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Applicability of Groundwater Dams in Semi-Arid Regions: A Study in the North-Central Turkey

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Abstract: Groundwater dams are a method to store and save groundwater, particularly in sand-gravel aquifers for generally small scale water supplies in arid and semi-arid regions of the world. The operation involves the construction of an impervious cut-off wall to hinder the groundwater flow downstream and the storage of more water in the aquifer upstream of the dam. Stored water can be abstracted by pumping from wells or gravitational flow if possible, depending on the topographic, geologic, technical, and economic conditions.
In this study, the applicability of groundwater dams in the alluvial sand-gravel aquifers in semiarid north-central Turkey is studied from hydrological, hydrogeological, environmental and technical aspects. The study area has a semi-arid climate and water resources are insufficient. The groundwater resources need to be developed and artificially recharged. In this context, the application of groundwater dams may be a solution, particularly for small scale water supplies. The nature of the region is suitable for groundwater dam construction in many ways including the suitability of size and morphology of the valleys, existence of sand-gravel aquifers, sediment transport due to storm flow, quality degradation through downstream in many secondary basins, and deficiency of surface waters and fluctuation of groundwater level in wet and dry periods. Some project types were suggested for various cases in the study area and in any other regions of the world if desired.

Keywords: Groundwater dam, sand-gravel aquifer, water supply, north-central Turkey

I. INTRODUCTION

Groundwater dams, which are a method to store and save groundwater, are used in most regions of the world, particularly Brazil, Africa, and the Middle East (Nilsson 1988; Apaydin et al. 2005; Hut et al. 2007). In these countries, groundwater dams were generally constructed in sand-gravel aquifers in narrow valleys; however, some dams were constructed in limestone by a grout curtain or slurry wall, as in the Japanese islands (Nagata et al. 1993). The method consists of retardation and storage of the groundwater in the aquifer by forming an impervious barrier on the impervious underlying layer. There are basically two types of groundwater dams, namely subsurface dams and sand-storage dams. A subsurface dam is constructed below ground level to arrest the flow of a natural aquifer, whereas a sand storage dam impounds water in sediment pores leading to accumulate by the dam itself (Hanson and Nilsson 1986). The main advantage of storing water in groundwater dams is that evaporation losses are lower than those in surface reservoirs. The problem of land submergence, which is normally associated surface dams, is not present with groundwater dams (Archwichai et al., 2005) and there is no danger of breaching due to natural or manmade disasters (Ishida et al. 2011). Actually, the main purpose of groundwater dams is to prevent the downstream flow and storage of groundwater in a subsurface reservoir by increasing the saturated thickness behind a wall, hence the method is considered to be an artificial groundwater recharge method. Stored groundwater can be abstracted by pumping or gravity flow depending on the topographical, geological, technical, and economic conditions. Water storage by groundwater dams (Nilsson 1988) or underground dams (Matsuo 1977) have been used for a long time in the world, however, such infrastructure is new in Turkey. Despite the fact that groundwater dams are being put in place in most countries or regions, such as India, Brazil, China, and Africa, these technologies were first developed in the Japan islands (Nagata et al. 1993, 1994). Generally, groundwater dam developments can be successful if a suitable location is selected and the appropriate technique is used, even though some projects have failed in the past (Nilsson, 1988).

Groundwater dams have a smaller storage capacity compared to surface dams; however, they also have some advantages. The most important advantage is that the groundwater reservoirs occupy a small area of land, contrary to surface dams. Moreover, the construction of surface dams is difficult because of topographic, geologic, economic, environmental, and social considerations. Generally, groundwater dams are constructed and maintained in areas where the construction of surface dams is not favorable.

Using concrete cut-off walls is a common practice in many parts of the world, notably in India, Africa, Brazil, Japan, and southwest Saudi Arabia (Fakharinia et al. 2012). Technology has been used in different applications including the consumptions of industry (Milanovic, 2004) and agriculture (Da Silva, 1988) and controlling sedimentation (Haveren 1987).

Turkey is not experienced in the construction and development of groundwater dams compared to Brazil, Japan and some Asian countries. Although some groundwater dams were constructed in recent years, this issue is in the early stages and not widely applied, and few studies have been performed thus far (Yilmaz 2003; Onder and Yilmaz 2005; Apaydin et al. 2005; Apaydin 2009; Apaydin et al. 2010) on this issue. A typical example is the Yahsihan groundwater dam constructed in 2000 in central Turkey. This dam was constructed in Kirikkale province in collaboration with the State Hydraulic Works (DSI) and the General Directorate of Rural Affairs. Another underground structure is the Malibogazi groundwater dam located in a valley 10 km from the town of Kalecik and 100 km from Ankara. Malibogazi groundwater dam is an earth dam, which is used for irrigation (Apaydin 2009). One of the newest groundwater dams is the Iskilip groundwater dam (constructed in 2010), which serves as a drinking water supply to the town of Iskilip.

There are some challenges to the water supply in the north-central region of Turkey (Fig. 1). The region belongs to a semi-arid climate and the surface water resources are insufficient. The groundwater resources suffer from the effects of draughts and over exploitations. Quality degradation is another problem, particularly in the downstream basins. The groundwater resources need to be developed and artificially recharged. In this context, the application of groundwater dams may be a practical solution for small scale water supplies. The aim of this study is to investigate the applicability of groundwater dam projects in the region in terms of environmental, hydrogeological, topographic, social, and technical conditions. This study may be a model for which the results can be exploited in other locations where similar geo-environmental conditions prevail.

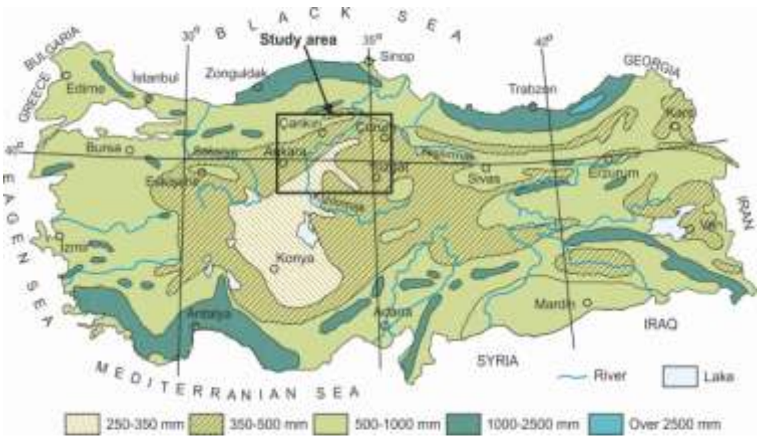

Fig. 1: Location of the study area on precipitation map of Turkey (variation from www.meteo.gov.tr)

II. SITE SELECTION AND PHASES OF GROUNDWATER DAM CONSTRUCTION

Apaydin (2009) has proposed a flow chart for groundwater dam construction with particular consideration of central Turkey. The preliminary site investigation results and content for site selection for the different operation phases are presented in aforesaid chart. As shown in Fig. 2, groundwater dams are similar to surface dams in terms of investigation phases, but detailed hydrogeological investigations are carried out for groundwater dams.

Some natural conditions must be present to be conducive for site selection of groundwater dams in sand-gravel formations within valleys. These conditions are: (1) an aquifer that has sufficient aerial extent and thickness, (2) sufficient recharge, (3) high storage coefficient and hydraulic conductivity, (4) impermeable-low permeable geological formation that underlie the aquifer, (5) a narrow section of the valley and the aquifer (preferred), (6) high quality groundwater, and (7) high quality and cheap construction material for the dam wall.

In addition to the above conditions for site selection, the method of water intake (gravity or pumping), location of the intake facility, and the number and locations of the wells must be assessed. Moreover, the cost of construction is also important. This is mainly controlled by: (1) exploration and drilling, (2) construction material, (3) transportation, (4) excavations, (5) water intake facility or production wells, (6) pumps, and (7) power plants. Each component mentioned above requires expertise and proper planning.

III. GENERAL CHARACTEISTICS OF THE STUDY AREA

The study area, the north-central region of Turkey is situated in semi-arid climate (see Fig. 1). The average annual rainfall ranges between 300 and 500 mm. The mean annual temperature of the region ranges from 8 to 12°C with summer temperatures up to 20°C. The average annual potential evaporation varies between 1000 and 2000 mm. The region has low-lying broad plains and large valleys along the Kizilirmak and Yesilirmak rivers, and medium to small scale basins formed by relatively narrow secondary and tertiary valleys. The region varies in elevation from 600 to 2000 meters from west to east.

In general, the region is underlain by metamorphic, crystalline, or volcanic rocks in **the** upstream segment. These formations bear fresh groundwater and surface water. Oligo-Miocene age evaporitic formations outcrop in the lower parts overlying these formations. The water coming from the adjacent evaporitic formations impairs the quality of groundwater in the alluvial aquifers. The groundwater quality is impaired in the alluvial aquifers located in the lower parts of the basins, where underlying rocks are evaporites. Generally, there is gradual quality degradation in the alluvial aquifers from upstream to downstream in most basins (Fig. 3). For example, the hardness of groundwater in the alluvial aquifers in the upstream segments of Derincay (Corum) and Tatlicay (Cankiri) basins ranges from 18 to 35 (F°H), while it exceeds 100 (F°H) in the downstream segments (Apaydin 1996; Apaydin and Demirci Aktaş 2012). In addition, the anthropogenic pollution increases downstream due to the agricultural and industrial activities.

Most settlements in the lower parts of the smaller basins lack fresh water and they are compelled to obtain water from the upstream parts of the region. However, due to limited extent of the aquifers and recharge area, the potential of groundwater decreases upstream. Moreover, the aquifers are vulnerable to draughts, resulting in a decline in groundwater levels in the dry season.

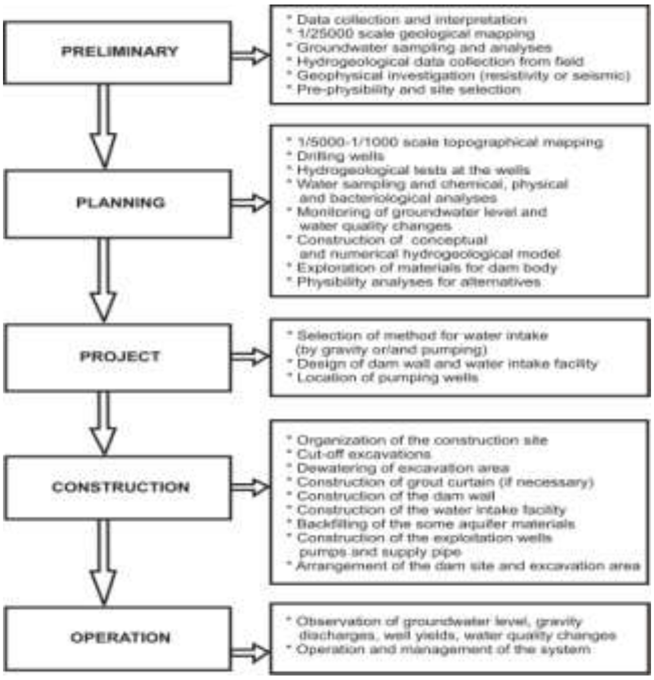

Fig. 2: Suggested flow chart for groundwater dam peculiar to central Turkey (revised from Apaydin, 2009)

IV. SITE SUITIBILITY ASSESSMENT OF THE STUDY REGION FOR GROUNDWATER DAM CONSTRUCTION

A. Morpho-geological Conditions

On average, the semi-arid Central Anatolia region consists of low–lying plains and large valleys along the Kizilirmak, Yesilirmak, and Sakarya rivers. The construction of a groundwater dam is not favorable for practical and economic reasons in the large valleys because the thicknesses of the alluvial aquifers **c**annot sustain a reasonable quantity of water **(it generally exceeds 30 m).** Sand-gravel materials have been deposited along the riverbeds in the small basins (catchment area varies between 40 and 300 km^2). Occurrence of a narrow valley (for example 20-100 m) downstream and relatively large alluvial deposits constitute the most favorable site in terms of simplicity and low cost of the construction of a groundwater dam.

B. Hydrogeological Features

The most suitable site for a groundwater dam is in the narrow section of a valley with sufficient aquifer reservoir characteristics on the upstream side. The aquifer should have adequate thickness from the viewpoint of excavation costs. In most cases, a wide site where the impermeable bedrock is shallow enough (but aquifer thickness should be large enough to store a reasonable quantity of water) is usually more preferable than a narrow site with deep bedrock, considering the difficulty of excavation. Sand-gravel aquifers in the small valleys are generally suitable for groundwater dams in terms of boundary conditions, high storage coefficients, and hydraulic conductivity in north-central Turkey. Generally, the width of the aquifer varies between 50 and 500 m and the thickness ranges between 10 and 40 m in most of the valleys. In general, cut-off excavation is rather difficult and expensive if the aquifer thickness exceeds 20-25 m. However, the slurry wall technique removes this problem, because the necessity of excavation to the bottom of the aquifer is not under consideration in this technique. Consequently, hydrogeological conditions are generally suitable for a groundwater dam in terms of the cost and technical aspects in the region.

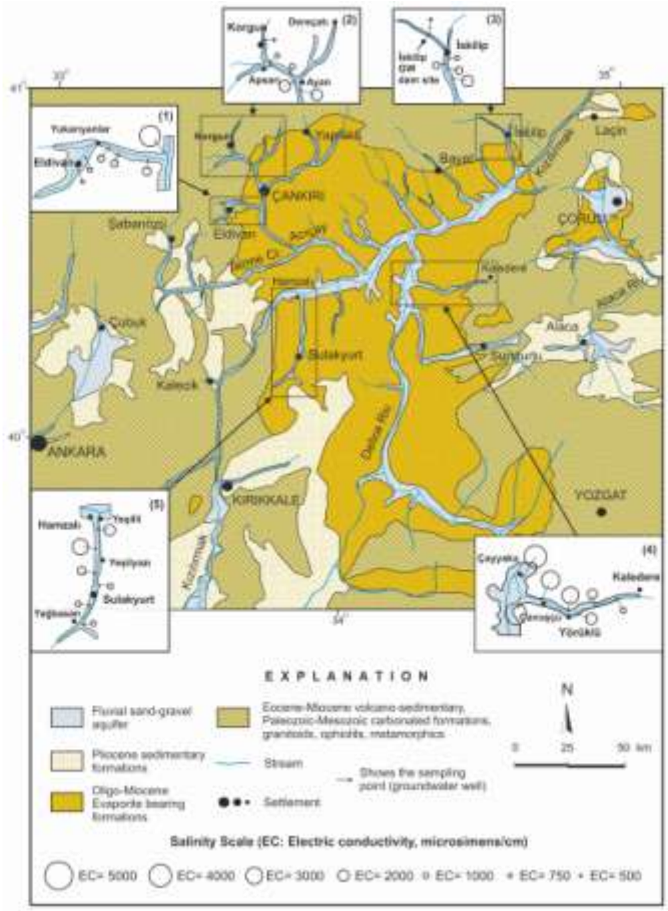

Fig. 3: Variation of groundwater quality from upstream to downstream in some small basins of the Central Anatolia region (Geological map have been revised from www.mta gov. tr)

C. Hydrochemical Conditions

Groundwater quality is generally high in the upper parts of the basins in the central region of Turkey. However, evaporitic formations and poor drainage cause serious quality problems in the downstream basins. Electric conductivity of groundwater generally exceeds 1500-2000 μS/cm and Na, Cl, and SO_4 are the dominant ions (Celik and Yıldırım, 2006; Apaydin and Demirci Aktaş, 2012). Consequently, sand-gravel aquifers with high quality groundwaters in the upper segments of these basins seem to be suitable for the construction of groundwater dams.

D. Erosion and Sediment Transport

A steep slope, semi-arid climate, sparse vegetation, and soil texture results in the erosion of large amount of soil material by streams in the study area. In particular, streams coming from the steep and bare slopes of the mountains lead to sediment transport along the streambeds. Roughness on the streambeds is increased due to sediment accumulation, particularly in Cankiri, Kirikkale, and Corum provinces. Sand storage dams can be constructed in this type of basin both for flood control and water supply, if the other conditions are satisfied.

E. Location of Settlements and Agricultural Fields

The alluvial fields along the valleys are the most productive agricultural land in the study area. In general, the lands become widespread and water demand normally increases downstream. Additionally, small settlements are located in the downstream segments of the alluvial valleys. Therefore, groundwater dam projects can be implemented for drinking and/or irrigation water in the upstream side of the settlements and agricultural lands.

F. Deficiency of Surface Waters

Rainfall is low (300-500 mm) due to semi-arid climate conditions and shows unsteady trends in the region. Effective precipitation generally occurs in winter and spring. In summer, water demand significantly increases, and most of the streams dry up or flow rates decrease significantly. This situation forces individuals to use groundwater. Consequently, the construction of groundwater dams in addition to surface dams is an inevitable method for a sustainable water supply.

G. Instability of Groundwater Levels

In some regions of Turkey, similar to most regions of the world, groundwater levels decline because of overexploitation or draught. On the other hand, groundwater levels fluctuate unsteadily due to the changes in precipitation in semi-arid regions, even if any exploitation does not occur. The fluctuations occur excessively in unconfined shallow aquifers, which are recharged from short-term or seasonal rainfall. In such aquifers, rainfall generally percolates through the aquifer and raises the groundwater level in a short period. On the contrary, the groundwater level declines considerably in a short drought. The sustainability problem that is caused by the fluctuation of groundwater levels and well yields (Fig. 4) endangers the sustainable water management in the region (Apaydin 2010). A groundwater dam is a solution in order to remove these kinds of problems.

H. Developments in Exploration and Construction Technology

Groundwater dam construction requires its own scientific and technologic perspectives compared to conventional methods. New technologies such as slurry walls, bored piles, or grout curtains have come into the sector. In particular, the slurry wall method can be easily applied to large sand-gravel aquifers. As a result, groundwater dam construction in various natural conditions is easier compared to the past in Turkey.

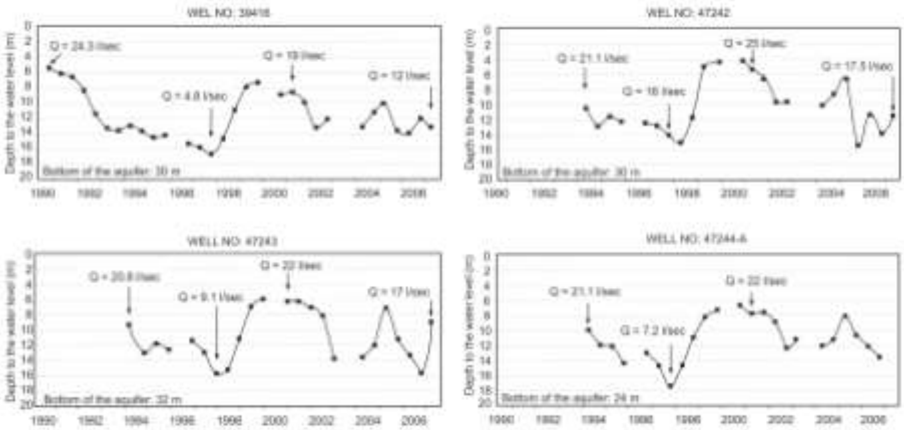

Fig. 4: An example of change in well yields according to the groundwater level fluctuations from semi-arid north-central Turkey, Halacli, Cankiri (Apaydin, 2010)

V. EXISTING GROUNDWATER DAMS AND POTANTIAL SITES SUITABLE FOR CONSTRUCTION IN THE STUDY AREA

A. Characteristics of the Existing Groundwater Dams

The former General Directorate of Rural Affairs constructed some small scale groundwater dams in Turkey between 1960 and 2003. The dams were used for small scale irrigation and domestic water supply (Apaydin et al. 2005), but there are no reliable data about them. In the early 2000s, construction of larger and more functional groundwater dams has entered Turkey’s agenda. Reliable data for new groundwater dams are actually available (Fig. 5; Table 1).

The Yahsihan groundwater dam is the one of the first experience in the 2000s in central Turkey constructed with the collaboration of State Hydraulic Works (DSI) and former General Directorate of Rural Affairs. The dam was constructed in 2003 and supplies domestic water to Yahsihan town. The Malibogazi groundwater dam is located in a valley 100 km from Ankara and was constructed in 2004 to obtain irrigation water by gravity (Apaydin, 2009). The Bahsili groundwater dam was constructed by the Bahsili municipality under the supervision of the Kirikkale governorship in 2009. The dam obtains domestic water for the town of Bahsili. On the other hand, another groundwater dam was constructed in 2005 in the village of Asagi Olunlu in Kirikkale province to obtain fresh domestic water for the four villages in the vicinity. The town of Iskilip is located in the northern part of the study area and has insufficient drinking water. A groundwater dam was suggested to be built in the Meydan creek alluvium in order to increase the amount of domestic water and the planning phase was completed at the beginning of 2010. The dam was constructed during the summer period of 2010.

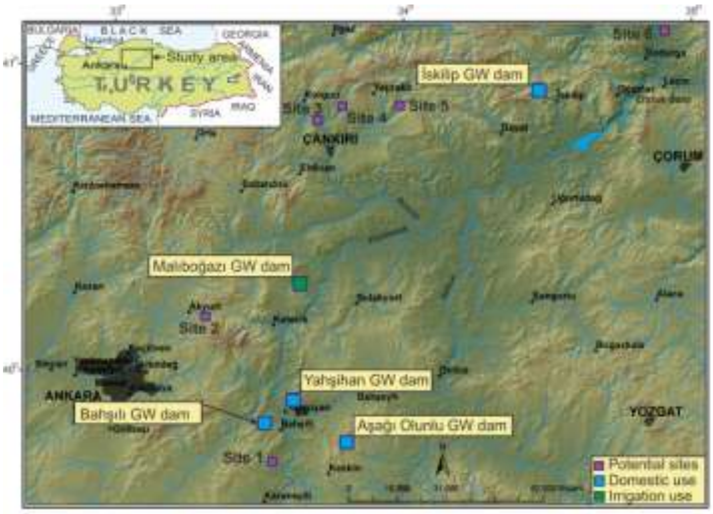

Fig. 5: Location of the existing groundwater dams and some potential sites suitable for construction

Table 1. Characteristics of some existing groundwater dams in the north-central Turkey (Apaydin et al. 2005; Apaydin, 2009; Apaydin et al. 2010)

Characteristics	Yahsihan	Malibogazi	As. Olunlu	Bahsili	Iskilip
Construction year	2003	2004	2006	2009	2010
Purpose	Domestic	Irrigation	Domestic	Domestic	Domestic
Dam type	Concrete and soil	Earth	Concrete	Earth	Earth
Length of the crest, m	20	50	69	50	50
Maximum excavation depth, m	34	26	15	15	14
Height of dam wall, m	14 (2 m concrete, 12 m soil)	20.60	13	13	13
Drainage area, km^2	-	80	10	-	48
Location of water intake facility	12 m above the bottom	12 m above the bottom	2 m above the bottom	10 m above the bottom	1 m above the bottom
Bedrock	Granite	Clay	Mudstone	Granite	Ultramafics
Aquifer	Sand-gravel	Sand-gravel	Sand-gravel	Sand-gravel	Sand-gravel
Max. aquifer thickness, m	32	34	15	20	15
Reservoir length, m	-	500	-	500	-
Reservoir width, m	20-50	60-70	20-60	30-60	15-60
Storage capacity	0.15 (estimated)	0.20	-	?	0.20
Water supply method	Gravity	Gravity	Gravity	Gravity	Gravity
Yield, l/sec	10-50	20-30	-	10 (average)	20-50

B. Examples for potential sites suitable for construction of groundwater dams

There are alluvial sand-gravel aquifers in some basins with watershed areas of 10-300 km^2 in the north-central Turkey. Groundwater dams can be constructed in these types of basins for the purpose of flood control and water supply. The width of the aquifer varies between 20 and 100 m and the thickness ranges between 10 and 45 m in most of the valleys in north-central Turkey (Apaydin 2009, 2010, 2012; Apaydin and Demirci Aktaş, 2012); however 50-100 m wide cross-sections and 10-20 m thickness is suitable considering the amount of water, cost, and difficulty in excavation. Actually, a groundwater dam is very site specific, much like other hydraulic constructions. In other words, site selection, dam type, and dimensions depend on intricate criteria, although these criteria can be generalized.

Data on some potential sites in the studied basins in the north-central Turkey are given in Table 2, Fig.6 (See also Fig. 5 for locations). As is seen, aquifer thicknesses vary between 8 and 30 m. The width of the aquifers varies between 15 and 400 m upstream of the dam sites. These dam sites were studied as a preliminary phase. Aquifer thicknesses and widths were determined by geological and geophysical studies. With the detailed studies, some data may be considerably changed and dam sites can be moved upstream or downstream. A lot of sites can be found by detailed explorations in the region.

Table 2. Data on some potential sites suitable for construction of groundwater dams in the north-central Turkey

Descriptive Data	Site 1	Site2	Site 3	Site 4	Site 5	Site 6
Province	Kirikkale	Ankara	Cankiri	Cankiri	Cankiri	Corum
Village/Town	Hacilar	Akyurt	Ic Yenice	Pasakoy	Kivcak	Gokdere
Stream	Derebogazi	Akyurt	Korgunozu	Handiri	Acicay	Gokdere
Basin area (km^2)	11.5	46	410	62	171	40
Main geological formation in the basin	Conglomerat, sandstone, mudstone	Tectonic complex (Schist, limestone, volcanic)	Ophiolite and volcanics	Ophiolite and sandstone-conglomerate	Ophiolite and sandstone-conglomerate	Schist, meta-greywacke
Aquifer	Sand-gravel	Sand-gravel	Sand-gravel	Sand-gravel	Sand-gravel	Sand-gravel
Aquifer thickness (m)	8-10	15-20	20-32	15-20	15-20	11-23
Width of the aquifer in the basin (m)	15-50	80-100	150-400	70-100	50-400	30
Length of the aquifer in the basin (km)	3.2	2.5	25	3	11	9.5
Crest length (m)	20	80	150	70	300	30
Bedrock	Conglomerate, sandstone, mudstone	Schist	Ophiolite	Conglomerate, sandstone, mudstone	Conglomerate, sandstone, mudstone	Schist, meta-greywacke
Suggested dam type	Multipurpose	Subsurface	Subsurface	Multipurpose	Multipurpose	Multipurpose
Suggested wall material	Earth or concrete	Earth or slurry wall	Slurry wall	Slurry wall	Slurry wall	Earth or concrete

Note 1: Multipurpose means sand-storage and water supply
Note 2: Aquifer thicknesses were determined by rezistivity soundings

Fig. 6: Photos of some potential groundwater dam sites

VI. SUGGESTED TYPE PROJECTS

Groundwater dams are usually constructed with concrete, earth (fig. 7), and masonry materials. New methods can be implemented such as slurry walls or bored piles (mix-in-place), considering the natural, technical, and economic conditions. Nevertheless, only earth and concrete dams have been constructed so far in the study area. It should be noted that slurry walls and bored piles can be applied without the need to excavate a trench.

The suggested types of projects for the various conditions are illustrated in Fig 8. The dam body was considered as earth type in the figure; however, it may be constructed by concrete, slurry wall, or other methods. The water intake facility is constructed near the bottom of the dam wall if the topography is flat, and considerable groundwater can be stored behind the dam wall (TYPE A). If the topography is steep and it is not possible to store a considerable amount of water, then there is no need to install a water intake facility at the bottom (TYPE B). Overflowing water from the dam body should be collected in this case. Exploitation wells are not needed in either model. To obtain the overflowing water above dam wall by gravity is possible; however, exploitation wells are needed to abstract more water from the aquifer, as shown in Type C and D. Regardless of the type of materials used and the method applied, the dam type and method of obtaining water are essential. Naturally, the thickness and width of the aquifer affect the excavation and construction cost. On the other hand, the water extraction method (by gravity or pumping) affects the construction and operation cost. If the water can be obtained by gravity, the operation cost is very cheap, but the construction of a water intake facility and excess excavation may increase the construction cost. The first preference should be the gravity flow method because operation cost is low; however, this condition does not always occur. These conditions naturally involve project design.

The amount of the additional storage capacity after construction depends on the topographical slope of the aquifer body in the upstream of the dam wall. The dam should be constructed with the water intake facility at the bottom of the dam wall if additional storage capacity can be created and the excavation cost is not high. Water may be pumped from wells adding to the overflowing water if the aquifer is thick and excavation cost is very high. The dam wall can also rise above the ground surface so as to allow the additional accumulation of seasonal sediments by flooding water (Fig 9). Thus, the storage capacity can be increased by creating an additional aquifer volume artificially. In summary, the project of a dam should be prepared in accordance with above conditions.

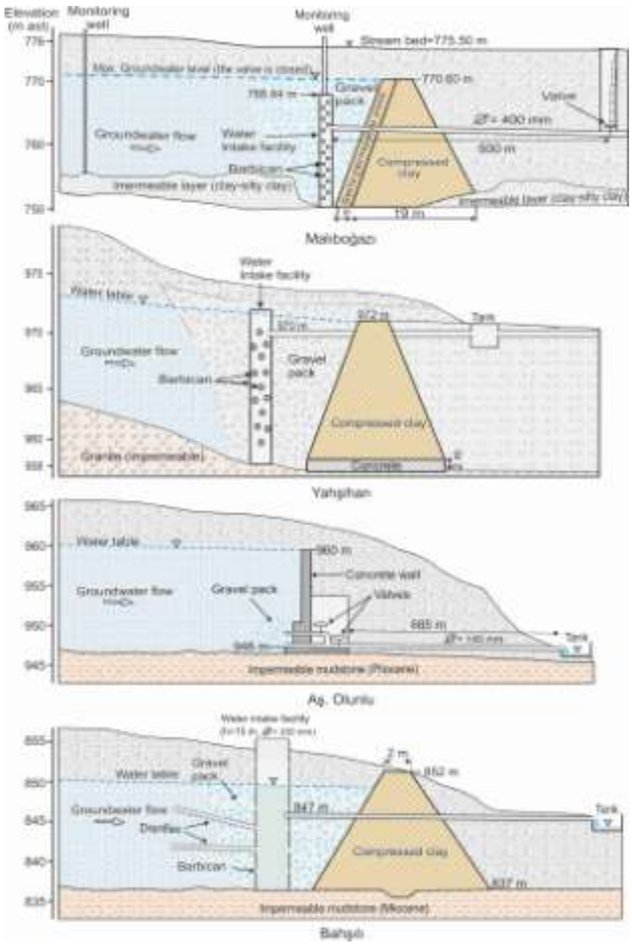

Fig. 7: Cross sections of various groundwater dams in the study area

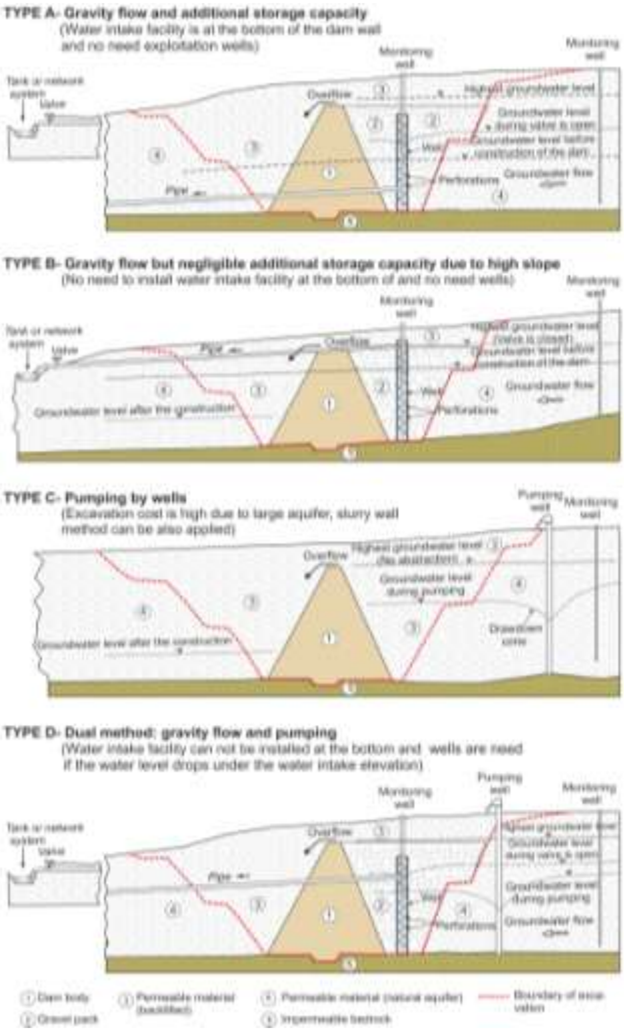

Fig. 8: Suggested project types of groundwater dam for alluvial sand-gravel aquifers (dam type was considered as earth in the figure, however it may be constructed by concrete, slurry wall, etc.)

VII. CONCLUSION, DISCUSSION AND SUGGESTION

The construction of the groundwater dam is an alternative method for the semi-arid central Turkey and similar regions of the world, because draughts and global warming may reduce rainfall and the recharge of groundwater, and increase loss through evapotranspiration particularly from the surface water body. North-central Turkey has suitable morphological, hydrogeological, climatological, social, and technical conditions for groundwater dam construction. The construction of groundwater dams have already been on Turkey's agenda in recent years, but it is yet in the early stages. With this study, it was concluded that groundwater dam projects are applicable, particularly for sand-gravel aquifers in the mid-to-small sized valleys. Of course, more detailed investigations should be performed on a local scale in the region. Additionally, similar studies can be performed in the other regions of Turkey. The suggested types of projects are applicable for similar conditions in any region of the world if desired.

In fact, the construction of a groundwater dam is a method to provide artificial recharge or water harvesting, and therefore, groundwater dams may be important for local people since they provide fresh and sustainable water, especially in rural areas. One of the most important advantages of underground dams is their being environmentally friendly and more practical compared to surface dams. For this reason, this method gradually began to be preferable for small scale water supplies. The most important issue is the amount of extra saturated aquifer volume that can be obtained after construction of the dam according to the water level and aquifer geometry and the amount of water that can be stored and abstracted. As mentioned earlier, water can be extracted by gravity or by pumping, considering the dam type, aquifer thickness, topography, technical facilities, and economics. Both methods can be also applied in a dam together. In order to complete the construction of the dam in a summer period (dry period) all machines and related auxiliary elements should be ready and all arrangements such as leveling on the ground, construction of the roads, and settlement should be completed prior to dam construction.

The most important problems in the excavation of aquifer for the cut-off wall are slope stability and the draining of the groundwater outside of the excavation area. For slope stability, the slopes should be designed based on the results of in situ and laboratory geotechnical tests. Clay material for the dam wall must be compacted to satisfy the optimum moisture content (OMC) and maximum dry density (MDD). The thickness of the clay core of the groundwater dam may be less than that of the surface dam. The water intake facility is installed in the specified location if the water is to be obtained by gravity. A large diameter shaft well is constructed behind the dam and a pipe that cut the dam wall perpendicularly reaches the well for gravity flow dams. A gravel pack may be filled around the well and drain flexes may be constructed to facilitate the groundwater flow through the well.

Leakage is the most common problem leading the failure of the groundwater dams. In order to overcome this problem the excavation should reach the bottom of the aquifer at the dam site and the dam wall should contact the underlying impermeable bedrock. A slurry wall or bored piles should penetrate a few meters into the bedrock. On the other hand, inserting the intake facility structure (pipe or concrete) to the impervious dam wall is an essential issue, because the leakages mostly occur through the contact zone between the dam wall and bedrock or between the intake facility structure and dam wall.

A valve and automatic flow meter should be installed in the pipe at the downstream of the intake facility for the gravity flow dams. Furthermore, a sufficient number of observation wells should be constructed in the upstream of the dam in order to monitor groundwater levels. Locations and numbers of the monitoring wells should be determined depending on the boundary and heterogeneity of the aquifer, and the abstraction method (gravity or pumping) of the water. Discharge and water level data give valuable information about the behavior of the system, recharge and storage capacity, and leakage risk. Consequently, the success of the system will be tested by the periodic measurement of flow and water levels, as well as water quality.

Another important issue is the re-arrangement of the stream bed after the dam construction. The filling of the pits and reconstruction of the slopes and streambed is essential for life and dam safety. For this reason, concrete or stone gabion should be constructed above the dam wall, particularly in soil dams, to prevent erosion of the bed by flood. On the other hand, the potential risk of wetland formation and salinization of the soil due to the rise of the groundwater level should be taken into consideration in site selection and design of the dam. More importantly, water needs and rights downstream of the dam should be taken into consideration. In fact, as in the construction of other hydraulic structures, the construction of groundwater dams should be considered within the framework of integrated water management.

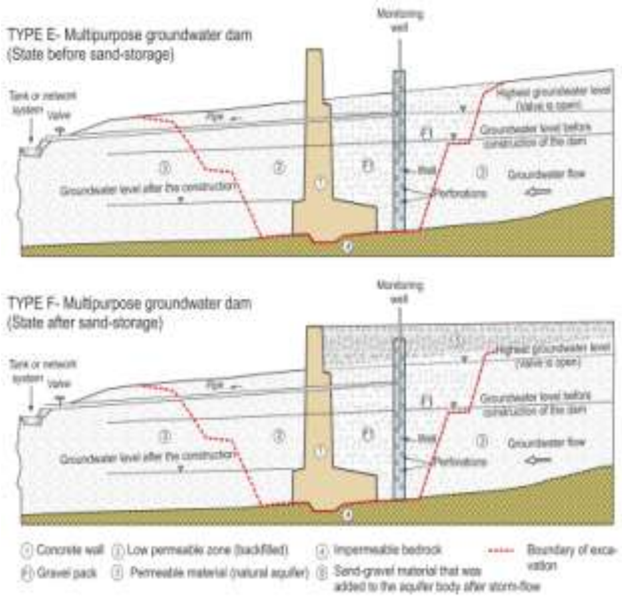

Fig. 9: Suggested project types of multipurpose (sand-storage and water supply) groundwater dam

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