INTEGRATED HYDROGEOLOGICAL AND HYDROCHEMICAL ASSESSMENT OF THE GROUNDWATER WITHIN THE INTERNATIONAL PROTECTED GÖKSU DELTA, SOUTHERN TURKEY

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Abstract

Göksu Delta is an important wetland where the Göksu River reaches to sea in the eastern of the town Tasucu-Ice1. The delta is classified as a Wetland of International Importance according to the Ramsar Convention on Wetlands of International Importance. In the Göksu Delta area, urban and agricultural expansions have caused an ever-growing need for fresh water. In this study, the flow of groundwater was determined through a three-dimensional model developed by the finite-difference program MODFLOW. MODPATH was calculated the advective pathlines of the water particles. The result of steady-state flow simulation show that the groundwater flow to south and east directions as it expected. Movement in the uplands is greatest in the upper sands with maximums of about 3.4 10^{-5} m/s. The types of groundwaters from alluvial aquifer are Ca-Mg-$HCO_{3,}$ but in the region where sea water intrusion is occured it changes and the Na and Cl ions are added to groundwater. The similar occurence can be observed in the groundwater from the limestone aquifer. The types of groundwater are Ca-HCO_3 or Ca-Mg-HCO_3 and they change to Ca-Na-Mg-HCO_3-Cl in the vicinity of seawater intrusion regions.

Key Words
Göksu delta-Turkey, groundwater flow modelling, groundwater chemistry

Introduction

The Göksu Delta is formed by Goksu River near the southern part of Silifke town in the Mediterranean region, Turkey. Göksu Delta is an important wetland (15000 ha) where the Göksu River reaches to sea in the eastern of the town Tasucu-Ice1 [1]. There are two aquatic ecosystems in Göksu Delta: Paradeniz Lake and Akgöl Lagoon.

The Mediterranean coastline stretching from the city of Silifke to the Susanoğlu region is heavily populated with recent (last 15 years) urban developments (e.g., villas, apartment complexes, and multi-storey buildings), which are mostly occupied during summer season for vacation purposes. Due to increased population influx from the surrounding cities, especially during the peak season (May to September); the population of this region increases several folds (e.g., 2–4 times).

The Göksu Delta is not only an urban area but it is also surrounded by densely cultivated orchards (mostly citrus), traditional vegetable farms and greenhouse cultivations, where farming activities continue all year long due to favorable climate.

In the Göksu Delta area, urban and agricultural expansions have caused an ever-growing need for fresh water. In this region, water supply for most municipalities, domestic use water for urban developments and irrigation water for agricultural activities are almost exclusively provided through hand dug or drilled wells. Therefore, water resources in the Göksu Delta area are subjected to intensive demands, stresses and pollution risks [2]. The expansion of irrigated agriculture induces the risk of groundwater quality degradation through high groundwater pumping rates and overexploitation of the aquifers, leading to seawater intrusion in the coastal aquifers. Agriculture is the dominant land use, mainly developed in small farms distributed throughout the relatively flat uplands. According to the Environmental Autoritys' information, there is an approximate input of 520 kg /ha of fertilizers.

Göksu Delta is an internationally important wetland due to its location being on a bird migration route. The Environmental Protection Department of the Ministry of Environment has declared the Göksu Delta as a Special Environmental Protection Zone to protect the area against pollution and exploitation, and to ensure that natural resources and cultural assets have a future. The delta is classified as a Wetland of International Importance according to the Ramsar Convention on Wetlands of International Importance.

The objectives of the present study are to characterise the main hydrogeological and hydrogeochemical features of the Quaternary alluvial aquifer of the Göksu Delta and pictorially represent it using the geographic information system (GIS). The purpose of this study is to define a conceptual framework of the shallow deposits underlying a representative agricultural catchment within Göksu delta, and describe the patterns and rates of groundwater movement within it. In addition, major ions are analyzed to get a better understanding of the groundwater chemistry of the site, and as a basis for the construction of a numerical model of contaminant transport in the district.

Site description

The Göksu Delta is situated in the Mediterranean Sea region of the southeastern part of Turkey and extends from $36^{o}15$ –$36^{o}25$ of latitude north to $33^{o}55$-$34^{o}05$ of longitude west (Fig. 1). The Göksu Delta area is bounded by the Taurus Mountains on the northern side and by the Mediterranean Sea on the southern and eastern side. The southern portion of the Göksu Delta area is a delta plain made up of sediments from Göksu River. The Goksu River flow regime is also strongly dependent on the seasonal rains and temperature. Average flow of Goksu River is 130 m^3/s where it reaches the highest value during May. Topographic structure in the north of the investigated area (Taurus Mountains) is rugged with altitudes ranging from 300 to 1,500 m.

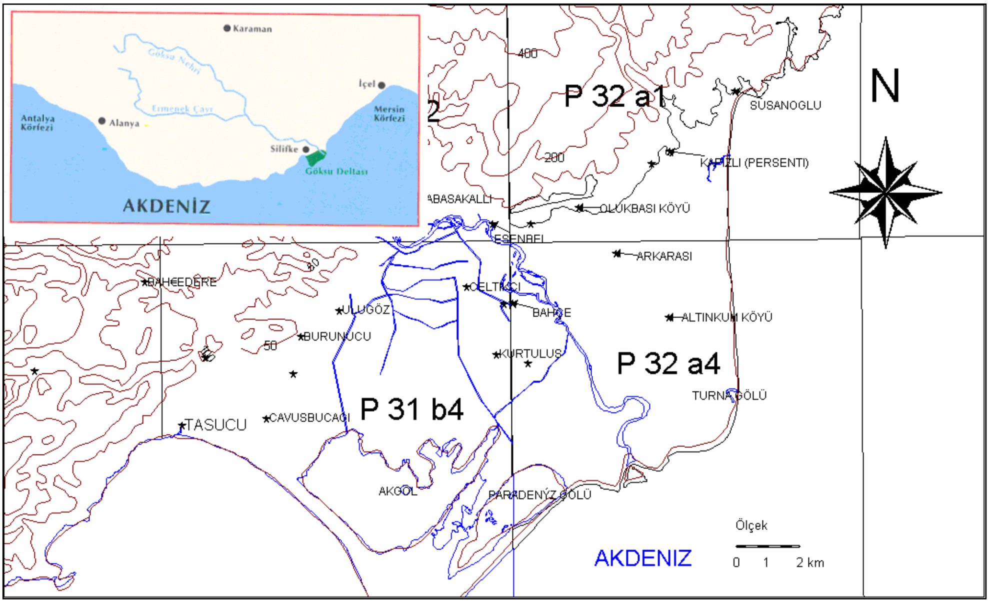

Figure 1: The location map of the study area

In the Göksu Delta area, climate is characterized by hot and dry periods in summer and by warm and wet periods in winter, which is typical for the coastal zones around the Mediterranean Sea. The mean annual temperature in this area is 19°C. Showers start in October, and continue till mid April and the maximum rainfall occurs in December. The Göksu Delta area receives slightly higher than 607 mm of precipitation annually, and extended periods (i.e., 3–4 months) without precipitation are common

The geological map obtained from the MTA (General Directorate of Mineral Research and Exploration) is used as the basis for this study. The map was updated and the sampling wells were interpreted through digital processing.

The study area was located in the southern part of Miocene carbonate rocks of the Tauride belt. The oldest rock unit of the Göksu Delta is Akdere Formation of Paleozoic Age, which consists of marble, schist and quartzite. Akdere Formation (middle-upper

Devonian) is generally found in the northern part of the study area (Fig. 2). Akdere Formation contains various rocks with differing compositions including sandstone, siltstone, dolomite and limestone. Kusyuvası Formation (Middle trias) consists of limestone. Tokmar Formation (upper jura-lower cretaseous) is found in the western part of delta and contains dolomite and limestone.

Tertiary units are composed of oligo-miocene Gildirli formation, lower-middle Miocene Karaisali formation and middle-upper Miocene Kuzgun formation. (Fig. 2). Tertiary rocks consist of a succession of marine, lacustrine, and fluvial deposits, which display transitional characteristics both vertically and areally in the study area.

The Quaternary basin-fill deposits are a heterogeneous mixture of metamorphic and sedimentary rock detritus ranging from clay to boulder size. The mixture includes stream alluvium, stream-terrace deposits, fan deposits, delta deposits, shore deposits. The basin-fill deposits vary greatly in lithology and grain-size, both vertically and areally. Accordingly, the hydraulic properties of these deposits can differ greatly over short distances, both laterally and vertically.

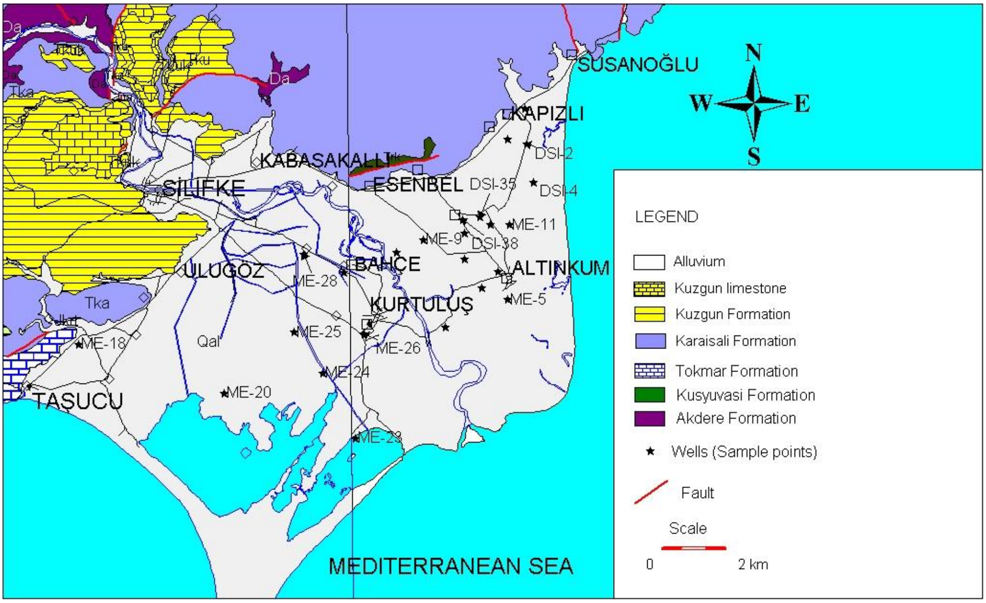

Figure 2: The geological map of the studied area and sampling points

The alluvial aquifer consists of a heterogeneous mixture of gravel, sand, silt, clay and sandy-clay. The mineralogical composition of the alluvial sediments comprising the aquifer matrix is also important in determining groundwater quality. The thickness of the alluvial deposits ranges from roughly 5 to 500 m [3, 4], with considerable spatial variation in the aquifer. Furthermore, the accurate definition of the geometry of the aquifer in the basin is complicated due to the heterogeneity of the sedimentary sequence. Different wells drilled into the alluvial aquifer, supplying water mainly for crop irrigation, show groundwater levels from approximately 1–10 m depth.

Conceptually the aquifer system in the delta is an unconfined aquifer. Recharge occurs by means of precipitation and infiltration at the top of the delta. The recharge rate is determined as 35.23 mm by using Visual HELP model [5]. Groundwater flow to the sea and the maximum flow velocity is determined as 3.4 10^{-5} m/s by Visual MODFLOW model [5].

Materials and methods

For chemical analysis, a total of 16 water samples from the Göksu Delta (9 from alluvial aquifer, 4 from limestone aquifer, 1 from Paradeniz Lake, 1 from Akgöl and 1 from Mediterranean Sea) were obtained in July 2006 from the sampling points shown in figure 2. Table 1 summarizes the chemical analysis results for water samples collected from the Göksu Delta.

Table 1: Results of the chemical analyses

Sampling	ME-1	ME-12	ME-20	ME-23	ME-24	ME-26	ME-28	ME-3	ME-18	ME-14	ME-15	ME-16	ME-21	Akgöl	Paradeniz	Sea water
	Alluvial aquifer									Limestone aquifer				Surface water		
pH	7.39	7.56	7.76	8.12	8.4	7.84	7.45	7.42	7.17	6.94	7.17	7.2	7.29	8.3	8.05	7.91
T	23.4	21.3	21.5	22	21.6	26	21.5	23.2	21.5	22.3	20.1	21.2	22.1	33.9	31	29.2
EC	1220	1988	925	2810	1031	711	598	756	719	1025	997	558	893	439	45300	53500
sal	0.4	0.9	0.2	1.3	0.3	0.1	0	0.1	0.1	0.3	0.3	0	0.2	0	29.6	35.5
DO	5.2	6.6	6.7	6.9	7.2	7.5	7.2	6.9	6.6	7	8.1	6.9	7.2	5.5	4.9	4.7
NO_2	0.1	0	0	0.26	0	0	0	0.26	0	0	0	0	0	0	0	0
NO_3	15	1.8	15.9	10.6	5.3	9.3	11.9	9.7	14.2	9.74	6.2	12.4	32.34	6.64	0	6.64
NH_3	0.13	0	0.07	0	0.43	0	0	0	0.02	0	0	0.012	0.012	0.34	4.01	4.01
PO_4	1.35	0.21	0.23	0.45	0.24	0.13	0.42	0.61	1.86	0.28	0.54	0.13	0.35	0.88	0.39	0.2
P	1	0.6	0.2	0.5	0.3	0.2	1.2	0.6	1.1	0.4	0.6	0.1	0.4	1.4	0.2	0.7
Br	1.05	0.47	0.5	1.93	0.47	2.64	3.38	0.53	1.63	0.64	0.59	1.54	0.58	0.72	0.42	0.58
I	0.1	0.5	0.3	0.3	0.1	0	0.5	0.1	0.1	0.1	0.1	0.2	0.2	0.2	3	0.2
F	0.93	0.46	0	1.97	1.16	0.21	0.3	0.22	0.08	0	0.56	0.34	0.45	0.83	0.81	1.96
Na	150	361	121	535	213	70.9	16.8	42.2	29.6	73.6	-	10.4	48.4	21.7	9556	10934
K	6.54	21.9	3.25	20	4.26	4.98	1.97	2.79	2.38	2.89	-	1.43	3.42	1.86	396	485
Ca	66.7	32.8	33.5	17.1	18.3	31.3	52.6	64.9	74.9	118	-	64.1	61.9	36.5	350	373
Mg	42.8	25.2	26.9	18.3	5.69	25.8	41.6	40.4	22.7	14	-	24.6	40.9	23.8	717	822
HCO_3	546	340	261	255	255	194	219	407	267	370	-	285	279	213	128	140
Cl	78.4	418	149	696	157	102	51.7	29	54.2	136	-	15	94.2	22.5	15177	17929
SO4	125	100	40.3	91.4	40.7	21.7	47.6	58	32.2	21	-	27.4	41.3	34.4	2470	2915
KOI	21	22	1	28	3	3	10	2	2	19	-	2	12	16	1050	1000
Mn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fe	7.5	0.2	3.41	5.5	5.5	5.5	4.16	0.8	2.07	0	0	0.03	5.5	0.5	0.5	0.06
Cu	0.27	0.37	0.41	0.14	0.35	0.26	0.17	0.29	0.24	0	0	0	0.21	0.9	0.4	0.77
SiO_2	48	12	20.6	2.8	5.5	17.7	28	11	10	2.6	2.8	8.2	29	17.4	7	0.14
Mo	0.3	0	0	0	0	0	0.1	0	0	0.6	0	0	0	0	0	0
Cr	0.047	0.026	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0.048

Electrical conductivity (EC), temperature (T), salinity (sal) and pH were monitored during pumping, and samples were collected only when values were stabilized or after at least three well volumes had been purged. Measurements of EC and pH were made in the field using a pH/Cond 340i WTW meter. For the pH measurements the electrode was calibrated against pH buffers at each location.

Aliquots were filtered through a 0.45-mm Millipore cellulose type membrane and stored in HDPE bottles. The sample bottles were rinsed three times with the filtered sample water before they were filled. Then, 0.25 ml/L of HNO_3 (nitric acid) was added to the first aliquot to prevent precipitation. The samples were refrigerated at 4^o C until analysis. Cations were analyzed by inductively coupled plasma (ICP) and anions by ion chromatography (IC). SiO_2 was analyzed mainly by visible spectrophotometry. Bicarbonates were determined by titration in the laboratory. Samples were analyzed in the laboratory of General Directorate of Mineral Research and Exploration (MTA) of Turkey in Ankara.

Followed by water quality analysis, a vector-based GIS software package MapInfo was used to map, query, and analyze the data in this study. Visual MODFLOW 4.2 is used for the groundwater flow simulation.

Results and discussion

The delta hosts a large number of water-wells with depths varying from a few meters to nearly 250 m. Most of these wells, which tap a multilayered aquifer made up of Quaternary sands and gravels, supply water for gardening and irrigation, while some are exploited by industry, though only a few for drinking water. It is difficult to state whether the sandy and gravelly aquifers are actually separated in the study area. Due to the geological evolution, with a succession of marine, continental and transitional facies, significant lateral and vertical variations in grain size can occur.

Average water-level fluctuations are not greater than 1 m between dry and wet seasons since 1999. The general direction of groundwater flow is from north to South and east. Horizontal hydraulic conductivity varies between 4.2 and 485 m/day[4].

As field observations are restricted by the density of the measurement points, the flow of groundwater was determined through a three-dimensional model developed by the finite-difference program MODFLOW. MODPATH was calculated the advective pathlines of the water particles. Visual MODFLOW is the most complete, and user-friendly, modeling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulation. A numerical simulation under steady-state provided an understanding of the groundwater behavior in the area. Prior to any interpretation, the model was calibrated against the observed water-level data. Initially, calibration was done by adjusting a set of hydrologic parameters to achieve an even better match between observed and calculated heads. For the Flow Simulation MODFLOW-2000 is selected. As the Background Map the geological map is used and for discretization of model domain 52*32 Finite Difference Grid are used. The size of the grids are 500*500 m but in some places the grid size are refined as 100*100 m (Fig. 3). The northern part of alluvial aquifer (Taurus Mountains) is defined as inactive zones (no-flow cells) within the model domain and the Mediterranean sea is a constant head boundary.

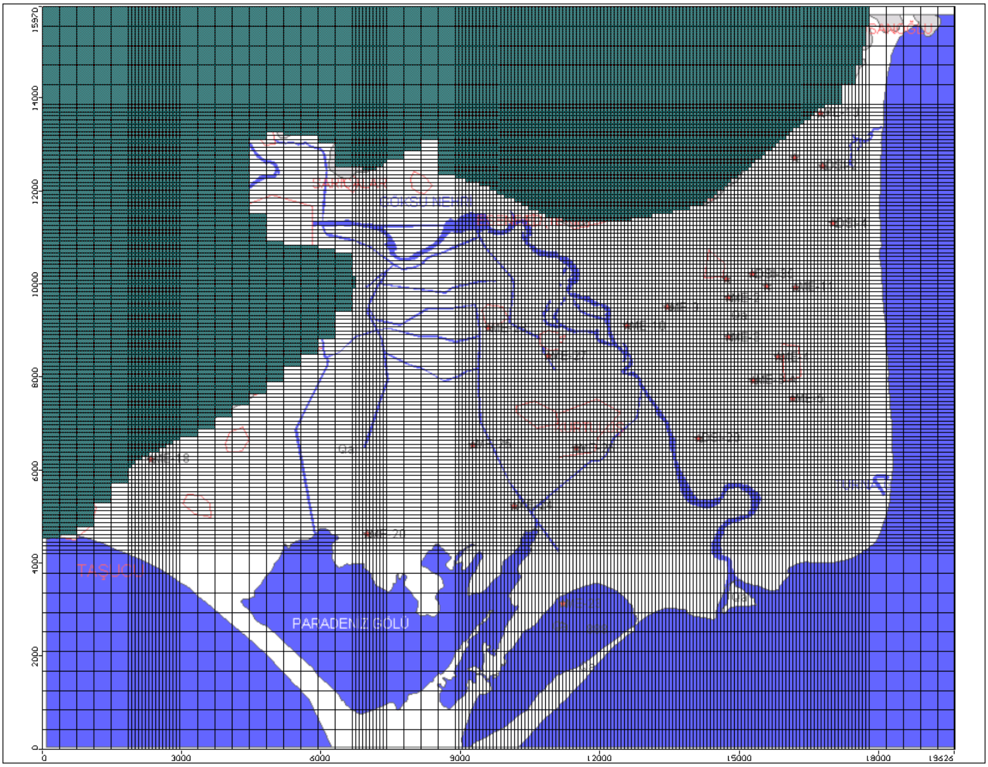

Figure 3: Discretization of aquifer

Visual Modflow calculate the permeability countours for whole model area and use this thematic map for simulation. Effective porosity for alluvial aquifer is expected to vary between 25 and 30%. The result of steady-state flow simulation show that the groundwater flow to south and east directions as expected (Fig. 4).

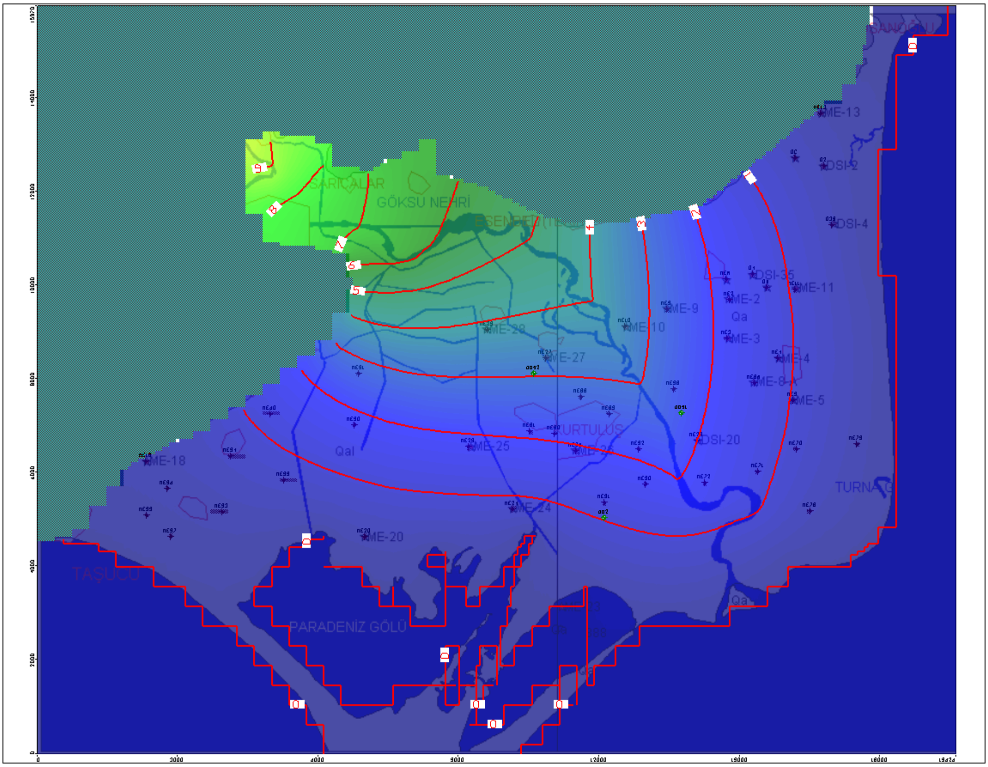

Figure 4: Groundwater flow and water table map (Result of simulation)

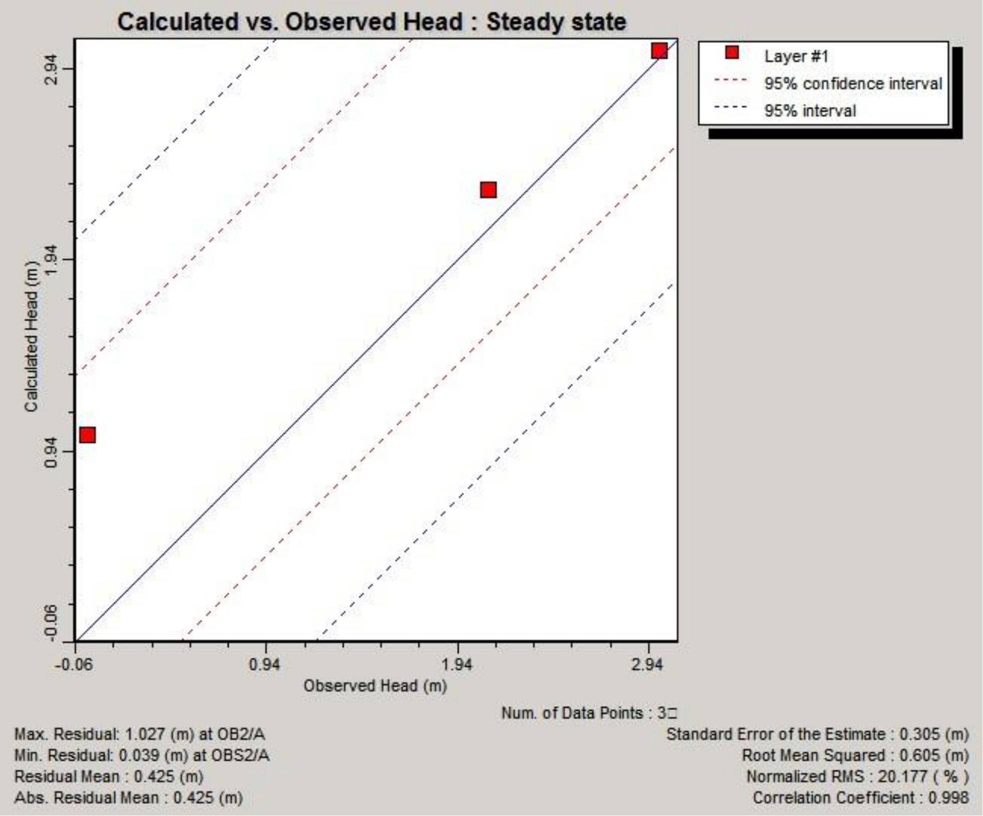

Figure 5: Results of model calibration

The result of simulation is controlled and calibrated by the comparation of calculated heads versus observed heads (Fig. 5). Figure 5 shows that there are a good match between observed and calculated heads.

Patterns of groundwater movement

The computer program MODPATH was developed by the USGS to calculate three-dimensional particle tracking pathlines from steady-state and transient flow simulation output obtained using MODFLOW.

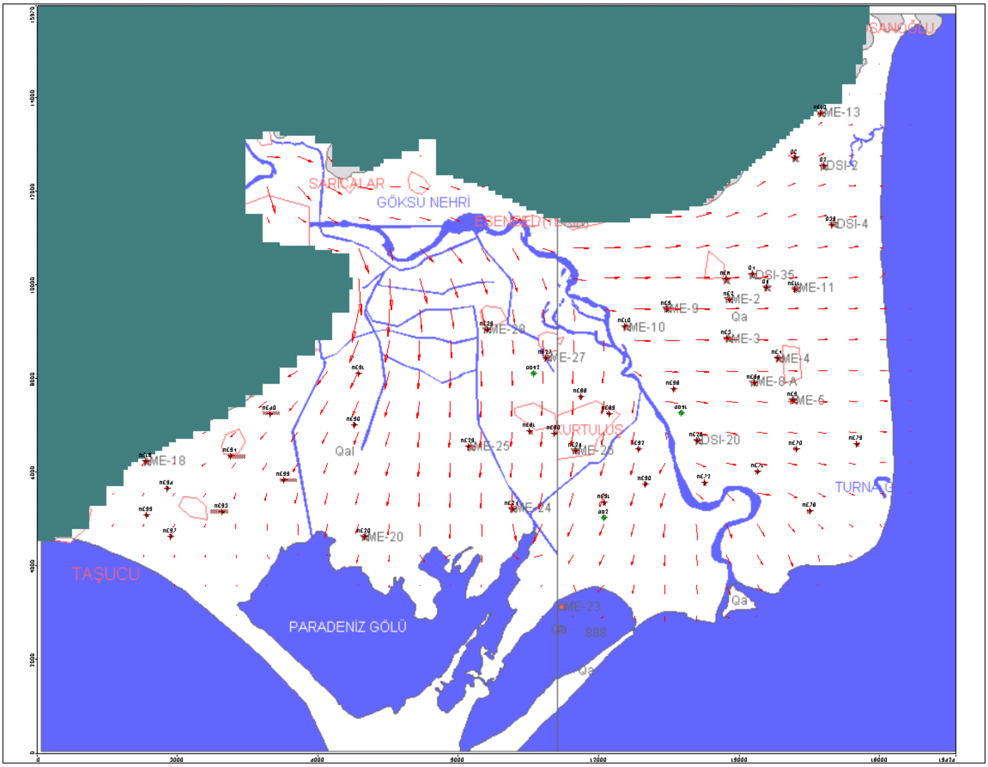

Figure 6: The vectors of groundwater flow velocities

The particle-tracking scheme also facilitated the calculation of travel times along the flowpaths. Calculated velocities generally increase from South to North along the flow lines, in direct response to variations in the land gradient. Movement in the uplands is greatest in the upper sands with maximums of about 3.4 10^{-5} m/s (Fig. 6).

In the eastern part of the study area some of the wells are polluted by heavy metals. The flow paths of 5 years travel time by back tracking indicate to the Göksu River as pollution source (Fig. 7). In the western part of the study area the land is used intensively by agriculture. The pollutans which leach in the groundwater in this area are transported by advection in 5 years to the Akgöl lake (Fig. 7).

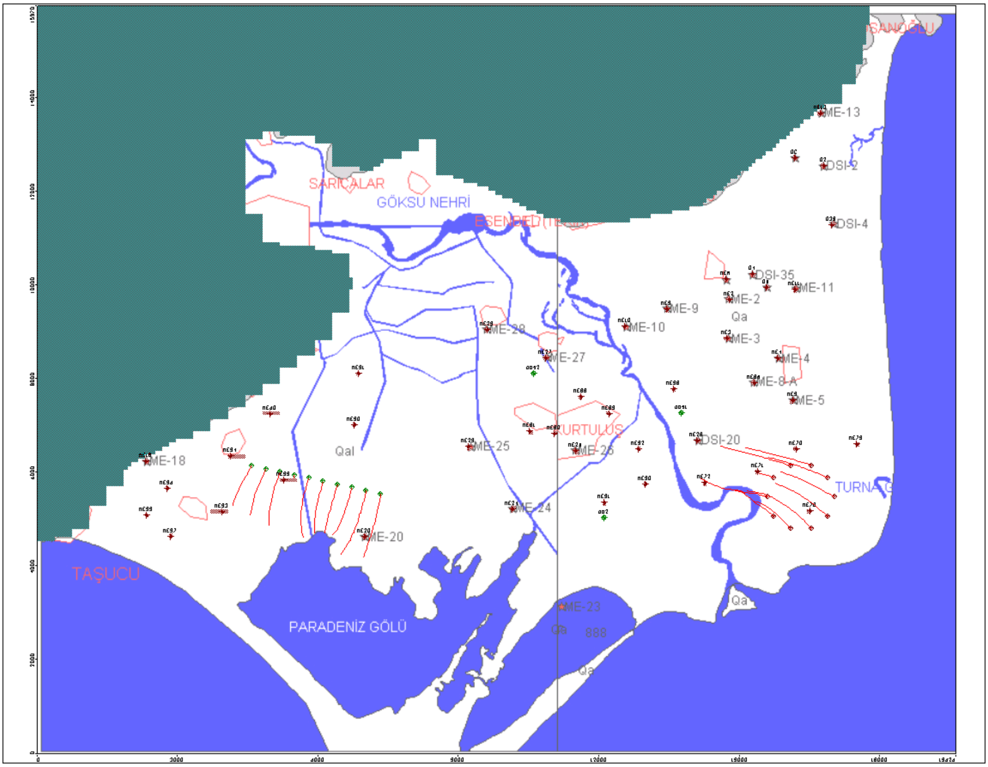

Figure 7: Groundwater flow path for 5 years of travel time

Hydrochemical characteristics

The major and minor and trace element ion concentrations of the water samples collected in September 2006 are listed in Table 1. The composition of groundwater is influenced by many processes, including wet and dry deposition of atmospheric salts, evapotranspiration, and water–soil and water–rock interactions [6]. Chemical properties of shallow groundwater in the alluvial aquifer of the Göksu Delta are controlled both by natural geochemical processes and anthropogenic activities. Under the influence of anthropogenic processes, the groundwater chemistry in this agricultural region can be substantially changed, which makes the understanding of the hydrogeological system more difficult.

The groundwater samples collected from the Göksu Delta are colorless, odorless and free from turbidity. The temperature of the groundwater in Göksu aquifer changes between 8.8 and 30.9°C and it depends very strongly on the atmospheric conditions.

Paradeniz Lake is a saltwater lagoon connected to the sea and the chemistry of Paradeniz water is similar to the Mediterranean Seawater. The EC values of sea water and lake water are 53000 μS/cm and 48000 μS/cm, respectively.

The types of groundwaters from alluvial aquifer are Ca-Mg-HCO_3 , but in the region where sea water intrusion occures it changes and the Na and Cl ions are added in the types of groundwater . The similar occurence can be observed in the groundwater from the limestone aquifer. The types of groundwater are Ca-HCO_3 or Ca-Mg-HCO_3 and they change to Ca-Na-Mg-HCO_3-Cl in the vicinity of seawater intrusion regions.

Groundwater samples were plotted on a Piper diagram (Fig. 8) and three hydrochemical types identified. Upstream of the Göksu Delta aquifer a Mg–Ca–HCO3 type is identified. Downstream, groundwater evolves to Ca–Mg–HCO3–Cl and Na–Ca–Mg–Cl–HCO3 types along the flow path and is accompanied by a gradual increase in the groundwater total dissolved solids (TDS) content, mainly controlled by sea water intrusion.

With very few exceptions, sample points fall within the mixing field of the Piper diagram (Fig. 8). Three regions are distinguished in the diagram. First region where the samples ME3 and ME 28 are placed show the aquifer region where the seawater intrusion does not occurre. The second place, the central of the Piper diagram where the samples ME1 and ME 20 are shows the aquifer region where the sea water impact begins. The third place,is very close to the Sea water sample ,where the samples ME 12 and ME 23 are shows the aquifer region where the sea water intrusion occurrs. The samples ME12 and ME23 are very close to the Sea and Paradeniz waters.

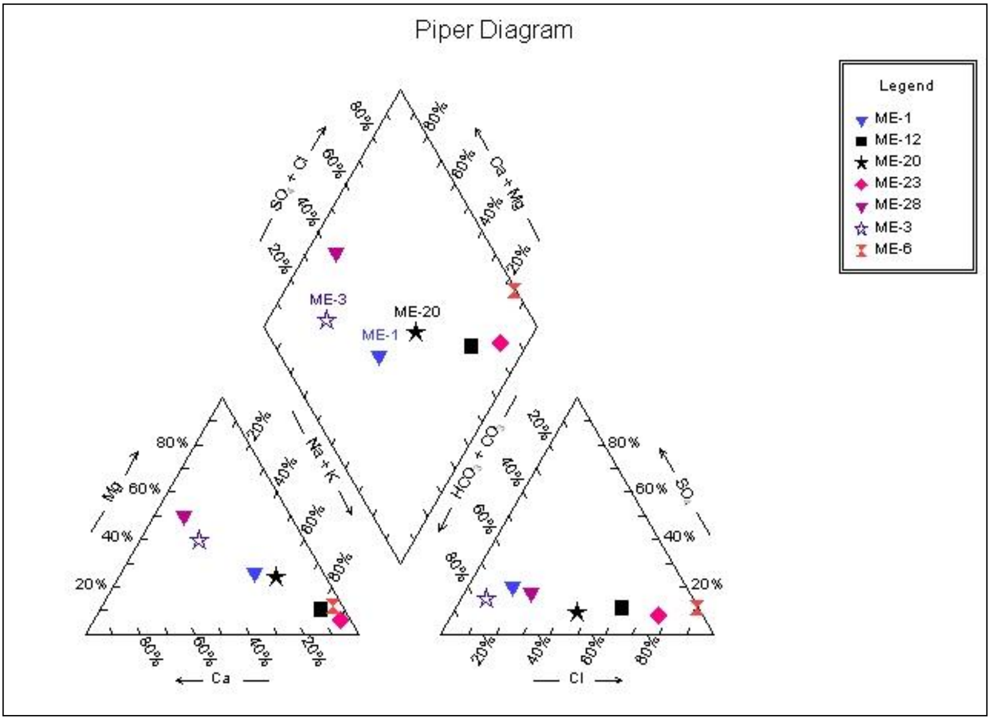

Figure 8: Piper diagram

Inverse geochemical modelling of hydrochemical data for groundwater samples collected in the study area, demonstrates an integrated approach to the assessment of hydrogeochemical processes in a regional aquifer system. The Aquachem software was additionally used to calculate the mineral saturation indices which indicate the tendency of groundwater to dissolve or precipitate a set of minerals. AquaChem is a software package developed specifically for graphical and numerical analysis and modeling of water quality data. In addition, AquaChem features a built-in link to the popular geochemical modeling program PHREEQC for calculating equilibrium concentrations (or activities) of chemical species in solution and saturation indices of solid phases in equilibrium with a solution.

Table 2: Calculated mineral saturation indices

Well number	Aquifer	Calcite	Dolomite	Quarz	Gibs
ME-9	Alluvium	0.3019	1.0354	-1.1781	-2.0801
ME-1	Alluvium	0.3264	0.79	0.9074	-1.6782
ME-12	Alluvium	-0.0428	0.1041	0.337	-2.0746
ME-20	Alluvium	0.12	0.4515	0.5658	-2.345
ME-23	Alluvium	0.0634	0.4718	-0.3112	-2.4293
ME-24	Alluvium	0.458	0.7203	-0.0213	-2.5723
ME-26	Alluvium	0.1198	0.5183	0.4312	-2.6016
ME-28	Alluvium	-0.0541	0.095	0.7005	-2.0798
ME-3	Alluvium	0.2786	0.6797	0.2656	-1.9478
ME-18	Alluvium	-0.0815	-0.3758	0.2543	-2.0884
ME-14	Limestone	-0.0045	-0.617	-0.3419	-2.1378
ME-16	Limestone	-0.0787	-0.272	0.1724	-2.2019
ME-21	Limestone	-0.0501	0.0336	0.7077	-2.1102

As seen in Table 2 the groundwater within alluvium is super saturated by calcite and dolomite.

Table 3: Ionic ratios and origin of water

Well number	HCO_3/SiO_2	Explanation	Mg/(Ca+Mg)	Explanation
ME-1	10.753	Carbonat weathering	0.514	Dolomite weathering
ME-12	27.189	Carbonat weathering	0.559	Dolomite dissolution, Calcite precipitation or Sea water
ME-20	11.96	Carbonat weathering	0.570	Dolomite dissolution, Calcite precipitation or Sea water
ME-23	83.778	Carbonat weathering	0.638	Dolomite dissolution, Calcite precipitation or Sea water
ME-24	42.130	Carbonat weathering	0.339	Limestone-Dolomite weathering
ME-26	10.114	Carbonat weathering	0.576	Dolomite dissolution, Calcite precipitation or Sea water
ME-28	7.373	Unknown	0.566	Unknown
ME-3	35.241	Carbonat weathering	0.507	Dolomite weathering
ME-18	25.548	Carbonat weathering	0.333	Limestone-Dolomite weathering
ME-14	32.353	Carbonat weathering	0.164	Limestone-Dolomite weathering
ME-16	33.403	Carbonat weathering	0.388	Limestone-Dolomite weathering
ME-21	9.105	Unknown	0.521	Unknown

HCO_3/SiO_2 ratios ranged from 10.7 to 83.7 (except two samples), which suggests carbonate weathering (Table 3). The Mg/(Ca+Mg) ratios suggest either a sea water origin and dissolution of dolomite and/or limestone.

Conclusions

This paper provides an improved understanding of the groundwater flow and the pathways and also of the factors that control the chemical composition and groundwater quality of groundwater in the shallow Quaternary alluvial aquifer of the Göksu Delta as influenced by water–rock interactions within the alluvial sediments. Despite some human influence having been detected, mainly due to agricultural activities, the chemical composition of the groundwater is mainly controlled by natural hydrogeochemical processes. The sea water intrusion is also one of the important factors for the quality of groundwater.

The Mg–Ca–HCO3 type is found upstream of the Göksu Delta whereas, downstream, groundwater evolves to Na-Ca–Mg–SO4–HCO3–Cl type along the groundwater flow path. These changes are controlled by the sea water intrusion.

This study demonstrates that the combined use of major ion chemistry, saturation index calculations and inverse geochemical modelling can successfully interpret hydrochemical processes in a regional aquifer system.

Groundwater is an indispensable resource for water supply for the towns on Göksu Delta, for the urban and for the agriculture. The salinization of the freshwater resources has seriously impeded the development of industry, agriculture and the improvement of the people’s living standards in this internationally protected region.

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