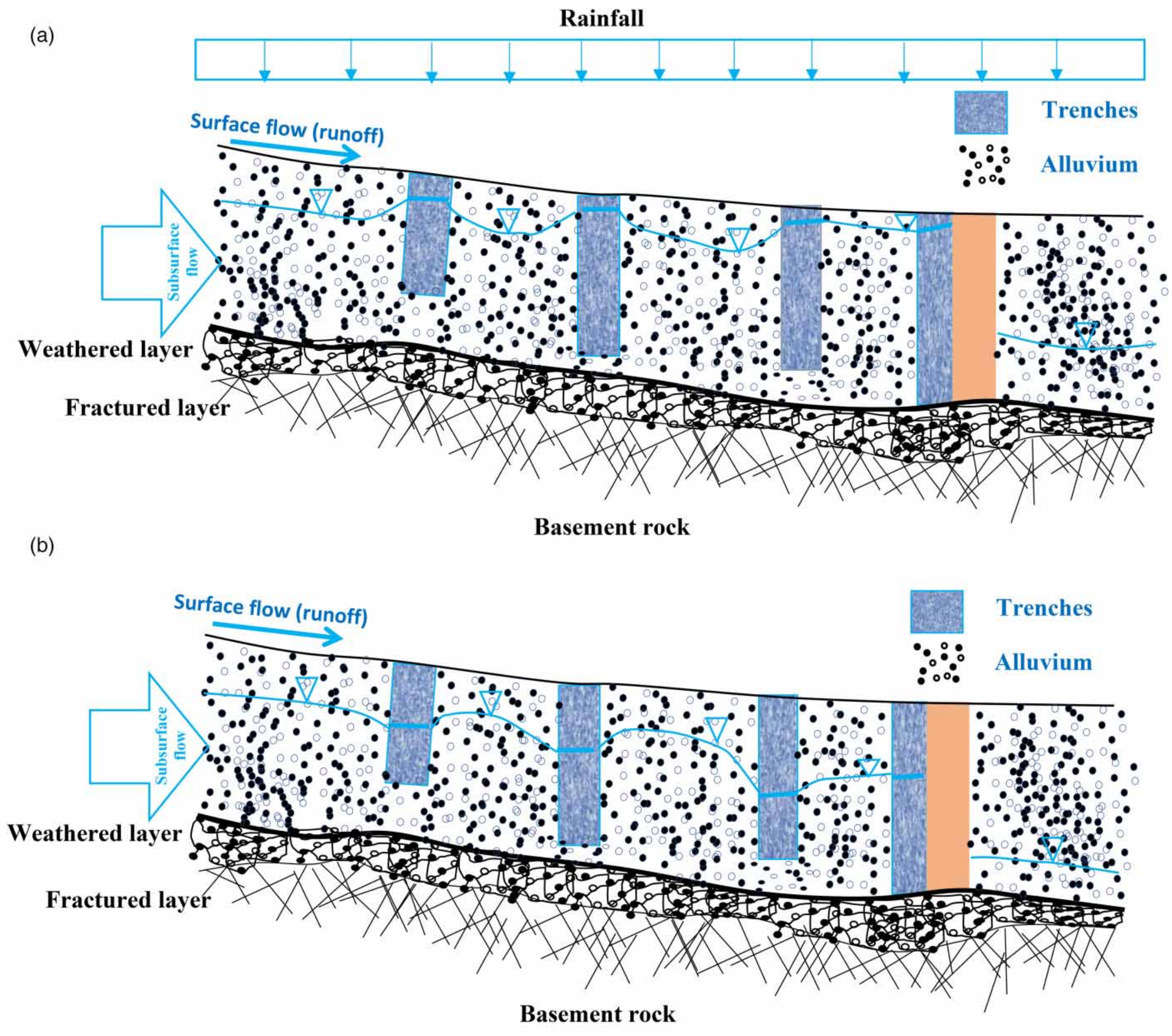


Figure 8 | Latitudinal trench-supported subsurface dam: (a) wet period groundwater recharge potential, (b) dry period groundwater abstraction.

(6) During dry periods, the groundwater table level is lower in trenches due to groundwater abstraction, and hence, trenches are recharged from the adjacent Quaternary deposits.
(7) Laterally supported subsurface dams perform better than longitudinal trench alternatives, because groundwater can be controlled parcel-wise between two successive trenches.
(8) The width and depth of the trenches can be adjusted according to the rainfall regime in the region. It is well known that the more frequent and intense the rainfall, the wider and deeper the trenches should be.
(9) The trenches also help to keep the groundwater quality of better quality due to the rapid recharge facility.
(10) Application of longitudinal or lateral trench structural composition provides greater groundwater quality and quantity, especially downstream of partially penetrating subsurface dams.
(11) To reduce sediment transport from the upstream portions, it is recommended to excavate large stilling basins prior to the upstream location of the trenches. In this way, the clogging of the trenches is largely prevented, and thus the trenches are relatively cheaper and more durable structures rather than costly injection-well constructions.
(12) Subsurface dams do not flood the land area, thus allowing land use and land change activities.

(13) There is no danger of socio-economic loss, because such structures do not cause migration, and support local communities with additional water supply.
(14) Groundwater is directly replenished by rainfall or runoff events, and therefore its quality does not change much and there is no pollution hazard.
(15) Subsurface dams are stable and do not require periodic maintenance. In case of dam collapse or breakage, there is no risk to life and property in the downstream settlements.

8. SUBSURFACE DAM CALCULATION

In general, there are detailed theoretical mathematical formulations of rainfall recharge and groundwater flow based on hydro-mechanical principles that require good software uses (Walton 1970; Bear 1979; Freeze & Cherry 1979). This section presents practical formulations for groundwater recharge and unconfined aquifer groundwater flow upstream of subsurface dams. The basic form of the water balance equation, input, I, output, O, and the change in the storage can be written in terms of ΔS as follows:

$$I - O = \Delta S \tag{1}$$

In the case of input–output balance,

$$I = O \tag{2}$$

Herein, input is limited by the groundwater recharge potential, G_R, the depth of excess rainfall is evenly distributed over the catchment, and water abstraction is defined in terms of A, so the net groundwater level fluctuation can be expressed as $G_W = \pm (G_R - A)$. According to RH literature and standard engineering hydrology texts, the first 10% of rainwater is lost for surface wetting, evaporation and transpiration (Kinkade-Levario 2007). Consequently, in any groundwater recharge design study, it is assumed that only 90% of runoff, including rainfall, can be collected for efficient use. Application of this balance equation is recommended based on monthly rainfall and runoff recording principles.

8.1. Groundwater recharge

Groundwater recharge calculation methodologies are not repeated herein, because there are different old and recent methodologies for this purpose in the open literature. For instance, Subyani & Şen (1991) proposed a groundwater recharge study based on the recharge-outcrop relationship in the Arabian Peninsula. One of the methods is to record groundwater-level fluctuations in observation wells and keep rainfall records near these wells, preferably at upstream meteorological stations. It is logically plausible that there is a direct relationship between groundwater-level fluctuations and rainfall amounts, provided there are no groundwater withdrawals, which must also be taken into account in the water balance equation (Walton 1970). Şen (2019) proposed a probabilistic methodology for estimating groundwater-level fluctuations from rainfall records. It is suggested that the cumulative probability distribution functions (CDFs) of groundwater fluctuation and rainfall amounts are interrelated, so that the further the rainfall moves away from the mean, the greater the groundwater recharge. Lerner *et al.* (1990), Lerner (1977) and Rushton (1997) discussed the channel water budget method by considering surface water gains and transmission losses on the bases of streamflow data.

Another study concerns outcrop rocks, particularly in arid regions, and groundwater recharge calculations from occasional and rather scanty rainfall events. It is stated by Subyani & Şen (1991) that there is good agreement between predictions based on groundwater velocity and those based on isotope information.

8.2. Groundwater movement

The combination of the water balance (continuity) equation with Darcy's groundwater velocity law provides the groundwater flow that governs the differential equation. The groundwater velocity, v, can be expressed in terms of the hydraulic conductivity, k, in the porous medium and hydraulic gradient, i, as follows:

$$v = ki \tag{3}$$

There are different methodologies to find the value of k from ready tables or pumping-test results depending on the geological formation or practically from sieve analysis as:

$$k = Cd^2 \tag{4}$$

where C is a constant. This method is based on a representative grain-size distribution effective diameter, d (Krumbein 1934), and the initial slope and intersection of the grain-size distribution curve (Al-Yamani & Şen 1993).

Provided that R is the rate of groundwater recharge and A is the ratio of the volume of water withdrawn per unit horizontal area, then net production can be expressed in terms of water density, ρ, and areal extensions Δx and Δy as:

$$\rho(R - A)\Delta x \Delta y \tag{5}$$

In unconfined groundwater reservoirs (aquifers), the production of water depends on the porous medium including specific yield and retention; where the specific yield is equal to the groundwater aquifer storage coefficient, S. The amount of released water, ΔV_w, or added to storage can be calculated as $\Delta V_w = S\Delta A \Delta h(x, y)$, and therefore the temporal ratio of water can be expressed as:

$$\rho \frac{\Delta V_w}{\Delta t} = \rho S \Delta x \Delta y \frac{\Delta h(x, y)}{\Delta t} \tag{6}$$

where h is the groundwater level and t is time. The substitution of this expression in the continuity (water balance) equation leads to:

$$-\rho d\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y}\right)\Delta x \Delta y + \rho U \Delta x \Delta y - \rho V_{z2} \Delta x \Delta y + \rho(R - A)\Delta x \Delta y = \rho S \Delta x \Delta y \frac{\Delta h(x, y)}{\Delta t} \tag{7}$$

where d is the leaky aquifer thickness, and U and D are the upward and downward leakage (vertical) groundwater movement rates. It is possible to simplify the equation for two-dimensional groundwater flow motion as follows, assuming the water density as 1 g/cm^3 and as a single point:

$$-d\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y}\right) + V_{z1} - V_{z2} + (R - A) = S\frac{\partial h}{\partial t} \tag{8}$$

Darcy x- and y-direction groundwater flows and upward and downward groundwatertable fluctuations can be expressed by the following equations:

$$V_x = -K_{xx} \frac{\partial h(x, y)}{\partial x} \tag{9}$$

$$V_y = -K_{yy} \frac{\partial h(x, y)}{\partial y} \tag{10}$$

$$U = K_1 \frac{[h_{1(x,y)} - h(x, y)]}{b_1} \tag{11}$$

and

$$D = K_2 \frac{[h(x, y) - h_2(x, y)]}{b_2} \tag{12}$$

where b_1 and b_2 are upward and downward leakage thicknesses. Substitution of Darcy's equation with these leakage terms in Equation (8) yields:

$$\frac{\partial}{\partial x}\left[bK_{xx}\frac{\partial h(x,y)}{\partial x}\right]+\frac{\partial}{\partial y}\left[bK_{yy}\frac{\partial h(x,y)}{\partial y}\right]+K_1\frac{[h_{1(x,y)}-h(x,y)]}{b_1} + K_2\frac{[h(x,y)-\ h_2(x,y)]}{b_2}+R-A=S\frac{\partial h(x,y))}{\partial t} \tag{13}$$

Finally, the main equation for two-dimensional flow in an unconfined aquifer takes the following form.

$$\frac{\partial}{\partial x}\left[(h-\ \eta)K_{xx}\frac{\partial h(x,y)}{\partial x}\right]+\frac{\partial}{\partial y}\left[(h-\ \eta)K_{yy}\frac{\partial h(x,y)}{\partial y}\right]+K_1\frac{[h_1(x,y)-h(x,y)]}{b_1} + K_1\frac{[h(x,y)-h_2(x,y)]}{b_1}+R-A=S_y\frac{\partial h(x,y)}{\partial t} \tag{14}$$

where η is the bottom elevation. The unknown $h(x, y, t)$ in the above equations can be determined using a suitable method and boundary and initial conditions.

Although each month generates a unique monthly average, the set of monthly averages remains the same for all designs. Therefore, the supply-side quantities for each case study and the generic model differ as a function of the size of the catchment area. The demand side of the equation has been developed specifically for each project, based on water demands for local use and landscape needs. The application of these equations was presented by Önder & Yılmaz (2005) for unconfined groundwater flow in subsurface dams.

9. CONCLUSION

In general, conventional subsurface dams are constructed as impermeable walls of suitable cross-sections of types fully or partially buried in Quaternary alluvium sedimentary channels. This paper proposes the development of subsurface dam constructions with longitudinal and lateral trenches with an artificial medium of high hydraulic conductivity compared with the surrounding Quaternary sediments in the arid zone drainage basins (wadis), which can also be applied in semi-arid, arid or subtropical wadis. The addition of longitudinal and lateral artificial high hydraulic conductivity trenches improves surface (external) and subsurface (internal) groundwater recharge dynamisms behind subsurface dams. Groundwater recharge injection or water supply extraction wells can be constructed in trenches for the most efficient and comfortable groundwater recharge, extraction and subsurface water movement. The paper describes mathematical formulation possibilities for groundwater recharge from rainfall and runoff and presents subsurface groundwater flow mathematical formulations. It is recommended to excavate lateral stilling basins prior to runoff entry into the trench area. Another suggestion is to develop more refined groundwater flow mathematical formulations for longitudinal and lateral subsurface dams in future studies.

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All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The author declares there is no conflict.

REFERENCES

Al-Yamani, M. S. & Şen, Z. 1993 Determination of hydraulic conductivity from complete grain-size distribution curves. *Ground Water* **31** (4), 551–555.

Amin, M. J., Qazi, R. & Downing, T. E. 1983 Efficiency of infiltration galleries as a source of water in arid lands. *Water International* **8** (4), 158–165.

Barkhordari, J. 2015 The pre-selection of suitable sites for small underground dams in arid areas using GIS (a case study in Yazd_Ardakan watershed). *International Geoinformatics Research and Development Journal* **6** (1), 18–27.

Bear, J. 1979 *Hydraulics of Groundwater*. McGraw-Hill Book Co, New York, NY, USA.

Borst, L. & de Haas, S. A. 2006 *Hydrology of Sand Storage Dams: A Case Study in the Kiindu Catchment, Kitui District, Kenya*. Master's thesis, VU Amsterdam, Amsterdam, The Netherlands.

Cotterman, K. A., Kendall, A. D., Basso, B. & Hyndman, D. W. 2017 Groundwater depletion and climate change: future prospects of crop production in the Central High Plains Aquifer. *Climatic Change* **146**, 187–200.

Dehghani Bidgoli, R. & Koohbanani, H. 2021 Site selection for underground dam construction by fuzzy algorithm in GIS platform. *ECOPERSIA* **9** (3), 159–168.

English, P. W. 1968 The origin and spread of *qanats* in the Old World. *Proceedings of the American Philosophical Society* **112** (3), 170–181.

Freeze, R. A. & Cherry, J. A. 1979 *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ, USA.

Hoogmoed, M. 2007 *Analyses of Impacts of a Sand Storage Dam on Groundwater Flow and Storage. Groundwater Flow Modelling in Kitui District, Kenya*. Master's thesis, VU Amsterdam, Amsterdam, The Netherlands.

IPCC, Intergovernmental Panel on Climate Change 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Ishida, S., Kotoku, M., Abe, E., Fazal, M. A., Tsuchihara, T. & Imaizumi, M. 2003 Construction of subsurface dams and their impact on the environment. *RMZ – Materials and Geoenvironment* **50** (1), 149–152.

Jamali, I. A., Olofsson, B. & Mörtberg, U. 2013 Locating suitable sites for the construction of subsurface dams using GIS. *Environmental Earth Sciences* **70**, 2511–2525.

Khairy, A. T., Al-Ghamdi, A. S. & Gutub, S. A. 2010 Analysis and design of a deep subsurface dam. *International Journal of Civil & Environmental Engineering IJCEE-IJENS* **10** (3), 32–41.

Kinkade-Levario, H. 2007 *Design for Water*. New Society, Gabriola Island, BC, Canada.

Kobori, I. 1980 *Qanawat Romani of Taibe Oasis*. Tokyo University Scientific Mission for the Comparative Study of the Foggara Oasis in the Arid Zone of the Old Continent, Report no. 1. Tokyo University, Tokyo, Japan.

Krishna, H. 2003 An overview of rainwater harvesting systems and guidelines in the United States. In: *Proceedings of the First American Rainwater Harvesting Conference*, pp. 21–23.

Krumbein, W. C. 1934 Size frequency distribution of sediments. *Journal of Sedimentary Petrology* **4** (2), 65–77.

Lerner, D. N. 1977 Groundwater recharge. In: *Geochemical Processes, Weathering and Groundwater Recharge in Catchments* (O. M. Saether & P. de Caritat, eds), A.A. Balkema, Rotterdam, The Netherlands, pp. 109–150.

Lerner, D. N., Issar, A. S. & Simmers, I. 1990 *Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge*. Verlag Heinz Heise, Hannover, West Germany.

Lightfood, D. R. 2000 The origin and diffusion of qanats in Arabia: new evidence from the northern and southern Peninsula. *The Geographical Journal* **166** (3), 215–226.

Lloyd, J. W. 1986 A review of aridity and groundwater. *Hydrological Processes* **1** (1), 63–78.

Mahmoud, S. H. & Alazba, A. A. 2016 Towards a sustainable capital city: an approach for flood management and artificial recharge in naturally water-scarce regions, Central Region of Saudi Arabia. *Arabian Journal of Geoscience* **9** (9), 92.

Mahmoudian, S. A. & Mahmoudian, S. N. 2012 Water and water supply technologies in ancient Iran. In: *Evolution of Water Supply through the Millennia* (A. N. Angelakis, L. W. Mays, D. Koutsoyiannis & N. Mamassis, eds), IWA, London, UK, pp. 91–126.

Mostafaeipour, A. 2010 Historical background, productivity and technical issues of qanats. *Water History* **2** (1), 61–80.

Nilsson, A. 1988 *Groundwater Dams for Small-Scale Water Supply*. Intermediate Technology Publications Ltd, London, UK.

Önder, H. & Yılmaz, M. 2005 Underground dams. A tool of sustainable development and management of groundwater resources. *European Water* **11–12**, 35–45.

Raju, N. J., Reddy, T. V. K. & Munirathnam, P. 2006 Subsurface dams to harvest rainwater – a case study of the Swarnamukhi River basin, Southern India. *Hydrogeology Journal* **14** (4), 526–531.

Rushton, K. 1997 Recharge from permanent water bodies. In: *Recharge of Phreatic Aquifers in (Semi-) Arid Areas* (I. Simmers, ed.), A.A. Balkema, Rotterdam, The Netherlands, pp. 215–255.

Şen, Z. 2006 *Manevi ve Bilimsel Açılardan Zemzem Water (Zamzam Water from Scientific and Spiritual Perspectives)*. Turkish Water Foundation, Press, Istanbul, Turkey.

Şen, Z. 2008 *Wadi Hydrology*. CRC Press, Boca Raton, FL, USA.

Şen, Z. 2014 *Practical and Applied Hydrogeology*. Elsevier, New York, NY, USA.

Şen, Z. 2016 Groundwater structures throughout Turkish history. In: *Underground Aqueducts Handbook* (A. N. Angelakis, E. Chiotis, S. Eslamian & H. Weingartner, eds.), CRC Press, Boca Raton, FL, USA, pp. 241–260.

Şen, Z. 2019 Groundwater recharge level estimation from rainfall record probability match methodology. *Earth Systems and Environment* **3**, 603–612.

Şen, Z. 2021 Reservoirs for water supply under climate change impact – a review. *Water Resources Management* **35** (11), 3827–3843.

Shalamzari, M. J., Zhang, W., Gholami, A. & Zhang, Z. 2019 Runoff harvesting site suitability analysis for wildlife in sub-desert regions. *Water* **11**, 1944.

Subyani, A. & Şen, Z. 1991 Study of recharge outcrop relation of the Wasia aquifer in central Saudi Arabia. *J KAU: Earth Science* **4**, 137–147.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., Gurdak, J. J., Allen, D. M., Shamsudduha, M., Hiscock, K., Yeh, P. J.-F., Holman, I. & Treidel, H. 2013 Groundwater and climate change. *Nature Climate Change* **3**, 322–329.

United Nations 2015 *Adoption of the Paris Agreement Resolution of the Conference of the Parties to the Framework Convention on Climate Change*. FCCC/CP/2015/L.9, United Nations, Paris, France.

Voudouris, K., 2012 Diachronic evolution of water supply in the Eastern Mediterranean. In: *Evolution of Water Supply through the Millennia* (A. N. Angelakis, L. W. Mays, D. Koutsoyiannis & N. Mamassis, eds.), IWA, London, UK, pp. 77–89.

Walton, W. C. 1970 *Groundwater Resource Evaluation*. McGraw-Hill, New York, NY, USA.

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