Development of strategic water reserve for the Holy City of Makkah, Saudi Arabia

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ABSTRACT

This contribution presents part of the work that had been done to develop the water resources in Wadi Naman east of Makkah City to form a strategic water reserve for the city of Makkah and the nearby holy shrines. The aim of the strategic water reserve is to be used as water supply in emergencies when the desalination plant or the pipelines from the desalination plant to the city have to be out of the service for a considerable amount of time due to planned or unplanned shutdowns. The development plan calls for a constructing of a subsurface dam across the Wadi at a prescribed location. The proposed subsurface dam will extend from 3 m below the natural ground surface to a depth of 2–3 metres inside solid bedrock. The suggested dam may be constructed using plain plastic concrete and utilizing the diaphragm wall technique for construction. The crest of the subsurface dam can serve as a buried spillway to convey access water downstream and the overflow freeboard will provide a room for utilities that passes through the wadi to serve cities and villages upstream. The alluvium thickness upstream of the proposed dam location is ranging from 20–70 m and the total volume of the alluvium behind the dam that can store water is $218 \times 10^6\,m^3$. Pumping test revealed that the transmissivity is $1{,}376\,m^2$/day and the yield storage coefficient is 0.15. The safe water yield that can be stored in the alluvium behind the dam due to natural recharge of $6.53 \times 10^6\,m^3$/year and interception of the groundwater flow by the dam can reach an amount of 32.7 million cubic metres of water in a period of about 5 years from the date of completion of the dam. This amount of water can serve the city and the nearby holy shrines for a period of up to four months with a good demand management program. However, to maintain the desired levels of water quality and quantity in the reservoir and to minimize the adverse effect of the dam on the downstream area a very strict management program of the basin has to be followed. This management program can be used to control the urban and rural development in the area upstream of the dam and enhancing artificial and natural recharge in the upstream and downstream sides of the dam.

Key words | diaphragm wall, groundwater dam, Makkah, strategic water reserve, subsurface dam, Wadi Naman

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INTRODUCTION

The Holy City of Makkah, the capital city of Muslim world, located in the eastern province of Saudi Arabia, has permanent residents of 1.4 million persons, but during pilgrimage (Hajj and Omrah) season the population of the city exceeds 3 millions. The main water supply for the city comes from Shoaiba desalination plant which is located on the Red Sea coast some 110 km west of Makkah. Most of the nearby Wadis (where wadi is an Arabic word used in Middle east and north Africa to refer to a valley, gully, or streambed that remains dry except during the rainy season),

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which used to be the main source of water for many centuries, are now almost dry due to drought and over pumping. The water supply from these Wadis to Makkah ranges from 20,000 m^3/d to 30,000 m^3/d and contributes about 10% of the city total water supply. The water supply from the desalination plant is 216,000 m^3/d during regular season and reaches a maximum of 248,000 m^3/d during high season (Makkah Development Commission 2004). Due to the shortage in water supply, the city water distribution system is operating intermittently, and residents rely frequently on water delivered by trucks from Wadis alluvium around the city. The city has two major man-made strategic reservoirs, Almoaisim reservoir which accommodates 1,000,000 m^3 and Joranah reservoir with a capacity of 600,000 m^3. In addition, another 48 operational water tanks scattered around the city with capacity ranging from 1,000 to 90,000 m^3 (Al-Ghamdi & Gutub 2000, 2002). The two strategic water tanks are usually gradually filled with water before the pilgrimage season and used mainly as strategic reserve to supply water to the pilgrims and the residents if the water supply from the water desalination is interrupted for any reason. With a good water management, this water reserve can supply water in case of emergency for a period of 5–10 days. After the season, the water stored in the strategic reserved tanks is used as a source of supply to meet the city demand. The desalination plants, like any other artificial source, are subject to planned and accidental shutdown for a short or a long period of time. The shutdown could be due to regular maintenance of the desalination units, mechanical failure of one or more production units, fire accidents, coastal pollution at intake locations, criminal acts on the plants or the pipelines and natural disasters. If such shutdown requires a considerable amount of time to rectify the problem, the city will face a sever water shortage. The situation may aggravate if the accident occurs just before the pilgrimage season and before filling the strategic reserve tanks. To avoid such vulnerable situation, the development of water resources in adjacent Wadis needs to be considered seriously to form a natural reserve of water capable of supplying the city with water in an emergency case. In this contribution, a plan for the development of water resources in Wadi Naman, which is located east of Makkah, as an strategic water reserve for the Holy City of Makkah and the Holy shrines is presented.

WADI NAMAN POTENTIALITY

Wadi Naman is one of the major Wadis that originate from the scarp of Alhada Mountains and flows westward to the Red Sea passing Southeast of Makkah, as shown in Figure 1. The alluvium in the valley is considered to be one of the best locations for a strategic water reserve for the Holy City of Makkah and the nearby holy shrines for a

Figure 1 | Location of Wadi Naman (After Space Image Atlas for the KSA (2007)).

number of reasons; 1) its proximity to the city of Makkah and the holy shrines (only less than 3 km from the holy shrine of Arafat and less than 10 km from Makkah), 2) the favorable geological formation of the Wadi with alluvium thickness ranging from 20–70 m bounded by mountains from both sides, 3) it has a relatively high recharge rate compared to other Wadis in the region, 4) the relatively high porosity of the alluvium, and 5) the water quality in the Wadi is very good and used to be, for many centuries, the main source of water for Makkah and holy shrines through Ein Zubaidah water gallery, which was established in the Seventeenth Century and abandoned in the seventies of last century.

As being the major source of water for Makkah residence and pilgrimage for centuries, Wadi Naman was subjected to several geological and hydro-geological studies over the years to enhance the water quality and quantity in the Wadi (Italconsult 1967; Jamaan 1978; Sogreah 1980; Al-saifi 1983). These studies needed to be updated using the latest technologies and utilizing new investigations and construction techniques. An ambitious study sponsored by the Custodian of the Two Holy Mosques, King Abdullah Bin Abdulaziz, the King of Saudi Arabia, to rehabilitate Ein Zubaidah gallery and to enhance water resources in Wadi Naman was carried by Water Research Center at King Abdulaziz University since1998. This study, was multi-stages and comprehensive in nature and consists of hydrological, hydro-geological, geophysical, hydraulic, water quality and environmental investigations. The outcome of the early stages of the study suggested the construction of a subsurface dam across the Wadi in the location shown in Figure 2 to serve as a barrier wall to intercept the groundwater flow and hence storing the water in the alluvium behind the dam for future use. The water will accumulate over the years in the alluvium behind the dam due to the natural recharge from the runoff water coming down from steep sloped Alhada Mountains. This accumulated water can serve as a strategic water reserve for the city of Makkah and the holy shrines. A well-field can then be constructed in the alluvium upstream of the dam and connected through appropriate pipelines to Makkah water distribution system to make the water supply ready for utilization in case of emergencies only. The option of the subsurface dam was selected for several reasons:

1. The subsurface dam does not submerge land area as it stores water under ground. Therefore, it does not seriously damage the environment, nor does it cause socioeconomically problems such as the forced migration of the local people or relocation of roads.
2. Reserved water is not lost by evaporation because water is stored under ground and there is very little evaporation, in contrast with a surface dam that often loses a significant amount of reserved water due to evaporation in this arid region where evaporation may exceed 10 mm/day.

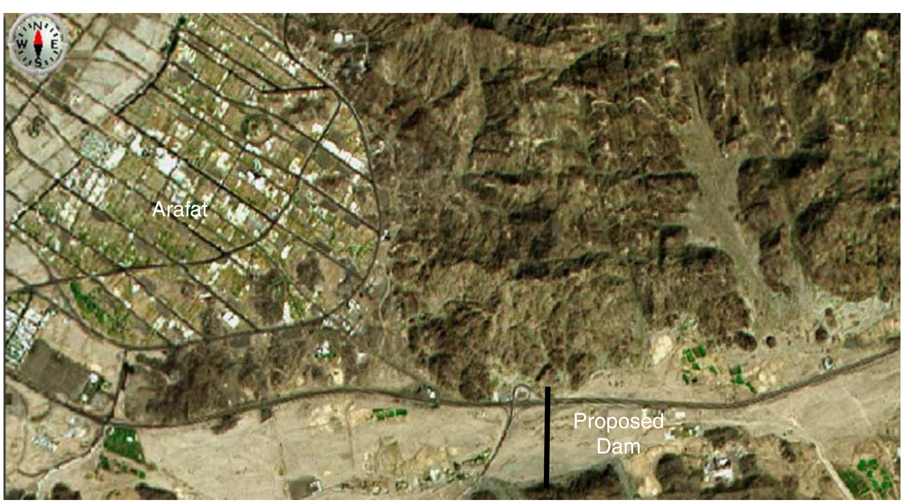

Figure 2 | Location of the proposed subsurface dam in Wadi Naman (After Space Image Atlas for the KSA (2007)).

3. Reserved water using subsurface dam is of fairly good quality because it is stored underground, and is less subjected to pollution.
4. Storing water underground will eliminate the epidemic water diseases spread by mosquitoes and other insects.
5. The subsurface dam is stable from the viewpoint of dynamics because it is buried under ground, and thus does not need maintenance.
6. If the dam breaks, for any reason, there is no damage or lost of live in the downstream area because the breakage occurs under ground.

However the shortcoming of the subsurface dams must be taken into considerations, when designing the subsurface dam, such limitations include the following;

1. Difficulties in site selection, where surveys for site selection and estimating the water storage capacity of subsurface dam rely on estimates of underground geological structures.
2. Low effectiveness of water storage as the water is stored in the pores of geological strata. Therefore, the volume of reserved water is determined by the volume of those pores (effective porosity), and reaches only 10 to 30% of the volume of the reservoir layer.
3. Interception of downstream groundwater flow may prevent downstream groundwater flow, and have a negative impact on the downstream area. Alternative solution for downstream has to be provided.
4. Detailed geophysical and geotechnical investigations is required to locate the fractures and faults that may exist in the rock base of the aquifer and propose the necessary grouting to minimize the water seepage out of the aquifer.

Site visits along with geophysical, hydrological investigations and review of previous geological studies of the area provided the preliminary bases for selecting the location of the dam. Once the preliminary dam location was selected a detailed field surveying, soil investigations and pumping tests were conducted in the area to collect more information needed for structural design of the dam and determination of the aquifer parameters. The minimum width of the Wadi at the proposed dam site reaches 912.87 m, which is almost the narrowest section of the Wadi. The dam alignment was selected to avoid, as far as possible, the geological faults in the Wadi as determined by the geologists and to minimize the construction cost by avoiding the intersection with highway bridges in the area and minimizing the dam cross-sectional area.

Aquifer characteristics

To estimate the amount of water that can be stored in the strata behind the dam and the amount of the water that can be extracted, the previous geological studies of the Wadi (Italconsult 1967; Jamaan 1978; Al-saifi 1983) along with the findings of geophysical investigations conducted by the geophysics team were utilized. Based on Jamaan (1978) geophysical investigations of the bedrock and the field survey of the ground surface, the contour lines and the 3-D for the bedrock upstream of the proposed dam location were constructed, as shown in Figure 3. Figure 3 is used to estimate the storage capacity of the proposed dam. The bed rock elevations ranges from 280 m–380 m above mean sea level (AMSL), with a bed slope of 1.5×10^{-2}. The alluvium thickness is ranging from 20–70 m and the total volume of the alluvium bounded by the bedrock and the horizontal surface extending from the crest of the proposed dam in the upstream direction is estimated to be $218 \times 10^6\,m^3$.

To determine the vital aquifer parameters, a 65 m deep test well and two observation wells with depths of 25 m and 53 m were dug in the upstream of the dam for performing pumping test. By using the Jacob method of analysis, the aquifer's transmissivity, T, was found to be 1,376 m^2/day and the storage coefficient, S, of 0.15. Thus the gross capacity of the reservoir (i.e. the amount of groundwater in the reservoir area at the full reservoir level that can be stored and extracted) is about 32.7 million cubic metres. This amount of water is sufficient to provide the water supply for the Holy City of Makkah in regular season for a period of four months if the average consumption is regulated to 200 litre/capita/day.

Although Wadi Naman itself lies in an arid region with mean annual precipitation near the proposed dam site of 130 mm, but its catchment area extends to the top of Alhada Mountains where the mean annual rainfall on those mountains reaches 260 mm. The runoff from Alhada Mountains provides the major source of water for the Wadi. Table 1 provides the recharge rate in the Wadi

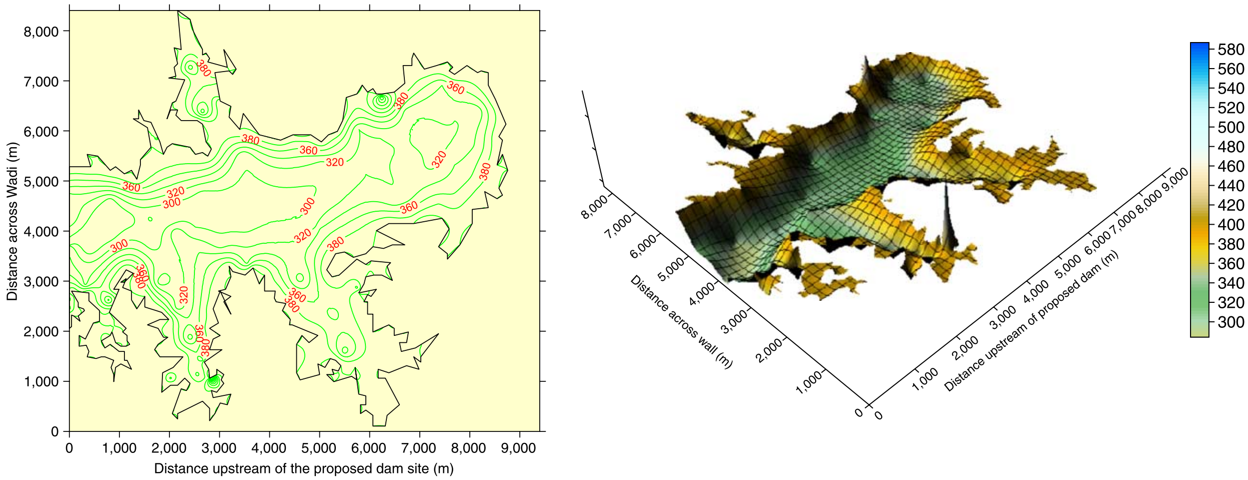

Figure 3 | Bed rock Contour lines and 3-D bedrock surface Upstream of Dam site.

upstream of the dam as determined by previous studies based on Wadi characteristics and hydrological data. This table indicates that the annual recharge rate of 6.53 million cubic metres per year is possible, which means that the alluvium upstream of the dam will be fully saturated in a period of about 5 years given that the subsurface dam is constructed in the proposed location and all the water wells in the Wadi are controlled such that no pumping is allowed during recharge period. The recharge rate may be increased if levees are constructed across the Wadi at different locations utilizing the materials borrowed from the Wadi so that artificial ponds are created.

Site investigations

Three boreholes were drilled along the proposed axis of the dam and the following field and laboratory analysis of the soil were conducted: Visual Examination, Standard Penetration test (SPT), Rock Quality Designation (RQD), Total Core Recovery (TCR), Grain Size Distribution, Moisture Content, Unconfined Compression Strength, Bulk Density and Soil Chemical Analysis.

The boreholes logs indicate that the soil type is in general a poorly graded coarse to medium grained Sandy Soil ranging from loose near the surface to very dense as we go deeper. Some intermediate layers have the sand mixed with gravel and there are occasional intermediate layers of boulders with cobbles of thickness 4–5 m. The bed rock consists of slightly to very highly fractured strong granodiorite rock. Chemical analysis of the soil samples revealed that the Total Dissolved Solids (TDS) range from 375–433 ppm, Chlorides (as Cl^-) range from 160–240 ppm, Sulphates range from 80–130 ppm as shown in Table 2. This chemical analysis indicates that the salinity of water stored in the alluvium will note be negatively affected by the soil and the soil will not be aggressive on the concrete of the proposed cut-off wall. Table 3 summarizes the bed rock properties as extracted from the field boreholes and laboratory soil investigations, while Table 4 presents the calculated soil properties needed from the structural analysis.

These soil properties can be used at later stage for the structural analysis and design of the dam. It should be pointed out that the structural design of the dam and its stability against sliding, overturning and failure require a rigorous analysis and will not be addressed in this contribution. This may be a subject of a future publication.

Table 1 | Annual recharge rate in the reach upstream of the dam site

Previous studies	Recharge (10^6 m^3/year)
Italconsult (1969)	6.00
Sogreah (1980)	7.30
Jilani (1985)	6.30
Average	6.53

Table 2 | Chemical analysis of soil samples

Species	pH	T.D.S. (ppm)	Chlorides as Cl^- (ppm)	Sulphates as SO_4^{2-} (ppm)	Moisture content (%)
Range	8.86–9.20	375–433	160–240	80–130	0.2–25.8

PROPOSED CONSTRUCTION METHOD

Subsurface dams, or groundwater dams, have been constructed in many parts of the world, notably in India, Africa, Brazil and Japan, to intercept or obstruct the natural flow of groundwater and provide storage for water underground. There are many methods for constructing the subsurface dams. For deep dams, such as the dam suggested in this study, the dams me be constructed using plastic concrete and utilizing secant piles or diaphragm wall techniques. The secant piles method has economical advantage over the diaphragm wall, as the latest needs special equipments and highly skilled manpower. However, the secant piles will have more joint and the leakage would be expected to be high, besides the verticality of the piles is hard to maintain. Therefore, it is recommended to use the diaphragm wall technique for constructing the proposed subsurface dam in Wadi Naman.

Mahboubi & Ajorloo (2005) conducted an extensive experimental parametric study of the mechanical responses of various types of plastic concrete in unconfined and triaxial compression tests. They observed that the behavior was more and more ductile when increasing confining pressure. It was shown, that any increase in confining pressure increases the compressive strength as well as the elastic modulus and the deformability of the specimen. It was concluded that an increase in cement factor increases the shear strength as well as the elastic modulus. It was noticed that the increase of bentonite content, decreases the compressive strength as well as the elastic modulus. Increasing the age of the specimens causes an increase of the compressive strength as well as the elastic modulus and also the shear strength parameters are affected. Also, it was found that the increase in confining pressure and cement factor reduces the permeability.

The property of the plastic concrete to be used in the dam and the required dam thickness will be determined at later stage by structural analysis of the cut-off wall using advanced 3-D finite element method. It is recommended that the cut-off wall extends at least 2–3 m into the solid bed rock to key the dam against sliding. Also it is recommended that the crest of the dam should be at least three metres below the natural ground surface to form an overflow freeboard. The overflow freeboard will allow access water to flow downstream through the soil layer to minimize evaporation and will provide a room for the utilities that passes through the Wadi including the desalination pipelines and telecommunication cables passing to Taif city through Alhada Mountain.

WADI MANAGEMENT

The proposed dam as discussed in previous sections is expected to provide a useful strategic water reserve that will be ready for emergencies use in a period of about 5 years from the date of completion of the dam. This strategic reserve can be used to supply water the Holy city of Makkah and the nearby holy shrines only if the water supply from the desalination plants is interrupted for any unavoidable reasons.

Table 3 | Properties of the bedrock at the site

Borehole no.	Bed rock depth (m)	RQD (%)	TCR (%)	Unit weight (g/cm^2)	Unconfined compressive strength (kg/cm^2)
A	19.5	90	91–94	2.762–2.804	591.6–656.9
B	$>61.5^*$	–	–		
C	55.0	0	35		

*Drilling terminated before reaching bedrock.

Table 4 | Calculated soil properties

Soil type	Friction angle Φ (deg.)	Relative density D_r %	Voids ratio, e	Specific weight, Gs	Dry weight, w_{dry} (kN/m³)*	Saturated weight, w_{sat} (kN/m³)†	Effective weight, w_{eff} (kN/m³)‡	Poisson ratio (υ)
Very dense sandy soil	30	24.9	0.55	2.65	16.73	20.23	10.23	0.3

*$w_{dry} = Gs\, w_w/(1+e)$.
†$w_{sat} = (Gs + e)\, w_w/(1+e)$.
‡$w_{eff} = w_{sat} - 1 \times w_w$.

However, in order for this strategic water reserve to be useful, a good management plan for the water resource in the basin is inevitable and a number of measures should to be taken by the authorities to maintain the water quality and quantity in the Wadi at the desired levels. In the past the Wadi used to supply the city of Makkah not only with water but with vegetables. But due to the migration of villagers to the nearby urban centers in Makkah and Jeddah searching for jobs and a better life style, the cultivated land in the basin dropped from 53% of the arable land of 31 km^2 in 1970 to only 12% in 2006 (Alboloshi 2008). Currently there are five small villages in the upstream of the basin located at a distance ranging from 15 km To 30 km from the site of the proposed dam in addition to a score of scattered small farms. The exact population of theses settlements is not known, but the statistics of students enrolled in the schools serving these communities show that the total number of enrolled students in elementary, intermediate and secondary schools is 1,193 student (Alboloshi 2008). By using the demographic information for Makkah region which indicate that 28.8% of the population is in the school age (5–19 years) (Ministry of Economy and Planning 2007), the population of these five communities can be estimated to be about 4,142 persons. The annual water demand for these communities is very small compare to the recharge rate. However, due to the seasonal shortage of water in Makkah and Jeddah cities, farmers tend to sell the water and transport it by water trucks to these cities. A successful water management plan for the basin should ensure the success of the project and in the mean time may not pose a negative impact on the existing settlements and private farms in the Wadi. Some of the measures that may be taken include the following.

1. The water in the underground reservoir immediately behind the dam has to be preserved for authorized use only. Settlements in the upstream of the Wadi may use the groundwater for their daily needs but may not be allowed to sell the water. All the privately dug wells currently existing in the Wadi to sell fresh water by water trucks should be abandoned and no new wells should be allowed except the well field to be constructed by water authority.
2. To avoid the contamination of groundwater, the small villages located in the upstream of the Wadi should be provided with a suitable sanitations system to replace the existing septic tank systems used by the residents.
3. With the exception of the existing settlements, the land upstream of the dam should be considered as a government property (or endowment for the project). No new urban development should be allowed in this area to avoid extensive use of water and preserve the water quality.
4. Cultivation of the land in the upstream part of the Wadi should not be allowed, as the use of fertilizers and pesticides will have a negative impact on the groundwater quality. The owners of the existing farms may be compensated for their land or provided with a proper agricultural development plan that will promote efficient irrigation system and minimum groundwater contamination.
5. All the gas stations along the highway in the upstream side of the Wadi should be relocated or properly monitored to prevent any leakage of the petroleum materials to the groundwater.
6. Enhancement of the natural recharge in the upstream of the dam site will reduce the time needed to fill the reservoir. This can be achieved by constructing a number of levees across the Wadi to reduce runoff and increase ponding time of rainfall and runoff water.
7. To minimize the impact on the downstream resulted from the interception of groundwater flow, the effluent

of Ornah Treatment plant which is completed in 2008 and located just few kilometres down stream of the proposed dam with a capacity of 250,000 m^3/d of a tertiary treatment, can be used to recharge the groundwater in the downstream of the dam.

CONCLUSION

This contribution presents the work that had been done to develop the water resources in Wadi Naman east of Makkah City to form a strategic water reserve for the city of Makkah and the holy shrines. This water reserve is meant to be used as water supply in emergencies when the desalination plant is accidentally down. The development plan calls for a constructing a subsurface dam across the Wadi using the diaphragm wall technique. The subsurface dam will extend from 3 m below the natural ground surface to a depth of 2–3 metres inside solid bedrock. The suggested dam can be constructed using plain plastic concrete and utilizing the diaphragm wall technique for construction. The crest of the subsurface dam can serve as a buried spillway to convey access water downstream and the overflow freeboard will provide a room for utilities that passes through the wadi to serve cities and villages upstream.

The alluvium thickness upstream of the proposed dam location is ranging from 20–70 m and the total volume of the alluvium behind the dam that can store water is $218 \times 10^6\,m^3$. Pumping test revealed that the transmissivity is 1,376 m^2/day and the yield Storage Coefficient is 0.15. The safe water yield that can be stored in the alluvium behind the dam due to natural recharge of $6.53 \times 10^6\,m^3$/year and interception of the gross capacity of the dam can reach an amount of 32.7 million cubic metres of water in a period of about 5 years from the date of completion of the dam. This amount of water can serve the city and the nearby holy shrines for a period of up to four months with a good demand management program. However, to maintain the desired levels of water quality and quantity in the reservoir, and to minimize the adverse effect of the dam on the downstream area a very strict management program of the basin has to be followed. Several measures have to be taken to control the urban and rural development in the area upstream of the dam and enhancing artificial recharge in the downstream as pointed out the paper.

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