European Water 11/12: 35-45, 2005.
© 2005 *E.W. Publications*

Underground Dams

A Tool of Sustainable Development and Management of Groundwater Resources

H. Onder[1] and M. Yilmaz[2]
Department of Civil Engineering, Middle East Technical University, Ankara-Turkey
[1] *Prof. Dr. , e-mail: onde@metu.edu.tr*
[2] *Former M.S Student*

Abstract: In this study, underground dams are briefly described, detailed information regarding the design and construction aspects is provided, and various types of dam wall are discussed. The use and usefulness of the underground dams as a means of sustainable development, and their performance in the management of groundwater resources are analyzed with the help of two example studies. In the first example a hypothetical idealized aquifer is considered, while in the second one, a real aquifer having relatively reasonable field data is selected. For the performance evaluation, and for the analysis of the impact of the underground dams on the groundwater behavior, numerical simulation is used. For that purpose, a well-known computer code, MODFLOW of U.S.G.S. is utilized. These examples demonstrated that underground dams may be a very useful instrument to substantially increase the available storage in the aquifers. They may also be used as a means of controlling the groundwater. For instance, if a groundwater dam is built, in a coastal aquifer, the recharged water that would flow towards the sea could be prevented by providing additional storage. This is a contribution to the sustainable development. It is also demonstrated that the approaches utilized in this study are useful for the planning and design of groundwater dams.

Key words: underground dams, subsurface dams, sustainable managements of groundwater, MODFLOW simulation

INTRODUCTION

As surface water resources become fully developed, for new development, groundwater offers the only possible option. Furthermore, in arid regions, where surface water resources are very scarce, or, even non-existent, the groundwater is the only available water resource. Increasingly, greater attention is being placed on how to manage groundwater in a sustainable manner. Groundwater sustainability may be defined as development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et al. 1999). In coming decades sustainability of water resources will be one of the key issues and the shift towards groundwater will be inevitable.

In order to generate additional water resources, the 1992-Rio Conference made the implementation of subsurface dams a prime goal in its Agenda 21. They are particularly suitable for use as small-scale water supply in arid and semi-arid regions. They are an anti-erosion device, as proclaimed by the 1992-Rio Conference. They are used to harvest water (Prinz and Singh, 2000), to raise groundwater levels, and to minimize the evaporation losses (Beaumont and Kluger, 1973). The underground damming may be an efficient method to fight against the desertification (Tsumuro, 1999).

A REVIEW ON GROUNDWATER DAMS

A groundwater dam is a structure that obstructs the natural flow of groundwater and stores water below the ground surface. There are basically two types of groundwater dams: i) sub-surface dams and ii) sand-storage dams. A sub-surface dam is constructed below ground level and arrests the flow in a natural aquifer, whereas a sand-storage dam impounds water in sediments caused to accumulate by the dam itself (Hanson and Nilsson, 1986). The cross-section of a typical subsurface dam and a sand-storage dam are given in Figure1 and Figure 2, respectively (Wateraid).

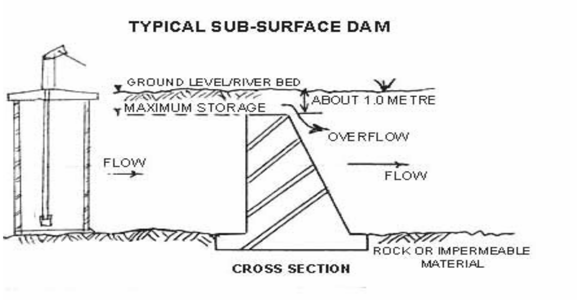

Figure 1. Typical sub-surface dam (Wateraid)

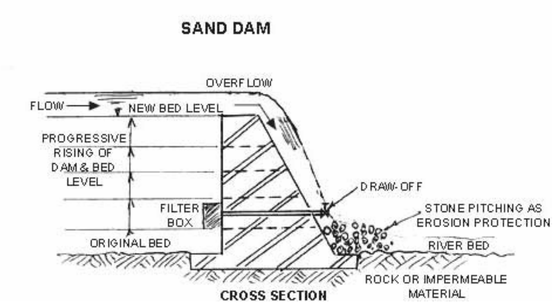

Figure 2. Typical sand-storage dam (Wateraid)

Subsurface Dams

The principle of a sub-surface dam is relatively simple: a trench is dug across the valley, reaching down to bedrock or their impervious, solid, impervious layer, at a suitable location. In the trench an impermeable wall or barrier is constructed and the trench is refilled with excavated material. A subsurface reservoir created this way retains water during wet season and may be used as a water resource throughout the dry season.

Various construction materials have been used for the impermeable barrier such as clay, concrete, stone masonry, reinforced concrete, brick, plastic, tarred-felt, sheets of steel, corrugated iron or PVC (Nilsson, 1988).

Impermeability may also be obtained by using injection screen. The choice will be dictated by several factors such as local hydrogeologic conditions, availability and cost of the material, the ease with which construction is made, the need for the skilled labor, etc. On Figure 3 some of the sub-surface dam types are presented

The average heights of subsurface dams generally vary in the range of 2-6 m (Nilsson 1988). Injection screens may, however, go up to 10 m or more. There is an attempt in Çeşme, Izmir, Turkey to prevent seawater intrusion into fresh water aquifer (Sargın, 2003 and Kocabaş, 2003).The crest of a subsurface dam is usually kept at some depth below the surface to avoid water logging in the upstream area. The water is extracted through a well which may be placed in the reservoir or by a gravity pipeline if the topographical conditions are favorable (Figure 4). By using gravity extraction, problems with pump installation, operation and maintenance are avoided (Nilsson, 1988). Sub-surface dams are generally built at the end of the dry season when there is minimum water in the aquifer. The excavation for the dam site should be dewatered during the construction.

Sand-Storage Dams

The general principle of a sand-storage dam is as follows: A weir of suitable size is constructed across the stream bed, sand carried by heavy flows during the rains is deposited, and the reservoir is filled up with sand. This artificial aquifer is replenished each year during the rains, and the water stored is used during the dry season (Wipplinger, 1958). Types of sand-storage dams include concrete, stone masonry, gabion with clay cover, gabion with clay core, stone-fill concrete and stone sand-storage dams. Some of these sand-storage dams are illustrated on Figure 5.

The body of the sand storage dam must be sufficiently massive to withstand the pressure and properly constructed for stability and tightness. Stone sand storage dam may not be completely water tight (Figure 5.f).A sand storage dam has to be well protected against erosion both along the banks and at the dam toe (Nilsson, 1988). The height of a sand-storage dam is typically 1-4 meters. Water is generally extracted by placing a drain at the reservoir bottom along the upstream side of the dam, and connecting the drain to a well or to a gravity supply pipe through the dam wall. Sand storage dams are more suitable for gravity extraction than subsurface dams (Figure 6). The design of a sand storage dam is considered in two parts. The first part is concerned with determining the overall size necessary to supply a given quantity of water.

This requires the determination of the storage capacity and yield of various sediments. The second part of the design concerns the formation of sediment deposits. A sand storage dam is built in stages (Figure 7). The technical efficiency and the cost of construction methods are discussed by Burger and Beaumont (1970) and Beaumont and Kluger (1973).

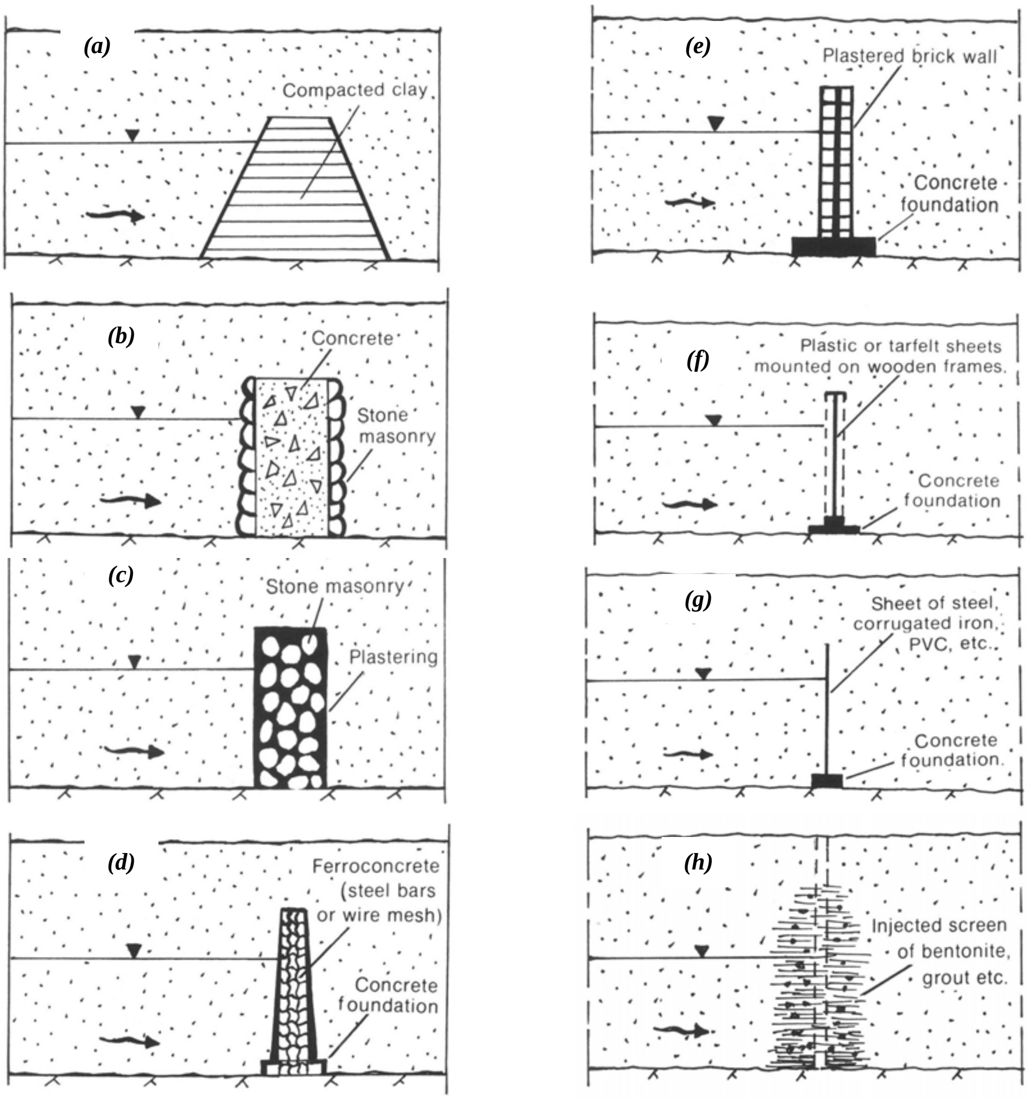

Figure 3. Sub-surface dam types: a) Clay dike,.b) Concrete dam, c) Stone masonry dam, d) Reinforced concrete dam, e) Plastered brick wall, f) Plastic or tarred-felt sheets, g) Corrugated iron, steel, or PVC sheet, h) Injection screen (Hanson and Nilsson, 1986, Nilsson, 1988)

ANALYSIS BY NUMERICAL MODELING

In coastal groundwater basins, the development of the groundwater using an underground dam, to store water in the aquifer, which otherwise is discharged to the sea without economic use, is an attractive solution to the water shortage problem. At the same time it prevents the problem of salt water intrusion. The suitability of an underground dam is highly site-specific and depends on aquifer properties, hydrologic conditions and the geological setting of the basin. A thorough hydro geological investigation coupled with model analysis is therefore needed to estimate the groundwater reserve and the yield of the aquifer. At the beginning of modeling process, the available data is often inadequate in quantity and in quality for a numerical analysis. A stepwise modeling approach that first uses a simple model with available data is proposed. As enhanced data becomes available necessary complexity is incorporated in subsequent versions of the model. For the numerical analysis, MODFLOW (McDonald and Harbaugh, 1988), is used. MODFLOW is a three-dimensional ground-water-flow model that has the capability to simulate transient conditions and a wide variety of hydrogeologic system features. It simulates ground-water flow using the finite-difference method where the model flow domain is divided into rectangular blocks by a three-dimensional grid. The grid of blocks is organized by rows, columns, and layers, and each block is called a "cell". Hydraulic properties and thickness must be defined for each cell within the ground-water system. Surface-water features are also assigned by row, column, and layer indices. The model code iteratively solves for heads and flows throughout the model domain given boundaries, inputs and stresses specified by the user.

SIMULATION RESULTS

Example 1: Hypothetical Case Study

In this example, an idealized hypothetical rectangular unconfined aquifer having a size of 4000 m x 800 m in a coastal area is considered. The plan view of the aquifer and the locations of the wells and underground dam are shown in Figure 8. The aquifer has one layer and is assumed to be homogeneous and isotropic with a hydraulic conductivity of 0.02 m/s. The water depth at the coastline is 1 m. A grid system of 8 rows by 40 columns is superimposed on the aquifer. Using MODFLOW computer package, simulation runs for steady and unsteady flow conditions have been performed, to analyze the effects of groundwater dam and its location on the storage and yield characteristics of the aquifer.

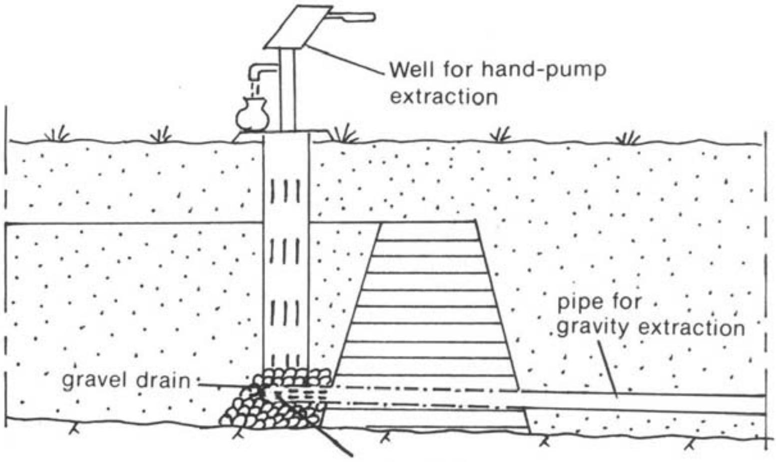

Figure 4 Water extraction alternatives from a sub-surface dam (Nilsson, 1988)

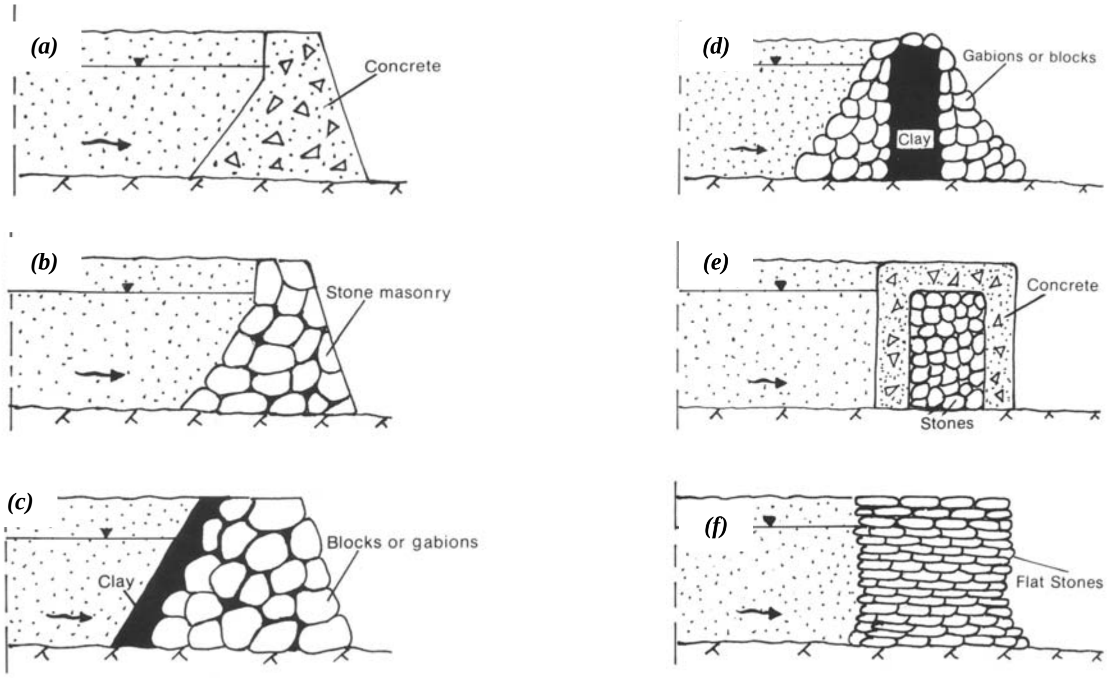

Figure 5. Types of Sand-Storage Dams: a) Concrete sand-storage dam, b) Stone masonry sand-storage dam, c) Gabion sand-storage dam with clay cover, d) Gabion sand-storage dam with clay core, e) Stone-fill concrete sand-storage dam, f) Stone sand-storage dam (Nilsson, 1988)

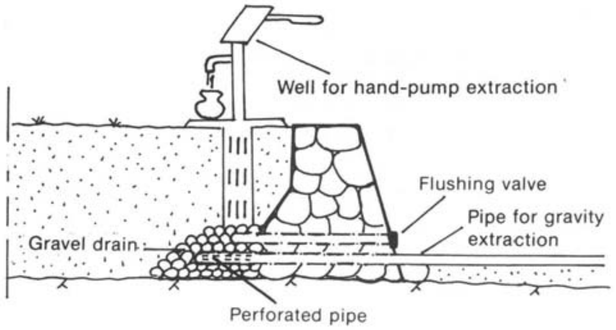

Figure 6. Extraction alternatives from a sand-storage dam (Hanson and Nilsson, 1986)

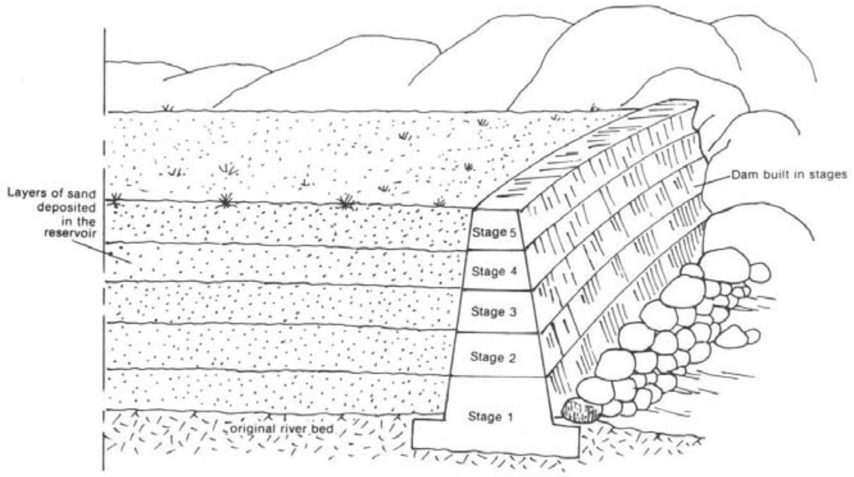

Figure 7. Construction principle of sand-storage dam (Nilsson, 1988)

Steady Flow Conditions

As a base case, first a simulation under natural conditions is performed. Then, wells are activated and the yield of the aquifer before the construction of the dam is determined. The objective of the next simulation is to see how the storage capacity is increased after the construction of the dam. Finally, how the yield of the aquifer is increased with the dam wall is the objective in the last simulation. In Table 1, various parameters and their numerical values are provided. The variations of water table elevation along x-axis, obtained from the results of MODFLOW simulation, for the above different cases, are given in Figure 9, 10, 11, 12, and 13.

The comparison of Figure 9 and 10 shows how the storage capacity of the aquifer is increased by dam. The sudden change in the water table elevation across the dam wall is to be noted. The influence of the dam wall location on the water table and on the storage capacity is observed by comparison of Figure 10 and 11. When the dam wall is closer to the coastline, wetland condition occurs (from 2400 m to 4000 m). This situation is an undesirable response of the aquifer. The maximum pumping rates are determined by repeated simulations by trial and error procedures as 5000 m^3/day without dam and 7005 m^3/day with dam respectively. The corresponding positions of the water table are given in Figure 12 and Figure 13, for the comparison purposes.

Table 1. Various parameters of Example 1

Parameter	Symbol	Numerical Value
Aquifer length	L(m)	4000
Aquifer width	w(m)	800
Aquifer thickness	b(m)	10
Dam wall thickness	t(m)	8
Mean sea level	h_{sea}(m)	1
Conductivity of soil	K_s(m/s)	0.02
Conductivity of dam	K_w(m/s)	0.0001
Recharge	R(m/day)	0.007
Discharge from W_1	Q_1(m^3/day)	–5000
Discharge from W_2	Q_2(m^3/day)	–5000
Specific yield	S_y(-)	0.02
Effective porosity	n_{ef}(-)	0.02

Unsteady Flow Conditions

The unsteady simulations of the groundwater flow under various operational conditions (scenarios) are essential tasks in aquifer management activities. The cases given in Figure 10 (where the aquifer is completely full) and in Figure 13 (where the aquifer is completely empty) represent two steady conditions.

Starting from the end of an irrigation period when the aquifer is completely empty, a question of practical value would be how many days it will be necessary for the aquifer to reach again to the full condition at the beginning of the next irrigation period? The result of unsteady MODFLOW simulation indicates that in 110 days, the underground reservoir is filled, the change of increase in head values become negligibly small and the steady state condition is reached.

A similar question would be how many days it will be necessary for the aquifer to be emptied completely, with a pumping rate of Q_1=Q_2=7005 m^3/day? The unsteady simulation indicates that it takes approximately 200 days.

Consider a particular dry season when the average recharge rate drops from R=0.007 m/day to R=0.003 m/day. Assume that the pumping rate is to remain as Q_1=Q_2=7005 m^3/day, and that the irrigation season requires 90 days pumping. Then the required information would be whether the proposed pumping can be sustained for 90 days, and if not, how many days it can be sustained? The simulation by MODFLOW indicates that, after a period of 20 days, the wells get dried for $Q_1=Q_2=7005$ m^3/day discharge and R=0.003 m/day recharge value.

Consider again the dry season when the average recharge rate is R=0.003 m/day and the irrigation season requires 90 days pumping. The question of what would be the safe yield for three months is a question of importance. By repeated simulation by MODFLOW the maximum extraction rate from the wells for 90 day is found to be 3500 m^3/day

The questions like the ones given above are often encountered in groundwater managements. The answers to these questions may easily be obtained by running MODFLOW in unsteady mode. In simulation runs, for some parameters, such as recharge rate, exaggerated numerical values are used to make their effects on groundwater behavior more visible in this hypothetical case. Actual values of these parameters obtained from field measurements may be quit different.

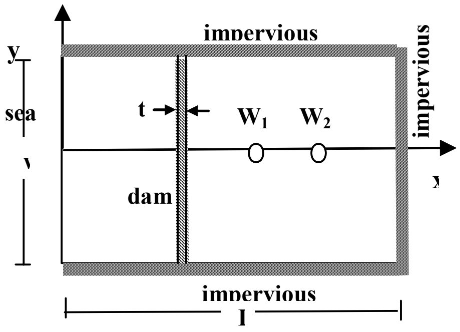

Figure 8. Plan view of idealized rectangular aquifer with dam wall and two pumping wells

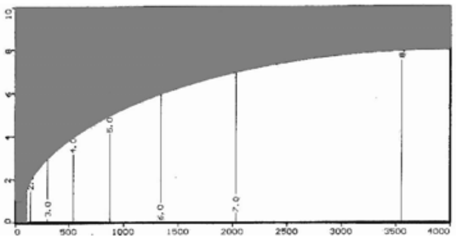

Figure 9. Variation of water table along x-axis under natural conditions

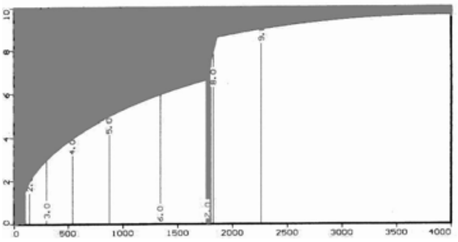

Figure 10. Variation of water table along x-axis after the dam wall is constructed at x=1700 m

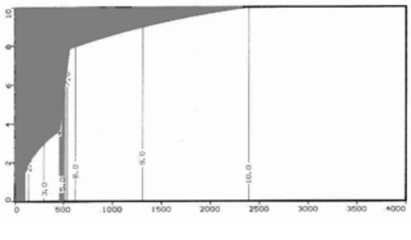

Figure 11. Variation of water table along x-axis after the dam wall is constructed at x=500 m

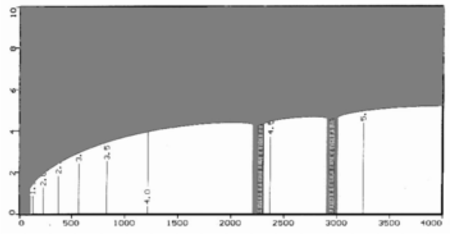

Figure 12. Variation of water table along x-axis with two discharging wells Q1=Q2=5000 m3/day

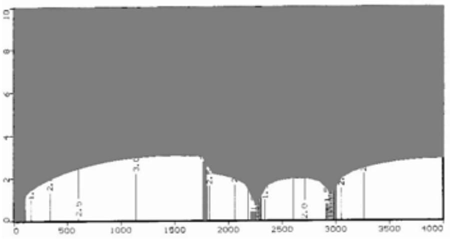

Figure 13. Variation of water table along x-axis with dam wall and two discharging wells Q1=Q2=7005 m3/day

Example 2: Camli Koyu Real Case Study

Description of the study area

The investigation area is located between 36° 57’ and 37° 00’ latitude north, and between 28° 15’ and 28° 18’ longitude east. It has a surface area of approximately 25 km^2. The site is near Kocaalan Creek in Çamlı Köyü, Marmaris, Muğla, Turkey. The aquifer can be considered as a single layer formation. From the field measurements carried out by DSI (1999), the average hydraulic conductivity (K) value of the aquifer was estimated to be 4.24x10^{-4} m/s. The average thickness is 68 m (Akdeniz, 2003). The approximate discretisized boundaries of the flow domain is given in Figure 14

The motivation behind this selection is that DSI performed a preliminary hydrogeological study on this area. The objective in this work was to construct a trial injection screen to augment the storage capacity of the aquifer and also to eliminate or reduce the intrusion of the salt water.

The available data was somewhat inadequate for a numerical simulation. For this reason, a set of appropriate assumptions have been made to run MODFLOW. As in the previous example both steady and unsteady simulations have been performed**.**

Simulation of Groundwater Flow under Different Conditions

The groundwater flow in the aquifer under natural conditions where the only excitation on the system is recharge is simulated. The net recharge rate is estimated as 25% of annual average precipitation. The variation of water table elevation obtained as a contour line map from the MODFLOW simulation is shown in Figure 14. The same variation on a cross-section with horizontal distance is presented in Figure 15. In Figure 16 the impact of an injection screen on the behavior of the ground water is provided. The corresponding contour lines of the water table are provided in Figure 17. Logically this impact should be a function of the hydraulic conductivity, the location, and the height of the underground dam. In this example the location selected by DSI for the trial injection screen is adopted (The location of the dam wall is used as given in the original report). The selected height is taken as equal to the depth of the aquifer which means that it penetrates the aquifer completely. For the hydraulic conductivity of the underground dam, an assumed value is used.

In Figure 18, for the case when each one of the two well pumping at a constant rate of 4302 m^3/day, the variation of the water table elevation is given.

The sudden change in the ground water elevations across the dam wall can easily be seen in Figure 16 and 18.

As it is seen in Figure 18, the slope of the hydraulic head across the dam wall is toward inland, consequently, there is a flow of salt water from sea to aquifer. Therefore the pumping rate of 4302 m^3/day cannot be accepted as a safe yield since it produces an undesirable consequence. A pumping rate of 1200 m^3/day is obtained as the maximum rate that does not cause unacceptable consequences, that is no salt-water intrusion and no drying of the wells. This value is determined by using the criterion that the slope of the water table on the seaside of dam wall should be toward the sea. Obviously, this pumping rate may be increased by decreasing the hydraulic conductivity, K_w of dam wall, or by creating completely impermeable dam wall. Several unsteady runs have been conducted. The details can be found in Yilmaz (2003). As the available data is rather incomplete and some assumed values are used, the results are to be considered with some degree of precaution. As new enhanced data is available, the new runs can be conducted to incorporate the necessary complexity of the system.

Table 2. Parameters of Example 2

Parameter	Symbol	Numerical Values
Aquifer length	L(m)	5000 m
Aquifer width	w(m)	2000 m
Aquifer thickness	b(m)	68 m
Dam wall thickness	t(m)	10
Mean sea level	h_{sea}(m)	60.5
Soil Conductivity	K_s(m/s)	0.000424
Dam Conductivity	K_w(m/s)	0.0000025
Recharge	R(m/day)	8.175×10^{-4}
Discharge from W_2	Q_1(m^3/day)	-900
Discharge from W_2	Q_2(m^3/day)	-900
Specific yield	S_y(-)	0.15
Effective porosity	n_{ef}(-)	0.15

CONCLUDING REMARKS

When available water resources and the degree of their utilization are considered, it becomes obvious that Turkey is not a water rich country. Conditions are similar in other countries in the region. It is estimated that with the present trend in the increase of local population and expansion of tourism, the water demand will be much higher than the available water sources. This indicates that a severe shortage of fresh water supply in the not too distant future will be experienced. Various measures such as assessment and development of new potential water sources and demand management are required to alleviate the problem. The development of the groundwater basin and the concept of storing water in subsurface is an attractive solution to the water shortage problem, especially because of relatively low social and environmental impacts, and it offers a tremendous potential. At the same time to prevent seawater intrusion.

Storing water behind ground-water dams has advantages over surface reservoirs:

- Evaporation losses are reduced or avoided
- The designed storage is available for a very long time
- They are less susceptible to pollution and health hazards
- The land above the stored water can be used for other purposes
- They require low-cost and socially acceptable techniques

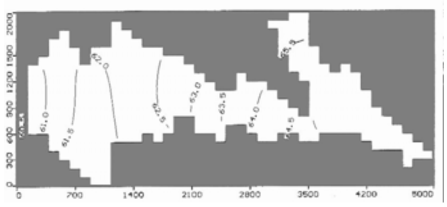

Figure 14. Map of contour lines under natural conditions and without dam wall

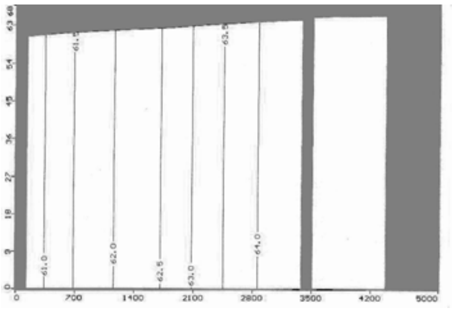

Figure 15. Variation of water table along x-axis under natural conditions

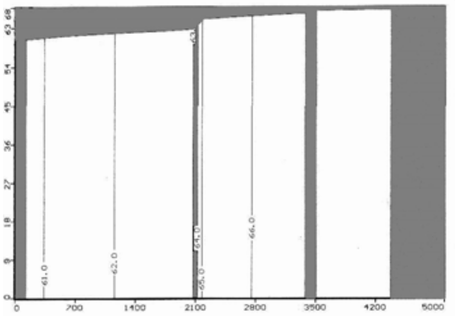

Figure 16. Variation of water table along x-axis after the dam wall is constructed

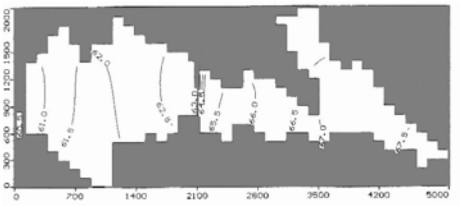

Figure 17. Map of contour lines under natural conditions and with dam wall

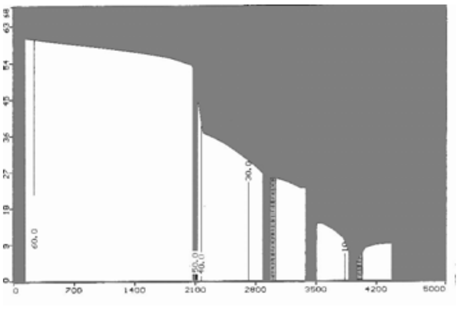

Figure 18. Variation of water table along x-axis with dam wall and two pumping wells (Q_1=Q_2=4302 m^3/day)

REFERENCES

Alley, W. M., Reily, T. E. , and Franke, O. L. 1999, Sustainability of Ground-Water Resources, U. S. Geological Survey Circular 1186, Denver, Colorado.

Akdeniz, U., 2003, 'Personal communication'. DSİ Geotechnical Services and Groundwater Department, Ankara

Beaumont, R.D.; Kluger J.W., 1973, 'Sedimentation in reservoirs as a means of water conservation'. IAHR Congress, Istanbul, 3-7 Sept. 1973, pp. A28-1-A28-6 (211-216).

Burger, S.W.; Beaumont, R.D., 1970, 'Sand storage dams for water conservation.' Convention: water for the future. Water Year 1970. Republic of South Africa, 9 pp.

Hanson, G.; Nilsson, A., 1986, 'Ground-Water Dams for Rural-Water Supplies in Developing Countries'. Ground Water, Vol. 24, No. 4, July-August 1986, pp. 497-506

Kocabaş, İ., 2003, 'Personal communication'. DSİ Geotechnical Services and Groundwater Department, Ankara

McDonald, M.G. and A.W. Harbaugh, 1988. 'MODFLOW-A Modular Three Dimensional Finite-Difference Groundwater Flow Model'. USDI, U.S. Geological Survey, National Center, Reston, Virginia

Nilsson, A., 1988, Groundwater dams for small-scale water supply. IT Publications, London.

Prinz, D. and Singh, A.2000. Technological Potential for Improvements of Water Harvesting, World Commission on Dams, Cape Town.

Sargın, A. H., 2003, 'Personal communication'. DSİ Geotechnical Services and Groundwater Department, Ankara

Tsumuro, T., 1998, Applying Environment Related Technology: Environmental Measures in the Construction Industry, Business Leaders' Inter-Form for Environment 21, Japan.

Wateraid, http://www.wateraid.org.uk/site/in_depth/technology_notes/302.asp

Wipplinger, O., 1958. 'The storage of water in sand'. South-West Africa Administration, Water Affairs Branch, 1958. 107 pp

Yilmaz, M., 2003, 'Control of Groundwater by Underground Dams', M.S. Thesis, Dept. of Civil Eng., METU, Ankara.