Annex 5

Groundwater Model Methodology

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1. Background Information

1.1 General Geology of the Coastal Aquifer

Gaza aquifer is part of the regional coastal aquifer which lies along the south eastern edge of the Mediterranean Sea and extends from the foothills of Mt. Carmel southward to Gaza and Northern Sinai. It is composed of Pliocene-Pleistocene age calcareous sandstone, unconsolidated sands, and layers of clays. In the Gaza Strip, the aquifer extends about 15–20 km inland, where it overlies Eocene age chalks and limestone or the Miocene-Pliocene age Saqiye Group. The Saqiye Group is a 400–1000 meter thick sequence of marls, marine shales, and clay stones. Approximately 10 to 15 km inland from the coast, the Saqiye Group pinches out, and the coastal aquifer rests directly on Eocene chalks and clastic sediments of Neogene age. Figure 1 presents a generalized geological cross-section of the coastal aquifer.

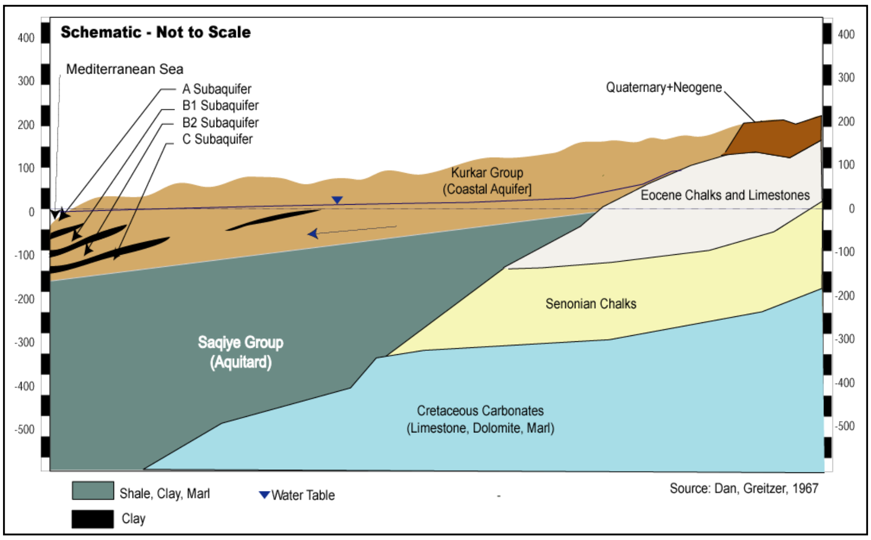


Figure 1: Generalized geological cross section of the coastal aquifer.

Near the coast in the Gaza Strip, clay layers subdivide the coastal aquifer into four separate sub-aquifers (Figure 1). They extend inland about 2 to 5 km, depending on location and depth. Further east, the marine clays pinch out and the coastal aquifer can be regarded as one hydro-geological unit.

Within the Gaza Strip, the thickness of the Kurkar Group increases from east to west, and ranges from about 70 m near the Gaza border to approximately 200 m the coast. Low permeable layers are found in the Kurkar group. These layers are more predominant closer to the coast.

1.2 Geotechnical Information in the Infiltration Basin

Field investigations had been carried out on the proposed infiltration site by SWECO, 2003, in addition, in 2010; PWA had finished the construction of 5 monitoring wells of the infiltration basin. Based on the information collected from the past investigations in the project area, five boreholes were drilled in a distance of 500 to 1000 m from the basin to complete the design of the recovery scheme.

All information collected from SWECO, PWA investigation, the past design project served as a fundamental source of information for the evaluations and conclusions of the current groundwater model and the SESIA report. A summary of the most important results is given in this section.

2. Groundwater Model

2.1. Software Description

Previously, there have been three modelling exercises related to the study area:

1) A regional groundwater model has been constructed for the southern part of the coastal aquifer focusing on Gaza strip and using the DYN software. This was a MS-DOS based software manufactured by CDM-consultants and is limited to the use of PWA and CAMP project.

2) A local groundwater model has been constructed for the hydrogeological evaluation of the infiltration system. The consultant (VA-Project AB, Sweco Viak AB and an under consultant at Tyréns, all in Sweden) has used MODFLOW. Modflow with its connected modules is a commercial product and operates in a Windows environment. It has been on the market for about 10 years and is well established. It is fully available for PWA and consultants.

3) Groundwater model of the Northern area for NGEST project under EA 2006 study. Visual Modflow (VMF) version 4.2 and its integrated modules were chosen. VMF is based on the finite-difference code MODFLOW (Harbaug & McDonald 1988) and contains four integrated modules: MODFLOW – Groundwater flow model, ZONE BUDGET – Water balance within user defined zones, MODPATH – Particle tracing and MT3D (Model Tracking 3D) – Substance or solute transport.

4) In the design of the recovery scheme 2010, the model used by EA is considered as the base of further modeling activities in that project. The conceptual model was considered valid, however, the modeling procedures were repeated for further calibration and verification of the model by input of new data from year 2004 until 2008.

5) In the current project for preparing the SESIA report, the same conceptual model used for the design of the recovery scheme is considered valid. The input data was updated for the last two years and up to year 2010. The groundwater level of 2011 was not considered since after review the raw data from PWA/Gaza office, the data was unrealistic in comparison with groundwater level data in year 2010. In general, the value of year 2011 data are greater than that in year 2010 which are not correct.

2.2. Conceptual Model

2.2.1. Model domain and boundaries

Based on the previous modelling efforts and the simulated water level contours for the year 2004, the model domain was chosen to fit stable boundary conditions. The Model Domain encloses an area of 17 x 23 km in the northern part of the Gaza Strip. Figure 2 shows the selected model domain as part of the coastal aquifer.

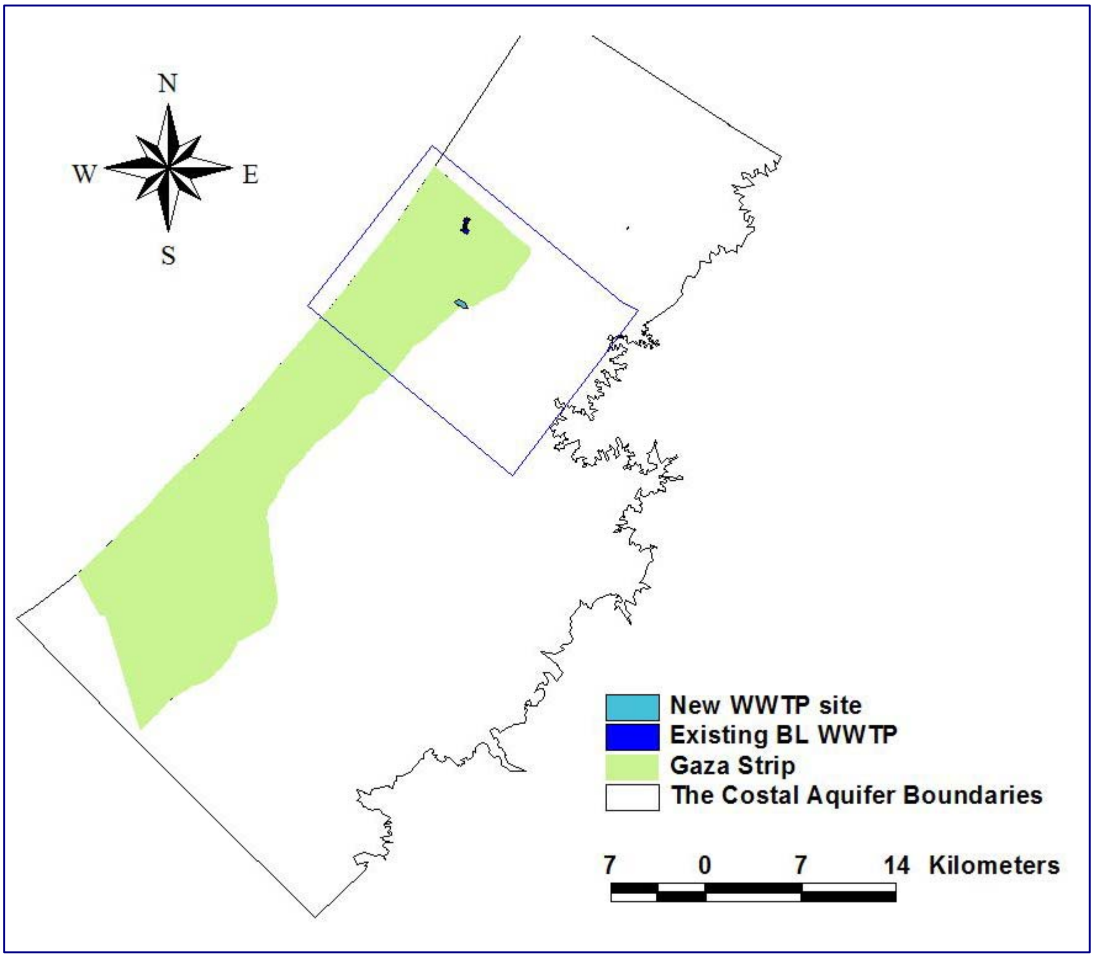


Figure 2: Model domain and boundaries

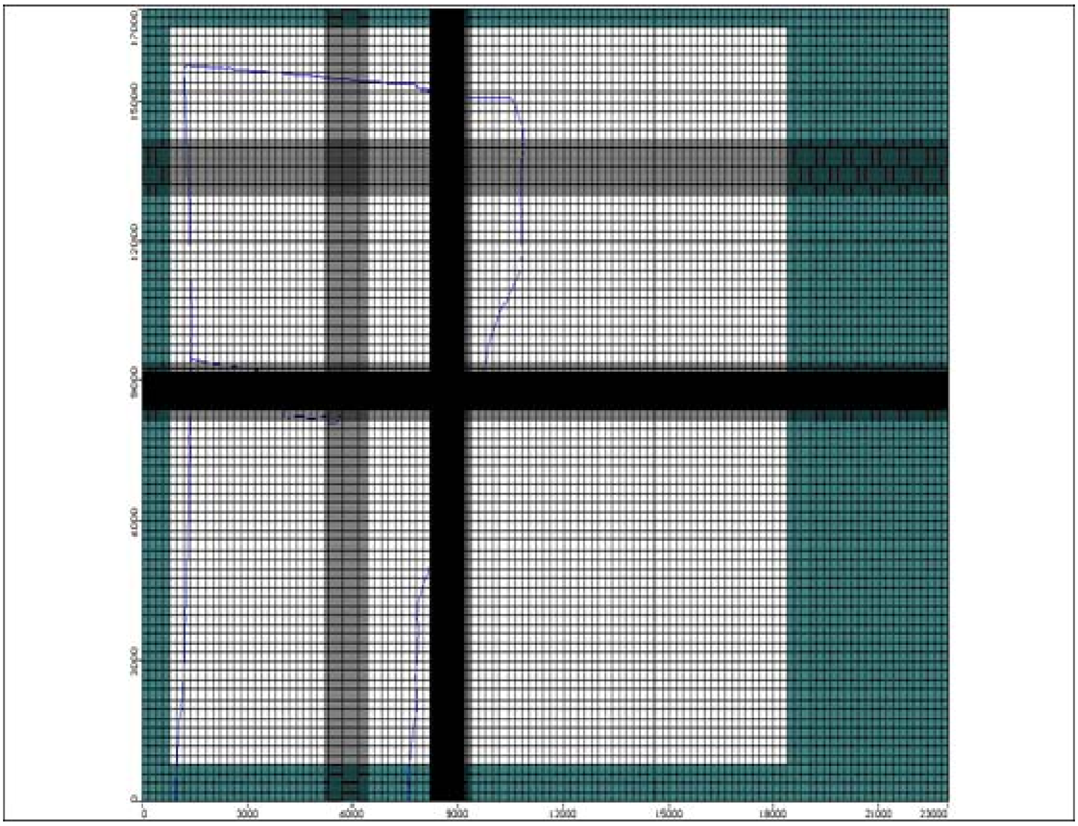


Figure 3: Model grid and the grid of the Infiltration Basin

Hydro-geologically there is not sufficient information available for the entire model domain. Therefore primary effort has been made finding data for the central part of the Model Domain. This is the area that will be affected by the infiltration water within a time of a few decades. The reason for expanding the Model Domain beyond the Data Area is to minimize the effects of Model Boundaries in the central part of the Model, the area of interest.

The model domain is divided into a horizontal grid with cell size 50x50 m at the BLWWTP site and 20 x 20 m at the new NGWWTP site and the cell size then increases gradually towards the model boundaries (Figure 3).

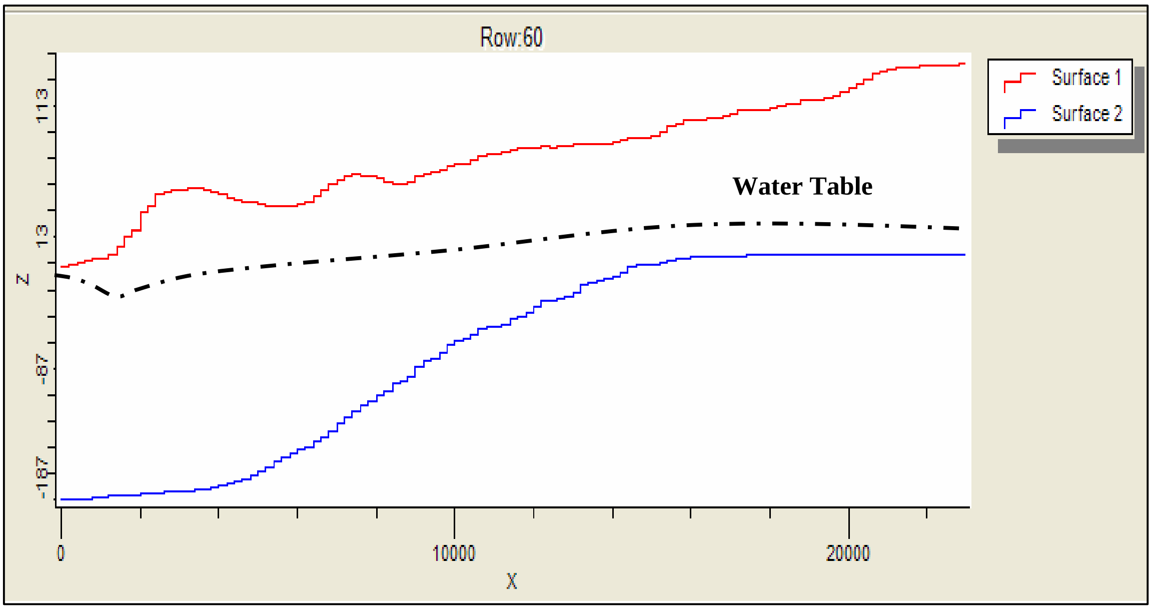


Figure 4: Bottom of the aquifer and the ground surface elevation

The model boundaries can be described as follows (Figure 3):

- East: General Head Boundary
- West: Constant Head Boundary
- North and South: No Flow Boundary

The lower boundary of the model consists of Saqiye's surface (see Figure 4). This has been adopted based on the regional DYN model consideration and the results from geophysical investigations, and borehole investigation at the site (DB4).

2.2.2. Stratigraphy

Although the greater part of the Gaza strip has a topsoil of stiff clay, the pumping test at the site (August 2002 in well DB4) clearly indicates that the aquifer is an unconfined, phreatic aquifer. Furthermore, clayey and silty layers have been found on the site during soil investigations by drilling. The layers are found both in the unsaturated and saturated zone. The arial continuity and hydraulic permeability of these layers do, however, not lead up to the conclusion that the aquifer is divided into several hydraulically separate sub aquifers. Instead, the **one aquifer approach is supported**.

The CAMP model final report indicates that the top clay layer extends up to 2 km inland. The second clay layer extends up to 1.5 km and the third deep clay layer extends up to 3.5 km inland. The average depths of those layers are -60, -100, and -130 to -60 respectively. Most, if not all, of the wells, screens are located above the deep clay layer. SWECO INT. in the previous modelling effort has indicated that the extent of infiltration influence is about 3 km in 20 years. In other words, the influence area is far from the coastal area where the thin clay layers separates the aquifer into three sub-aquifers. **Hence a single layer model will serve the purpose of the study.**

2.2.3. Recharge Components

A GIS module is designed to calculate the net recharge to the aquifer in winter days and in summer days. The net recharge comprises of; recharge from rain, irrigation return flow, water networks losses, wastewater leakages, existing treatment plants and recharge basins, and recharge from treated wastewater irrigation in the Israeli side of the model. The details are illustrated below:

2.2.3.1. Recharge from rain:

Recharge from rainfall was quantified as the average seasonal rainfall multiplied by an infiltration factor. Based on the rainfall records from 15 rainfall stations, Thiessen polygons interpolation method was used to calculate the aerial rainfall distribution over the model domain cells. The value of the rainfall in each cell is then multiplied by the infiltration factor based on the soil type. Infiltration coefficient 0.6, 0.25, 0.2 for clay, Loess, and Sand soil types (M&E, 2000 and OALS/IALC, 2001). Infiltration factor for impervious surfaces was considered zero.

2.2.3.2. Recharge from irrigation:

In the CAMP model report, it was assumed that 0.25 of water pumped for irrigation return to the aquifer in Gaza area. The same assumption was considered in the Israeli side for irrigated agriculture.

For Israel since we do not have the exact land use map, 80% of the land where we have irrigation wells is assumed to be irrigated (See the land use map of Israel, http://www.1uptravel.com/worldmaps/israel8.htm, for crop information). For Israeli part of the model, three water sources were considered: 1) irrigation directly from rainfall, the recharge from that is taken into consideration while calculating recharge from rain. 2) Irrigation from wells, 0.25 of the pumped water is assumed to return to the aquifer. 3) Recharge from wastewater reuse network at the far east of the model domain which was estimated at 35 MCM.

2.2.3.3. Recharge from un-piped wastewater:

In areas not connected to wastewater networks, people use septic tanks or cess/percolation pits to dispose their sewage. From 70% to 75% of the Northern Governorate population are connected to wastewater networks (Boliden Contech and Montgomery Watson, 1999; LEKA, 2003). Most of the produced un-piped sewage seeps to the aquifer through the percolation pits. The rest is transported to the wastewater treatment plant via tanker trucks. 80% of the water consumption is assumed to be a non-consumptive use and thus turns into wastewater. In each area the produced wastewater is multiplied by a seepage factor (1-network connection percentage) to estimate the leakage into the aquifer from the un-piped sewage (M&E, 2000).

2.2.3.4. Recharge from piped wastewater:

Piped wastewater is assumed to reach the treatment plants in the model domain area. The quantity recharged from each treatment plant is taken as recorded by other studies (M&E, 2000).

From Gaza wastewater treatment plant = 6,000 – 10,000 m^3/day
From Beit Lahia wastewater treatment plant and the pond = 6,000 – 8,000 m^3/day

2.2.3.5. Water supply network losses recharge:

This was calculated based on water consumption and the physical water supply network losses in each area in the model domain. Records indicate that the total annual water supply in the Gaza and the Northern Governorate is about 40.5 MCM (PWA, 2004). Physical losses are estimated at 30% in these areas (PWA, 2004).

Figures 4 and 5 show the GIS distribution of the 2002-2003 hydrologic year total recharge rate in winter and summer respectively. Figure 6 shows the recharge rate in year 2004 where all changes due urbanization in the northern area was considered in the map.

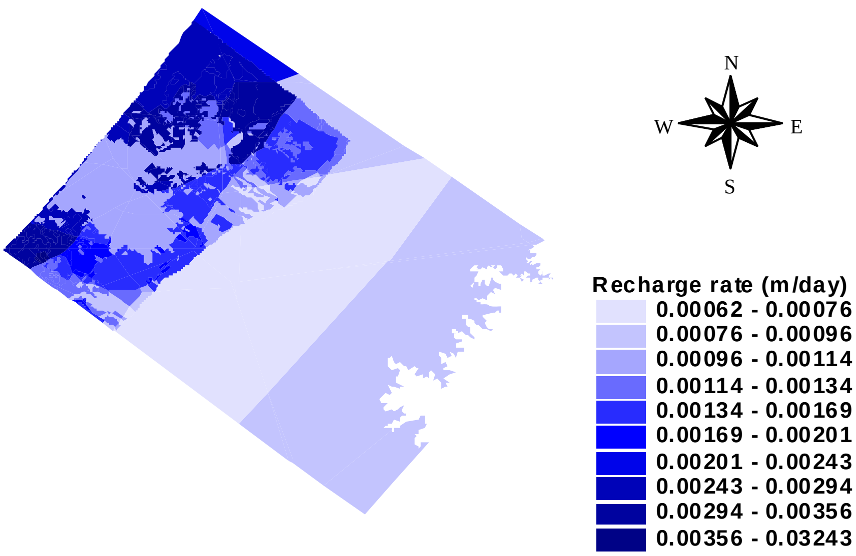


Figure 4: Recharge rate grid during winter 2002-2003 (EA, 2006)

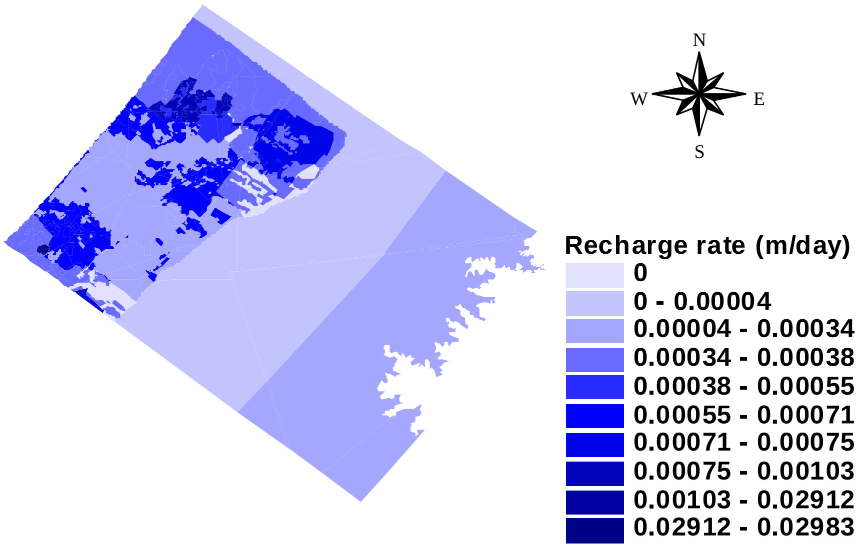


Figure 5: Recharge rate grid during summer 2002-2003 (EA, 2006)

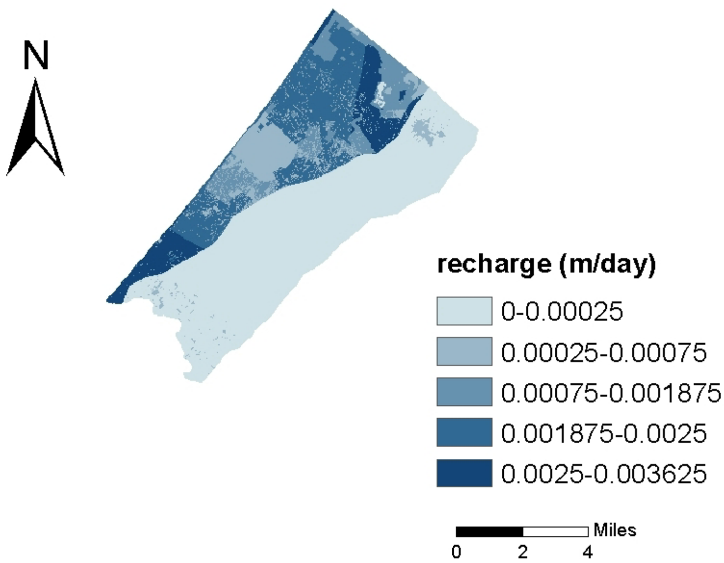


Figure 6: Recharge rate during year 2005 (m/day).

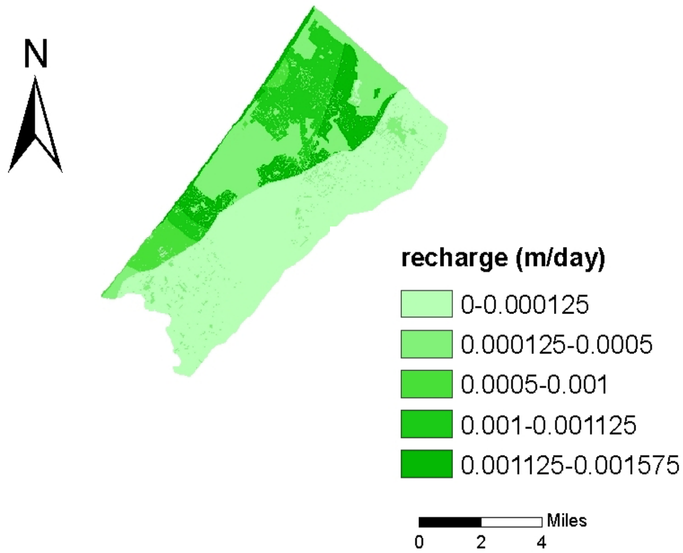


Figure 7: Recharge rate during year 2010 (m/day).

Based on the GIS recharge grid distribution, 24 recharge zones (Figure 7) were considered for the MODFLOW input. Each zone carry different values based on annual and seasonal recharge values.

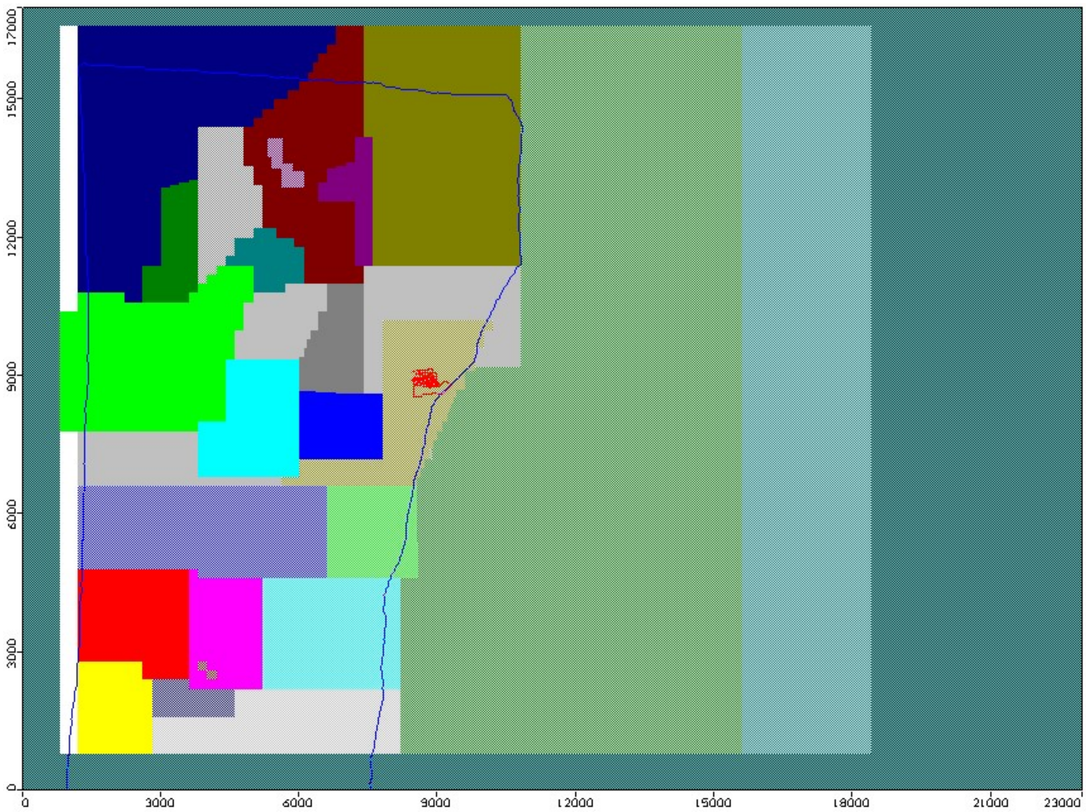


Figure 8: MODFLOW recharge zones for year 2010

2.2.4. Abstraction Components

Within the model area, 1185 agricultural wells have been defined and parameterized with a given average discharge based on available data (data from PWA and Ministry of Agriculture). In addition 100 domestic wells were also recorded based on data from Coastal Municipality Water Utility (CMWU). The abstraction from domestic wells is recorded monthly. Table 1 shows the average yearly abstraction rate from domestic wells. Very limited data is available about agricultural wells abstraction. In most of agricultural wells the abstraction rates were estimated based on information from Ministry of Agriculture about irrigated areas, crop patterns, and crop water requirements.

The 34 wells which were selected as head observation wells for the model regional calibration in the previous model is still used in the following calibration procedures (Figure 9). The selection was based on the availability of good hydrograph for these wells. More details are presented in the calibration section. It is important to note that the abstraction rate was kept as in year 2011 for the years up to 2025 since the reply on the aquifer will either be kept as in year 2011 due the fact that quality of the aquifer becomes highly deteriorated, or decrease since the resources for drinking water will be from desalination plants. The recharge rate was kept as year 2010 for prediction which is shown in Figure 7. The assumption used gives more safety factor the results of the model with concern to the extent of the pollution plume.

Table 1: Yearly Abstraction Municipal Wells

	Yearly Total Abstraction (m^3/year)							
	2004	2005	2006	2007	2008	2009	2010	2011
100 wells	44,857,962	42,337,345	46,783,858	45,348,932	43,757,892	46,054,107	60,101,764	57,009,902

Table 2: Municipal wells average abstraction rate

No.	Well Name	Yearly Average Abstraction (m^3/day)							
		2004	2005	2006	2007	2008	2009	2010	2011
1	F.191	-2639	-947	-1355	-2639	-79	-1218	-1200	-1200
2	A.180	-1748	-2076	-2456	-1810	-1786	-1786	-2466	-1854
3	A.185	-4489	-4647	-3437	-3040	-3812	-3812	-3435	-3041
4	C.127	-1169	-1502	-1149	-2124	-1358	-1358	-3049	-3278
5	C.128	-1706	-2235	-2234	-2100	-1981	-1981	-1449	-1760
6	C.76	-315	-425	-330	-427	-397	-397	-484	-471
7	C.79	-6	-221	-962	-1112	-1378	-1378	-1613	-1608
8	D.60	-1700	-1659	-2111	-2474	-2919	-2919	-2078	-1828
9	D.67	-4068	-1614	-3897	-1438	-1287	-1287	-1346	-1425
10	D.68	-4238	-3866	-5287	-4614	-3866	-6040	-1563	-1563
11	D.69	-3841	-3529	-3394	-3841	-3529	-3394	-1535	-1535
12	D.70	-2533	-3011	-3490	-2533	-3011	-3490	-3603	-3603

No.	Well Name	Yearly Average Abstraction (m^3/day)							
		2004	2005	2006	2007	2008	2009	2010	2011
13	D.71	-5130	-4349	-3707	-5130	-4349	-3707	-3620	-3620
14	D.72	-4309	-4245	-3908	-4309	-4245	-3908	-3568	-3568
15	D.73	-2887	-1458	-3144	-2579	-2407	-2407	-2885	-2677
16	D.74	-4068	-1614	-3897	-4354	-3223	-3223	-3882	-2823
17	E.1	-1393	-1414	-1591	-1672	-3488	-3488	-2231	-1575
18	E.11A	-490	-490	-466	-362	-337	-337	-407	-305
19	E.11B	-1381	-1381	-691	-1167	-1193	-1193	-1374	-1223
20	E.11C	-724	-724	-826	-871	-931	-931	-1188	-1124
21	E.154	-3052	-2998	-2623	-3246	-2998	-2623	-3	-3
22	E.156	-3382	-4298	-4564	-4941	-3536	-3536	-4038	-2867
23	E.157	-3625	-4728	-4686	-4728	-4686	-4728	-4386	-4386
24	E.4	-2375	-2516	-2640	-2837	-2804	-2804	-2670	-2048
25	E.6	-1660	-1660	-1597	-1660	-1597	-1597	-1739	-1739
26	E.90	-4617	-4132	-4115	-4013	-3198	-3198	-3581	-2520
27	Q.40B	-2823	-2919	-2919	-2823	-2919	-2919	-2919	-2919
28	Q.68	-3919	-5595	-5498	-3919	-5595	-5498	-4962	-4962
29	R.162D	-837	-596	-1370	-837	-596	-1370	-988	-988
30	R.162E	-1628	-957	-1156	-1628	-957	-1156	-1031	-1031
31	R.162G	-4819	-4686	-4603	-4819	-4686	-4603	-4334	-4334
32	R.162H	-3309	-1560	-2005	-3309	-1560	-2005	-3309	-3659
33	R.162HA	-2830	-2389	-2648	-2830	-2389	-2648	-2094	-2094
34	R.25A	-2765	-2802	-2953	-2765	-2802	-2953	-3443	-3443
35	R.25B	-4445	-4445	-4198	-4445	-4445	-4198	-5027	-5027
36	R.25C	-1402	-2202	-2577	-1402	-2220	-2577	-1077	-1077
37	R.25D	-869	-2900	-4201	-869	-2900	-4201	-4008	-4008
38	R.74	-150	-100	-265	-150	-100	-265	-184	-184
39	D.20	-1965	-2401	-1981	-1981	-1981	-1981	-2654	-1777
40	R.112	-1670	-1732	-2011	-1670	-1732	-2011	0	0
41	R.254	-1620	-1555	-1789	-1620	-1555	-1789	-1527	-1527
42	R.265	-1328	-1006	-1184	-1328	-1006	-1184	-1430	-1430
43	R.113	-1921	-1687	-1713	-1921	-1687	-1713	-2099	-2099
44	F.192	-761	-583	-862	-761	-426	-426	-375	-375
45	R.75	-1744	-1421	-1786	-1421	-1786	-1786	-4071	-4071
46	R/162CA	-1427	-728	-1065	-728	-1065	-1065	-688	-688
47	R/162BA	-1164	-459	-1148	-459	-1148	-1148	-900	-900
48	C.137	-2699	-2699	-2885	-2885	-2885	-2885	-1963	-1963
49	C.155	0	0	0	-253	-253	-253	-664	-664
50	C.20	-849	-1025	-1025	-1025	-1025	-1025	-2174	-2174
51	A.211	-1420	-1420	-1350	-1350	-1350	-1350	-3440	-3440
52	A.205	-1823	-1823	1713	1713	1713	1713	-2585	-2585
53	D.75	-2834	-2834	-2988	-2988	-2988	-2988	-2849	-1822

No.	Well Name	Yearly Average Abstraction (m^3/day)							
		2004	2005	2006	2007	2008	2009	2010	2011
54	E.142.A	1424	1424	-1164	-1164	-1164	-1164	-2332	-1726
55	Q.72	-1755	-1755	-2584	-2584	-2584	-2584	-3288	-3288
56	E.164	-651	-308	-308	-651	-308	-308	-577	-304
57	E.168	-900	-643	-643	-900	-643	-643	-945	-658
58	A.210	-450	-450	-450	-450	-450	-450	-479	-479

Source: CMWU and PWA Data

No.	Well ID	Yearly Average Abstraction (m^3/day)		No.	Well ID	Yearly Average Abstraction (m^3/day)	
		2010	2011			2010	2011
59	D.77	-1573	-1573	80	R/306	-264	-264
60	E.171	-1670	-1670	81	R/307	-873	-873
61	Aslan	-438	-438	82	R/308	-513	-513
62	Zain	-1169	-1169	83	Sabra4	-82	-82
63	AlFateh	-978	-978	84	R/310	-695	-695
64	Hirah	-1364	-1364	85	R/305	-836	-836
65	AlBosna	-320	-320	86	Zaitoun3	-540	-540
66	R/162LA	-2922	-2922	87	Zaitoun4	-783	-783
67	R/162LB	-2757	-2757	88	R/313	-1224	-1224
68	E/154A	-1403	-1403	89	R/314	-1059	-1059
69	Sh.R.17	-1262	-1262	90	Remal3	-441	-441
70	R/66B	-273	-273	91	R/317	-1041	-1041
71	R/309	-770	-770	92	R/316	-1014	-1014
72	R/312	-809	-809	93	Remal7	-1013	-1013
73	Shijaia7	-1343	-1343	94	R/315	-432	-432
74	Shijaia8	-320	-320	95	AlTufaa2	-7	-7
75	Shijaia9	-773	-773	96	R/311	-592	-592
76	R/277	-1773	-1773	97	R/270	-415	-415
77	R/280	-395	-395	98	R/161	-488	-488
78	R/293	-793	-793	99	R/299	-651	-651
79	ShiekhEgleen8	-1046	-1046	100	R/300	-814	-814

2.3. Groundwater Model Update

2.3.1. Aquifer Properties

The default model parameters were set based on the calibrated parameters from the design project and from EA 2006 study. The pumping tests carried out in the design project indicated the following parameters based on which the model was recalibrated. Kxy has been initially set with a general value of 60 m/day in the proximity of the proposed infiltration site and 35 m/d else where in the model domain. Little adjustments have been made thereafter in specific zones in connection to model calibration. In the same way, Kz has been set for 3 m/day, Sy for 0.15, Ss for 0.00002 m-1, ne for 0.25, and total porosity for 0.35.

2.3.2. Steady State Model Calibration

Data from year 2004 was used for the steady state calibration at year 2004. The recharge and abstraction rates were estimated based on year 2004 data. The modeled water level was then calibrated based on level records for 34 observation wells distributed throughout the model domain (**Figure 9**). The steady sate model shows 95% agreement with the observed value (Correlation Coefficient = 0.95) as shown in Figure 10.

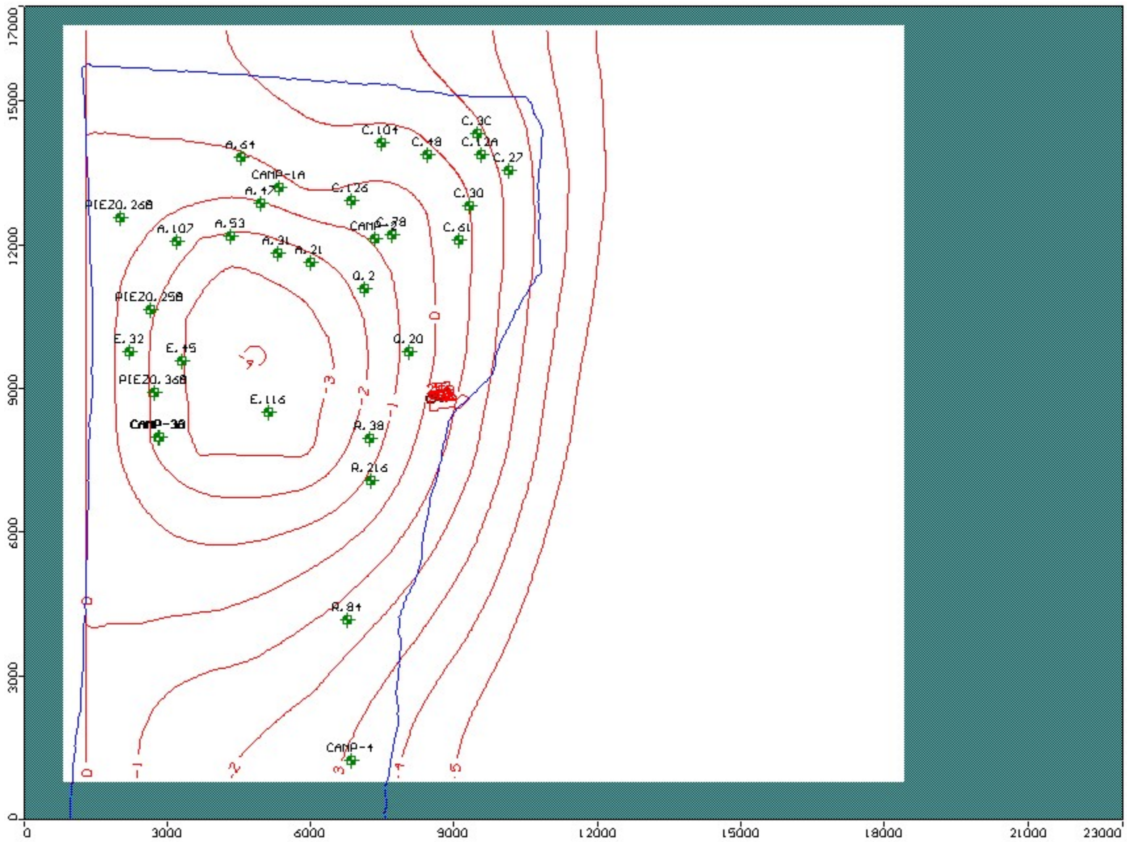


Figure 9: Steady state calibrated groundwater level contor map

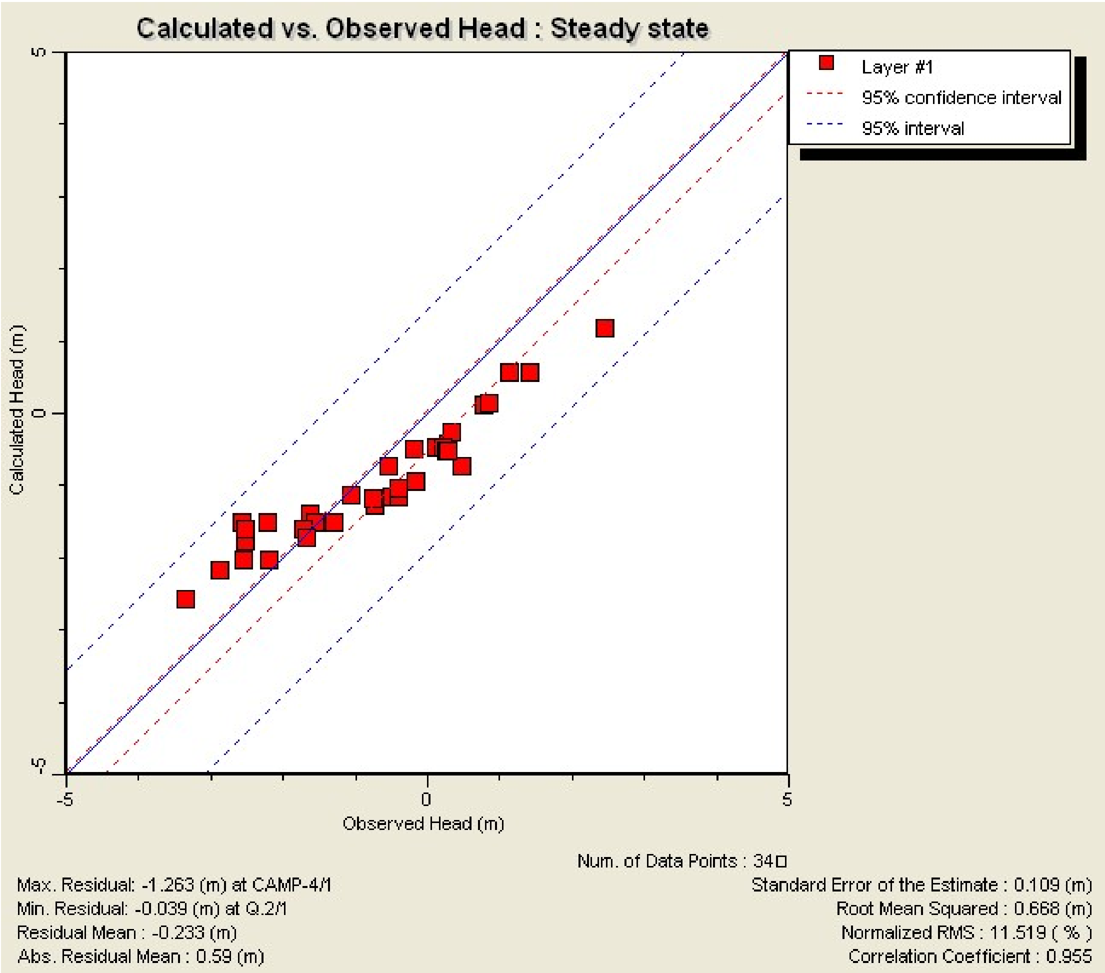
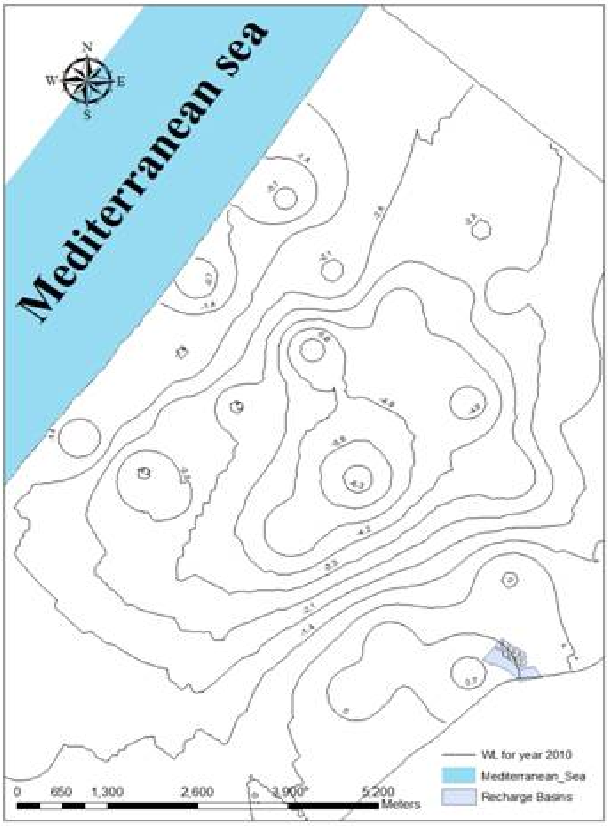


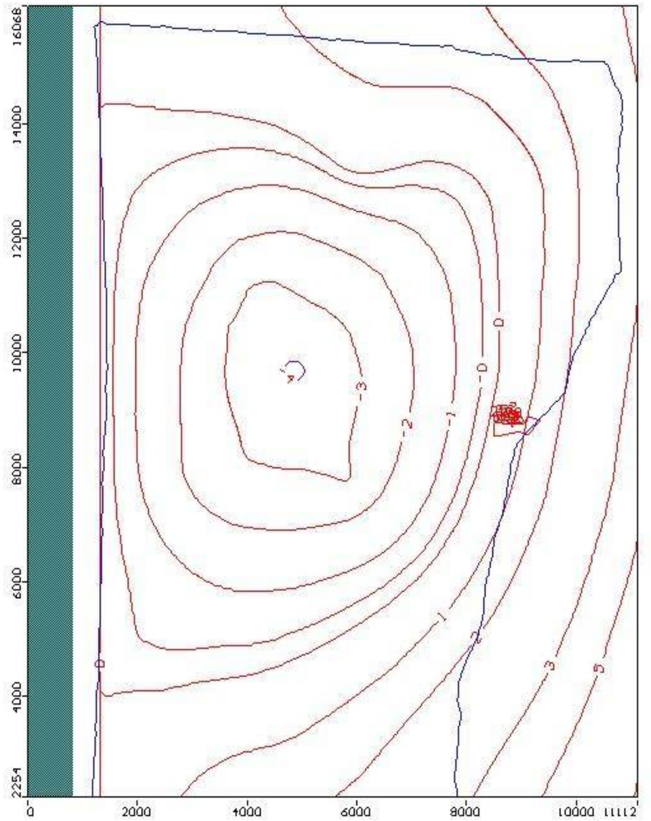
Figure 10: Steady State Calibration Results

2.3.3. Transient Flow Model Verification

Data from the period 2004 to year 2010 was also used for the transient model calibration. The abstraction and recharge components were earlier discussed. The same graph of the distribution of recharge rate used in the steady state is used in the current transient model. Since the aquifer properties were set based on the CAMP DYN model and the model developed by SWECO INT, the EA model and the design project model, the calibration was mainly performed based on the change of the abstraction of the wells which mainly highly influence the groundwater water level regime. The time step for the transient model was set daily. Figure 11 shows the modeled groundwater level contours at the end of year 2010 and the observed water level in the same year.



(a): Observed Groundwater level in year 2010



(b): Modeled Groundwater level contours in year 2010

Figure 11: Observed and (b) Modeled Groundwater Level Contours in Year 2010

Figures 12, 13 and 14 show the observed versus modeled water level hydrograph for wells A/47, Q/2 and R/38. Notice the summer and winter fluctuation of water level. Similar graphs are available for other wells in the model domain. The modeled water level showed good agreement with the observed water level both in the trend and in the value. The transient model shows 94% agreement with the observed value (Correlation Coefficient = 0.94) as shown in Figure 15.

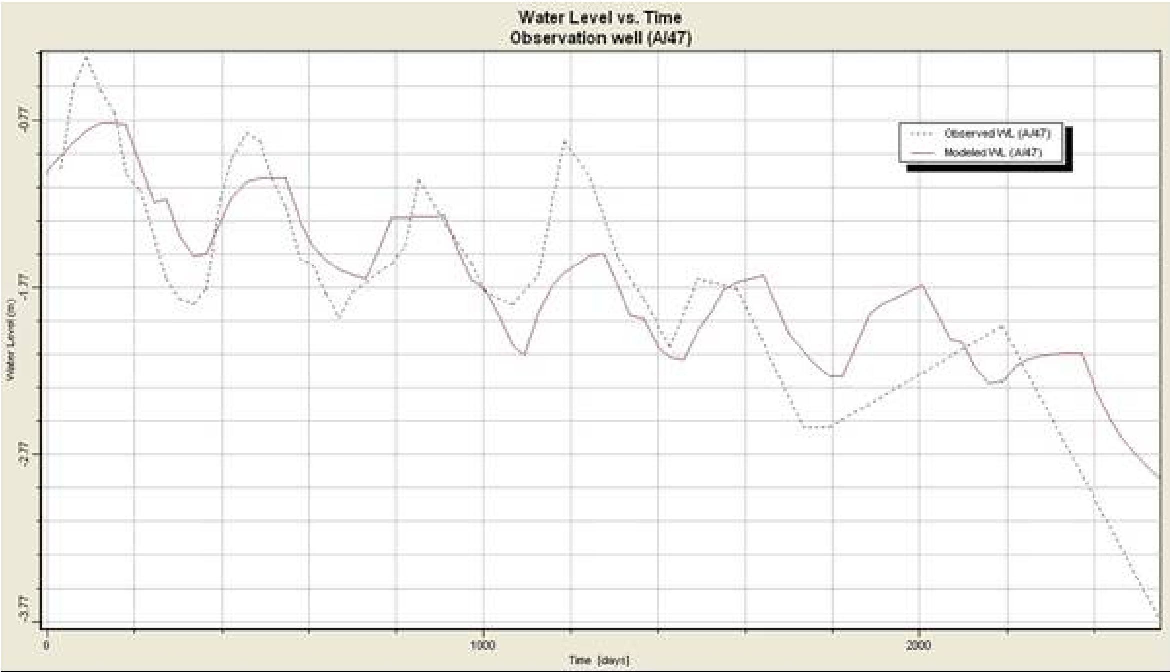


Figure 12: Observed vs. modeled water level for well A/47. Category axis shows days since 2004

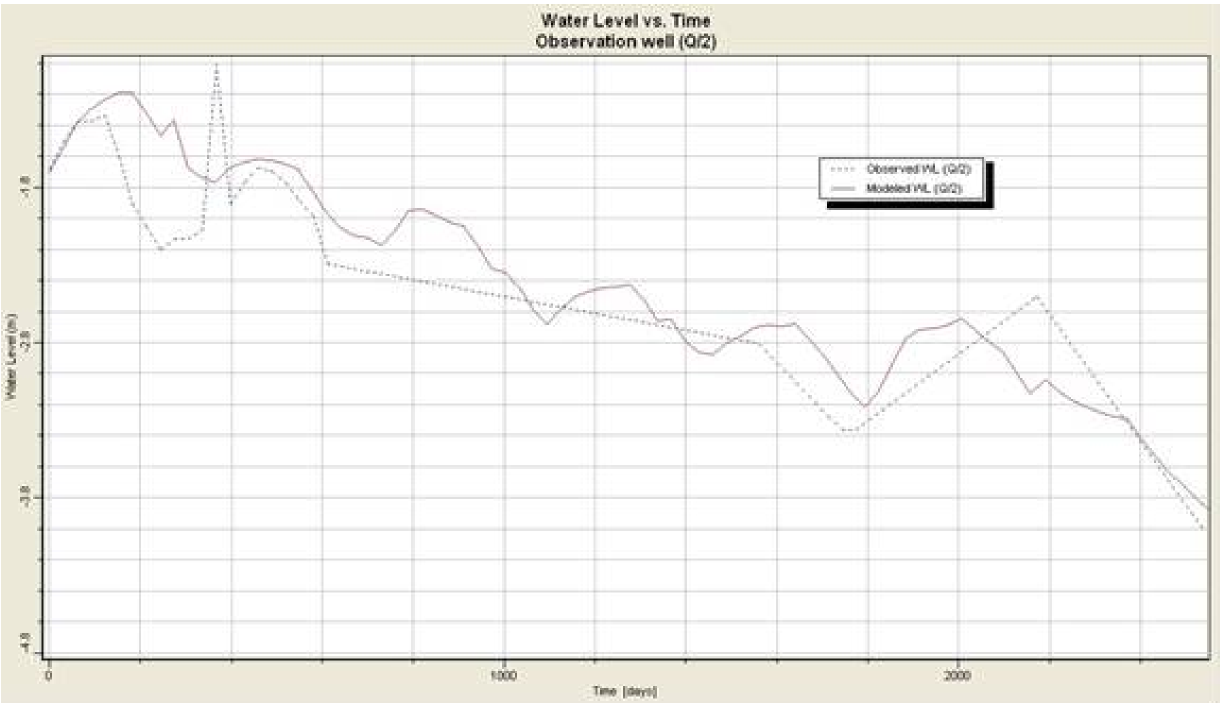


Figure 13: Observed vs. modeled water level for well Q/2. Category axis shows days since 2004

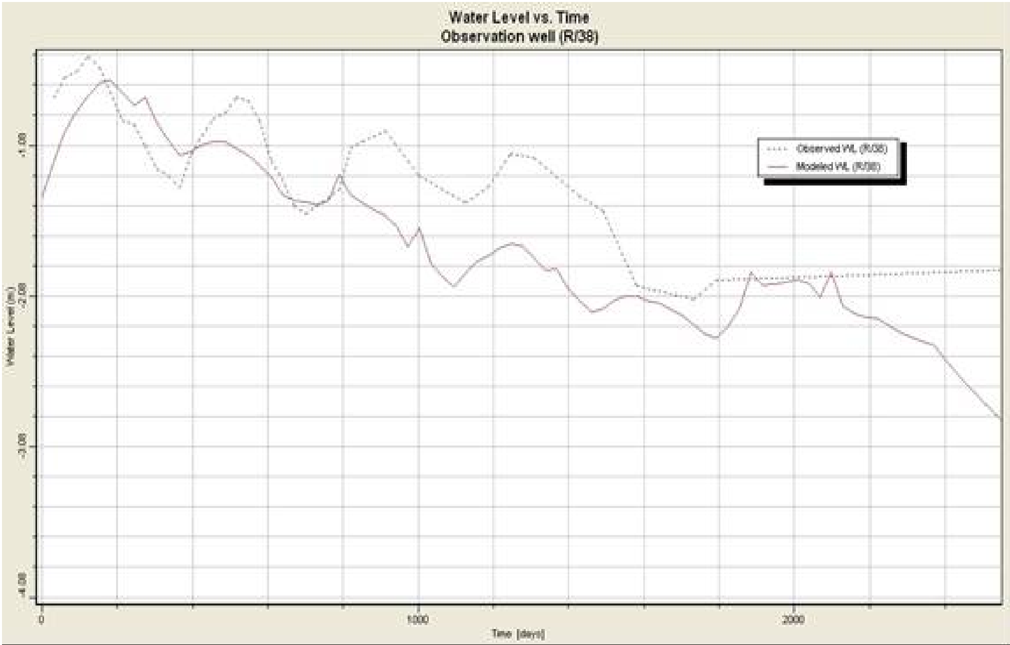


Figure 14: Observed vs. modeled water level for well R/38. Category axis shows days since 2004

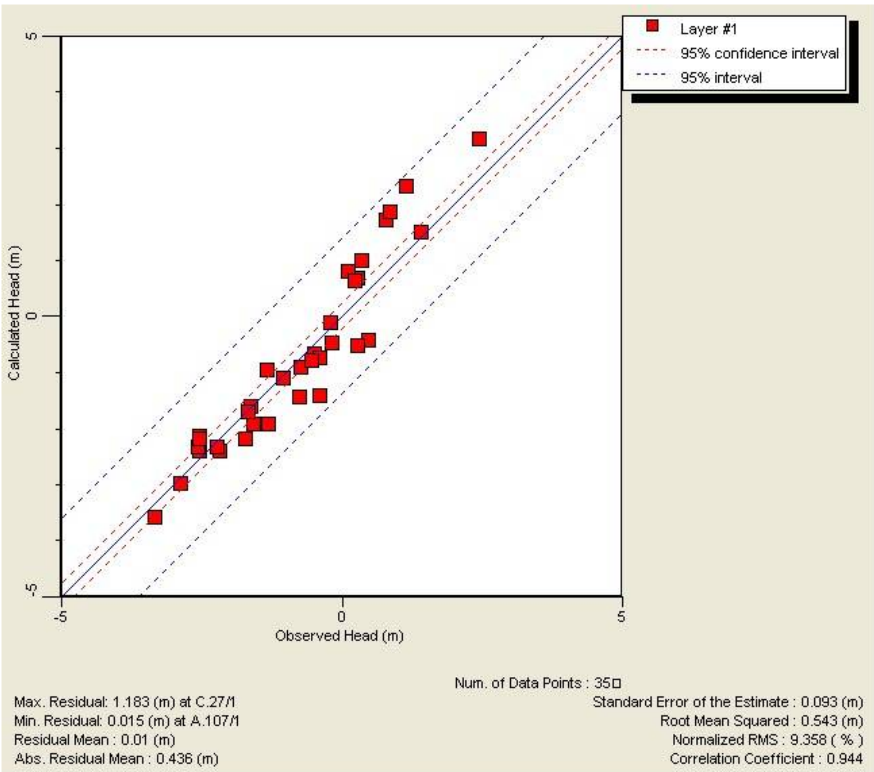


Figure 15: Transient Model Calibration Results

2.3.4. Transport Model

In order to study which part of the aquifer that will be directly influenced by the infiltration, the module Modpath was used to simulate the adjective transport. Thereafter the dispersion was examined by simulation of pollution in the infiltration water using the MT3D module for labeled water containing soluble, non-reactive contaminant.

The parameters that principally influence mass transport in the flow model are effective porosity and dispersivity. The effective porosity, ne, has been set to 25 %. The uncertainty for the parameter is considered to be small, approx. 5 % (CEP&FCG, 2010). Reducing ne will result in increased particle velocity which affects the time aspect in advective transport.

Dispersivity has been set to values ranging from 3 m to 12 m calculated by the following equation (SWECO INT, 2003):

$$\mathbf{D_L=0.83 \log L2.414}$$

where D_L= concerns longitudinal dispersivity and L is the length of the mass transport plume considered. Comparison of simulations shows that this difference in dispersivity does not result in any measurable changes of the diffusion plume.

In order to study the transport due to advection-dispersion, MT3D module simulation has been performed using a pollution tracer which could be Chloride, NO3-N or any chemical. However the NO3-N was considered as indicator for the influent which has a range of 10 to 100 mg/l which indicated the good quality and bad quality of water. The pollution initial concentration in the aquifer was set to 0 mg/l. This simulation allowed for a clear picture of the spreading of the labeled water, since, any deviations from the zero level is a direct effect of the infiltration. For example partially treated wastewater from BLWWTP is characterized by high N-content in all forms. Lacks of aeration in the aerated lagoon hinder the formation of nitrate and degradation of the organic matter. Moreover the lagoon system is unfit for denitrification process. Using large area infiltration basins with good management system will enhance the nitrification process in the soil top layers and de-nitrification in the deeper layers. The partially treated wastewater will supply Carbon to the soil deeper layers enhances the de-nitrification process, but this may not go further than few meters. Hence there will not be effective de-nitrification process during the emergency phase treatment or passage through the unsaturated and saturated zones.

Consecutive drying of the flooded basins will supply enough oxygen that will enhance the nitrification process. As a result it is assumed that 90% of the Kjeldal nitrogen will end up as nitrate in the aquifer. The transport model considered the infiltration of partially treated wastewater with total NO3-N as 80 mg/l starting in April 2009 infiltration rate equal 15000 m^3/day. Data from year 2009 to 2012 was used for the transport calibration at year 2012. The modeled Nitrate concentration model was then calibrated based on year 2012 Nitrate records for 8 groundwater quality observation wells distributed around the infiltration basins (Figure 16). The transport model shows 97% agreement with the observed value (Correlation Coefficient = 0.97) as shown in Figure 17.

Figure 18 and 19 show the observed versus modeled nitrate time series for wells Q/64 and Q/20 The figure shows a good agreement despite the number of measurements are small. The assumption behind that initial concentration under the infiltration basin was set zero can be acceptable since in year 2004 the groundwater quality was very good in term of nitrate concentration. Figure 20 shows the results of model in year 2010 for nitrate concentration.

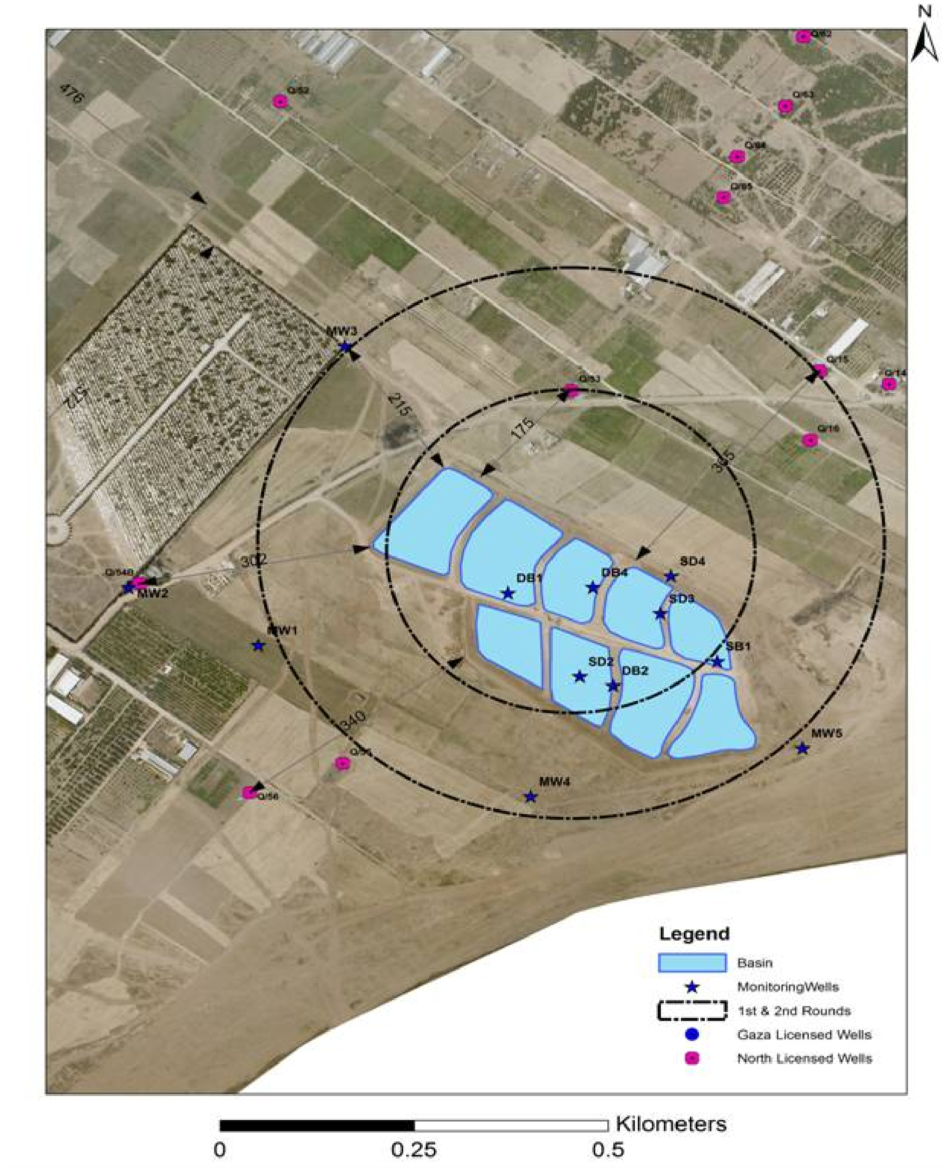


Figure 16: groundwater observation wells used for transport model calibration

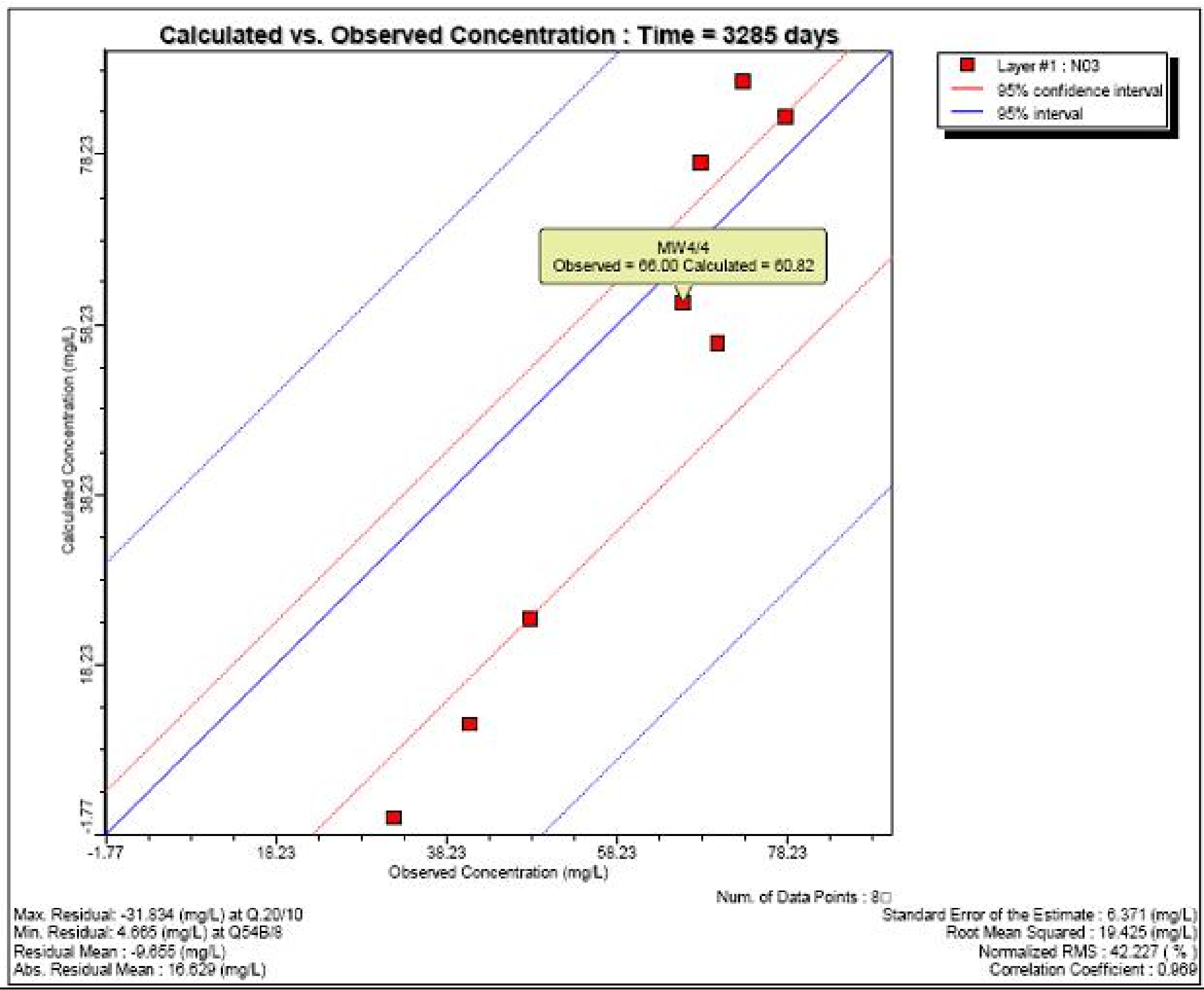


Figure 17: Transport Model Calibration Results

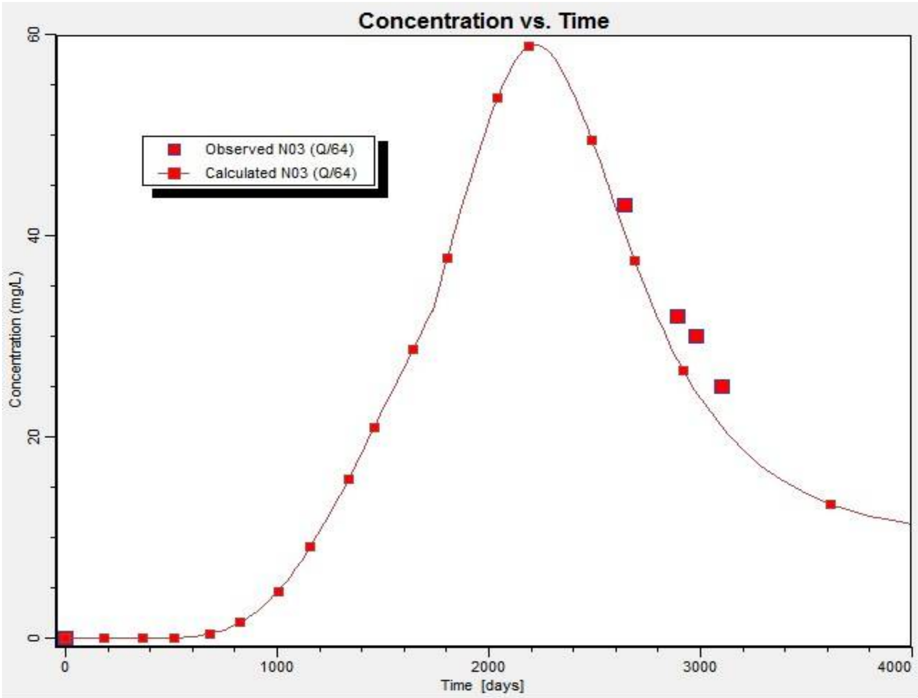


Figure 18: Model and observed nitrate concentration in well Q64

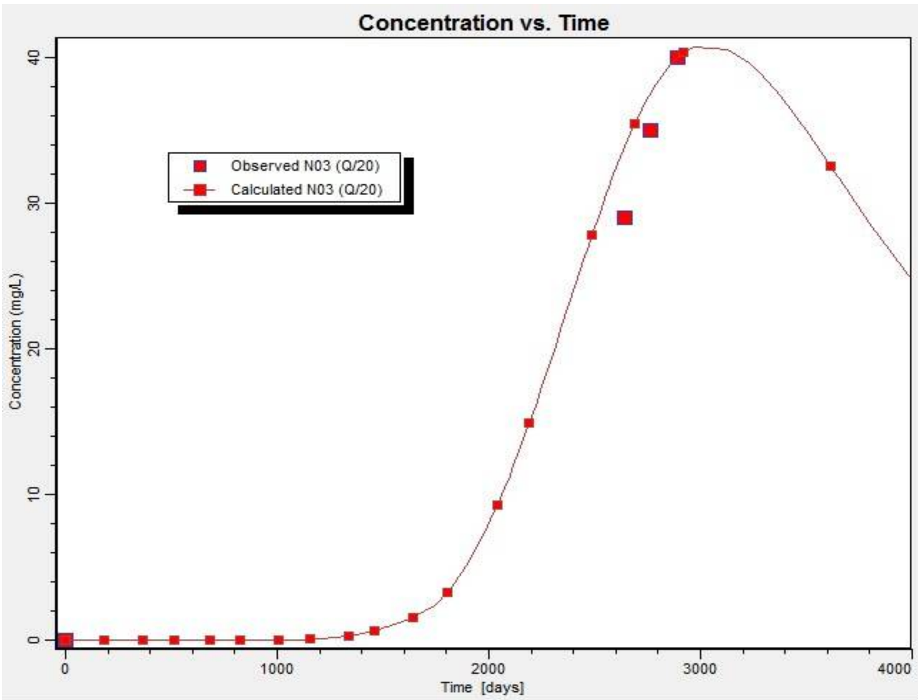


Figure 19: Model and observed nitrate concentration in well Q20

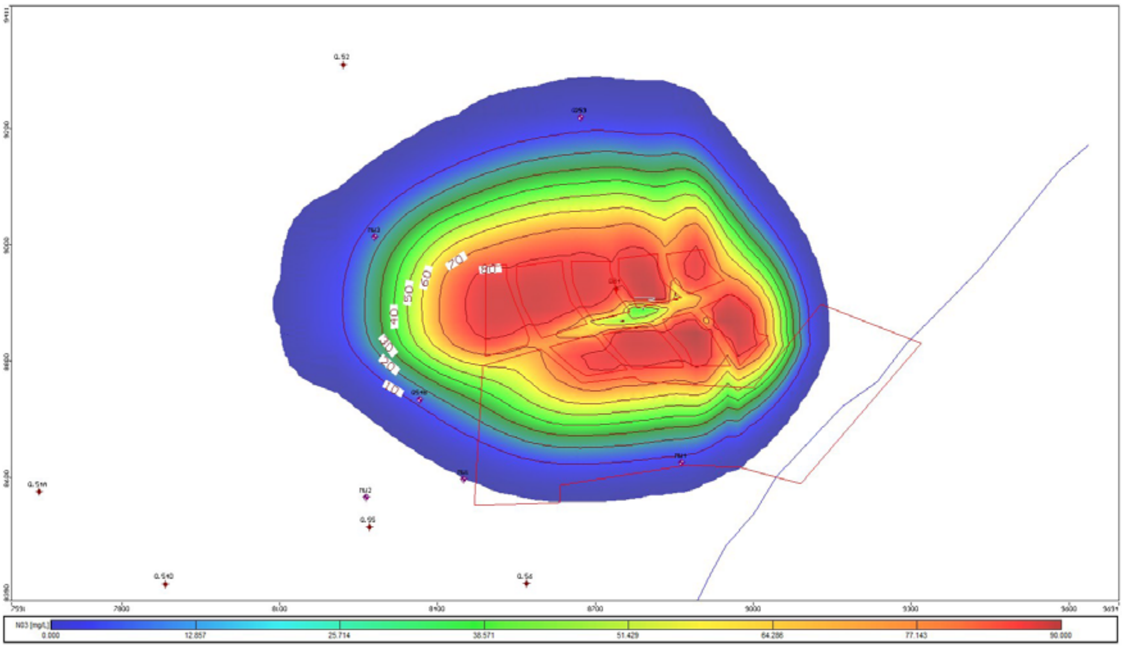


Figure 20: the Modelled NO_3 concentration for year 2010