5 FUTURE PREDICTION (PROGNOSIS)

5.1 Case Study Description

5.1.1 Groundwater modeling outline

a. Data used

The following table shows the items necessary for establishing a groundwater model and the data used in this Project.

Table 5-1: Data used in the groundwater model

Items		Data used
Hydrogeological structure		The data were based on the results of the analysis of the hydrogeological structure carried out by EIPH-La Habana. Special attention was paid to the characteristics of the limestone indicated in the existing columnar section that is used to study the distribution of layer facies in limestone.
Hydrogeological constants		The initial value of the hydrogeological constants (permeability coefficient, water reserve coefficient and others) was calculated from a ratio of stratum using the general value that can be estimated on the basis of the limestone facies. The ratio of the permeability coefficient for the horizontal and vertical axes was taken from the USGS (United States Geological Survey) report on Florida aquifers where the H/V value is equal to 1.5.
Volume of groundwater recharge		The data used were based on the groundwater recharge volume for the HSC-541 well, since the results of the well analysis are the closest to the actual value after having estimated by the tank model that said value would be 5 points between 1973 and 2015 (42 years). Below data used for carrying out the analysis from the tank model method are shown.
	Meteorology (Precipitation and temperature)	Precipitation: As data to be entered, the monthly precipitation data obtained from the observation points close to the analysis area of EAH-Mayabeque and EAH-Artemisa were taken. Temperature: The average monthly temperature in the period from 1973 to 2015 was taken from the information of the Weather Station of Casa Blanca in Havana, which is open for public viewing.
	Calibration data	As calibration data, groundwater level data monitored and managed by EAH-Mayabeque and EAH-Artemisa were taken.
Volume of groundwater pumped		The pumpage volume managed by EAH-Mayabeque and EAH-Artemisa from 2011 to 2015 was used for input value for the model.
Initial hydraulic head		A quasi-stationary calculation was carried out for a period of 36500 days and the value obtained on day 20440 (the number of days from the beginning of groundwater pumpage in the wells of Cuenca Sur to the present) was used as the initial head for the calibration at the beginning of the non-stationary calculation.
Salt concentration		The salt concentration distribution was estimated from the relationship between EC (electrical conductivity) and salt concentration measured by EAH-Mayabeque and EAH-Artemisa.
Model calibration data		As calibration data, groundwater level data monitored and managed by EAH-Mayabeque and EAH-Artemisa were taken.

b. Model structure

b.1 Scope of analysis and mesh size (grid set)

The plane grids of the 3-D model, as indicated in the figure below, extended beyond the target area to minimize the calculation tolerance within that area (especially in the boundary zone). Each grid measures 500 m x 500 m (X-axis: 320000-378000 (116 grids), and Y-axis: 305000-344000 (88 grids). 305000-344000 (88 grids).

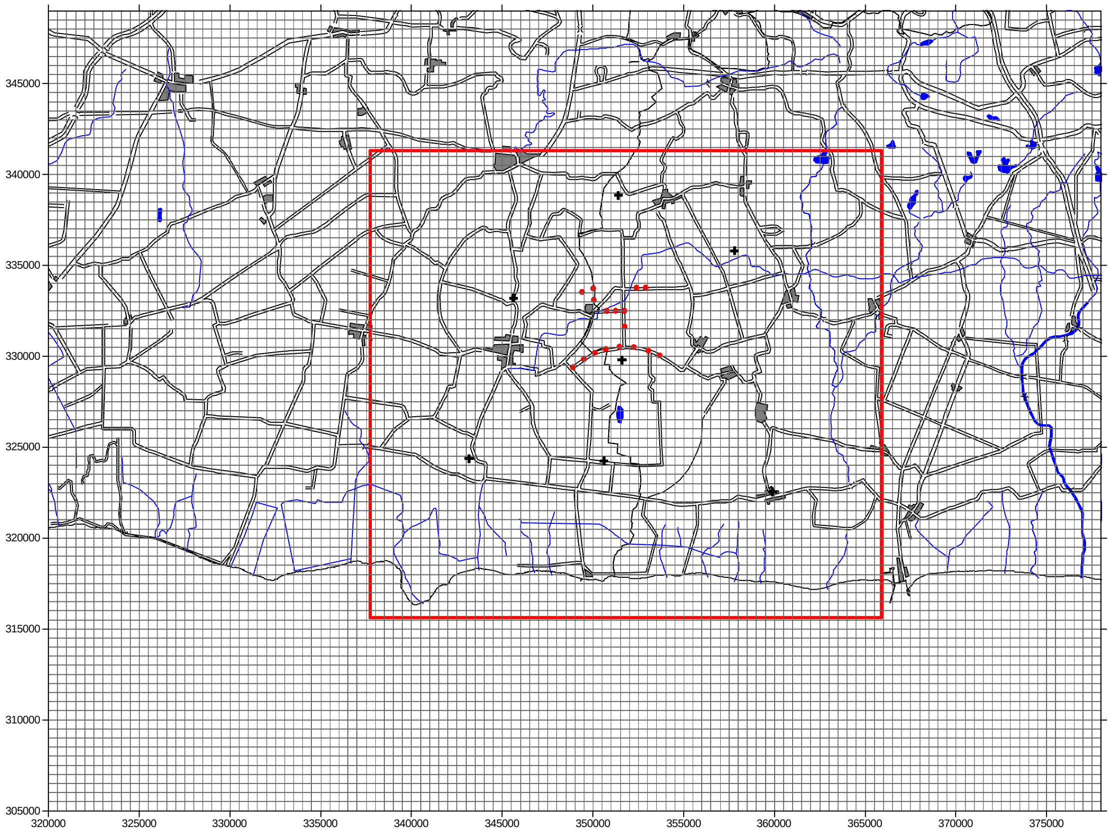


Figure 5-1: Scope of groundwater model analysis

b.2 Vertical structure

The cross-sectional structure of the 3-D model is broken down into 40 strata so that the penetration of seawater into the deeper zones can be shown in slopes, for which each stratum has been assigned the elevation indicated below. The elevation of the highest part of the model is 100 m and the lowest, -200 m.

- Elevation of 100 m ~ 50 m: 5 layers (thickness of 10 m)
- Elevation of 50 m ~ - 50 m: 20 layers (thickness of 5 m)
- Elevation of - 50 m ~ - 200 m: 15 layers (thickness of 10 m)

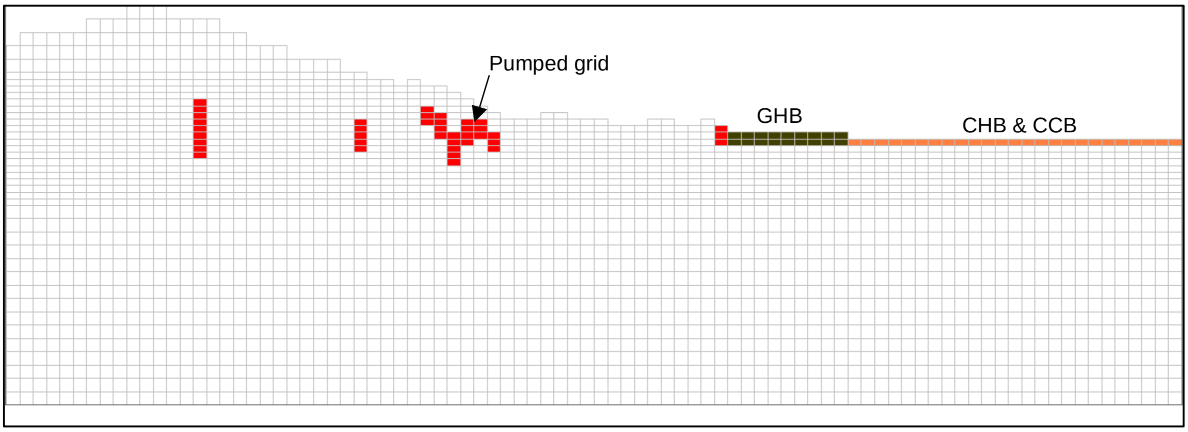


Figure 5-2: Example of the cross-section of the 3-D model

c. Parameters of the model

c.1 Hydraulic conductivity in horizontal direction

The permeability coefficient for the horizontal direction value was determined based from the information of 449 columnar sections divided according to facies (general value) or to model layers. The value of distribution data of permeability coefficient for the horizontal direction by model stratum was prepared so that the value can be changed and reproduced during the calibration with the actual groundwater status.

c.2 Hydraulic conductivity in vertical direction

Basically, the same method used in the horizontal direction was applied in the vertical direction. The permeability ratio (H/V value) in the horizontal and vertical direction has been set to change uniformly. After analyzing the water levels calculated by changing the H/V value from 20 to 1, it was concluded that HV = 1.5 (taken from the USGS report on Florida aquifers) is the best value for model reproduction.

c.3 Effective porosity rate (EP) and Specific yield rate (Sy)

The effective porosity (EP) and specific yield (Sy) values were selected from the general value derived from the characteristics of each stratum and then the spatial distribution data of EP and Sy were created. The same value was applied to both EP and Sy.

c.4 Specific storage rate (Ss)

The specific storage value (Ss) was selected based on the general value and then the spatial distribution data of Ss were created. The input value of Ss was changed for one 10 times greater than the initial value because the fluctuation range obtained for the calculated water level was much broader than expected.

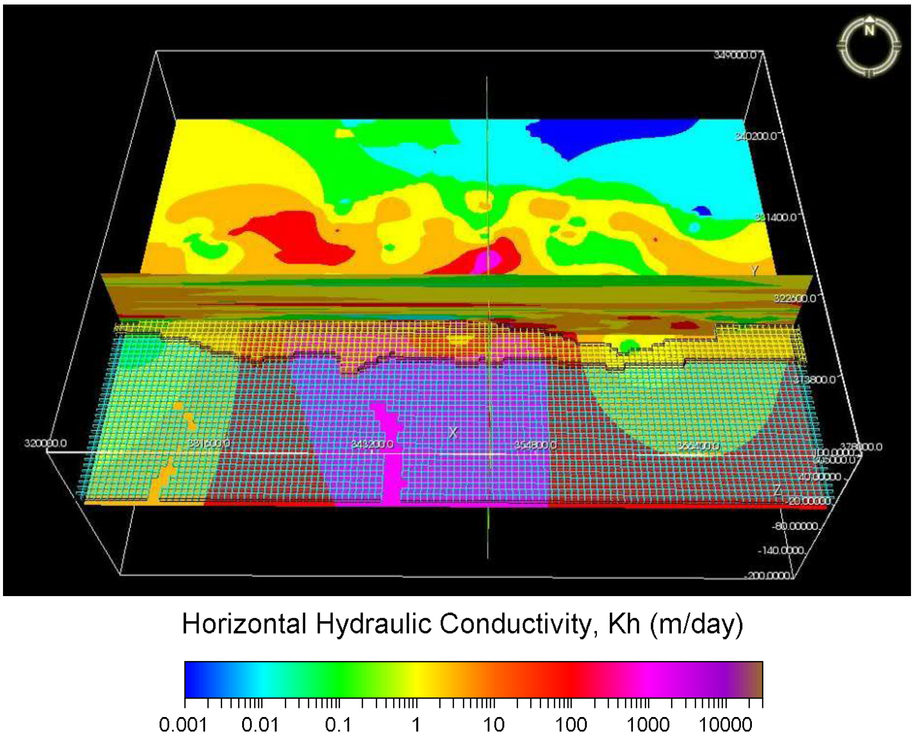


Figure 5-3: Example of hydraulic conductivity in horizontal direction

d. Estimated volume of groundwater recharge

The outflow analysis method was adopted with the application of the tank model to estimate the volume of groundwater recharge, which is one of the necessary datum for the calculation of the groundwater model. The analysis using the tank model was carried out in five points (calibration period: 1973 to 2015), although there were some problems such as the sudden increase in the actual groundwater level in Dique Sur since 1990, which was not in correspondence with the groundwater volume calculated. As a result, the groundwater recharge volume calculations were performed on the basis of the result for well HSC-541 (in this case the calculations resulted in the closest value to the actual groundwater level) and the precipitation distribution.

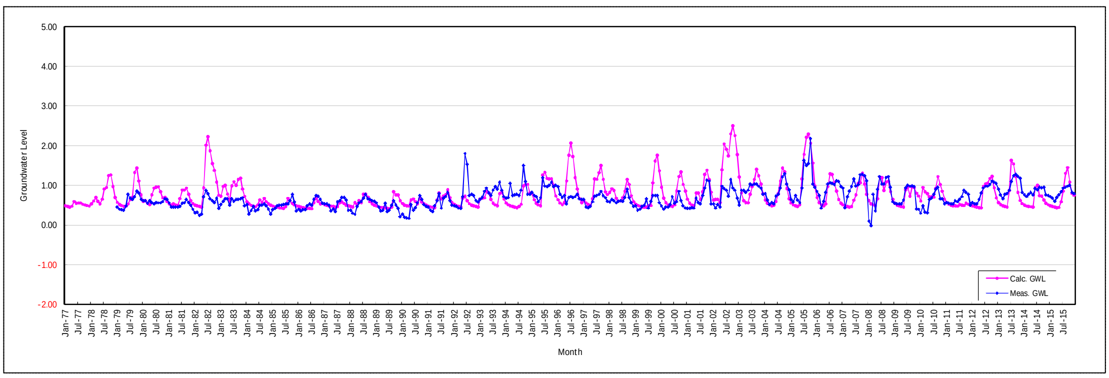


Figure 5-4: Example of calibration results of “Tank Model” analysis (HSC-541)

e. Estimated groundwater pumpage volume

The groundwater pumpage volume was estimated by applying the monthly pumping volume data for 711 wells from 2011 to 2015, which are managed by EAH-Mayabeque and EAH-Artemisa. As for the data to be input to the groundwater model, the intake layer was selected according to the depth of each well and the pumping volumes were distributed from the permeability coefficient of the intake layer calculated at c. 1. On the other hand, it was assumed that the volume pumped between 2005 and 2010 was equal to that of 2011 since there were no data for these six years of the calibration period.

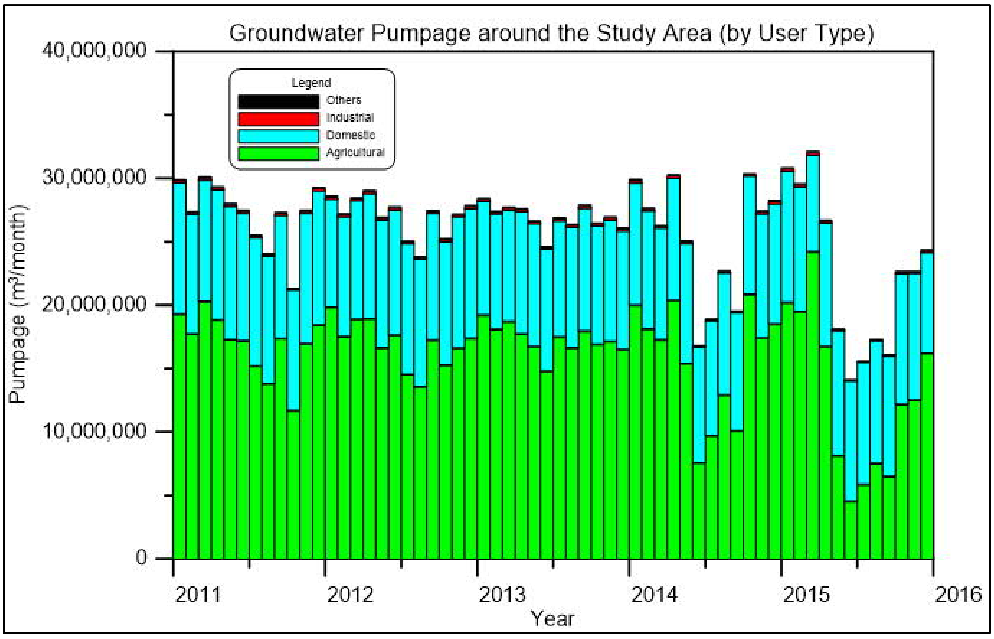


Figure 5-5: Estimated monthly amount of groundwater pumpage (2011-2015)

f. Initial hydraulic head

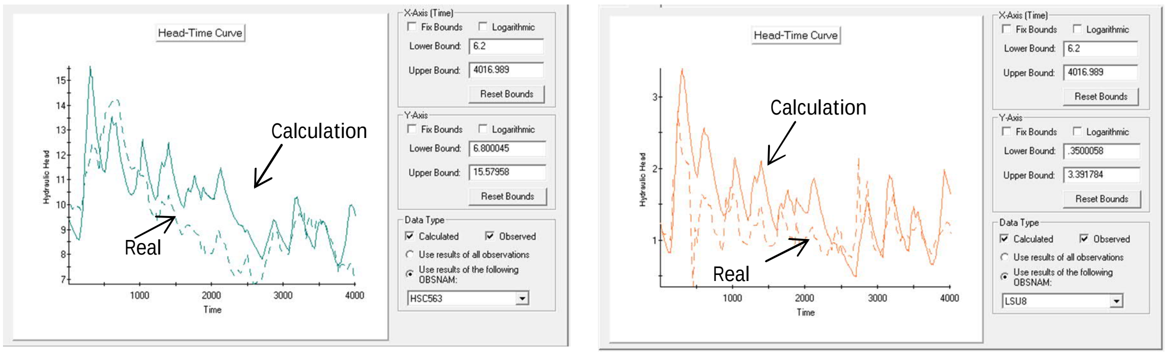
The quasi-stationary calculation was carried out for a period of 100 years and in each layer the groundwater value calculated in 1956 (20440 days: estimated groundwater volume pumped in the model area from 1950) was taken as the initial hydraulic head for the non-stationary calculation in the period from 2005 to 2011.

g. Distribution of salt concentrations

The spatial distribution of salt concentrations was determined on the basis of the EC distribution according to the depth of each well, which was measured in April 2015 by EAH-Mayabeque and EAH-Artemisa.

h. Calibration

Once the groundwater recharge volume parameters, pumped groundwater volume and others were input in each of the grids, a calibration calculation was made between 2005 and 2015 (11 years) using MODFLOW. The calculation unit is monthly (132 periods of tension) and the model was calibrated comparing the variation of groundwater level observed in monitoring wells and the variation of the calculated water level. A calibration example is shown in the figure below.



(HSC-563) (LSU-8)

Figure 5-6: Example of the comparison of the measured groundwater level variation with the variation of the calculated hydraulic head

5.1.2 Prediction calculation

Future predictive calculations were made from 16 scenarios designed by combining the following factors: ① transition patterns of pumpage and recharge volumes, ② sea level rise, and ③ installation of new wells, as shown in the following table:

Table 5-2: Future prediction scenarios

		RA0	RA1	RA2	RA3	RP0	RP1	RP2	RP3
		Repetition of the monthly average of the last 30 years	Decrease up to 80% in 2035	Decrease up to 90% in 2035	Increase by 110% in 2035	It remains at 100% in 2035	Decrease up to 80% in 2035	Decrease up to 90% in 2035	Increase by 110% in 2035
Q0	Repetition of 2015 values	Q0-RA0	Q0-RA1	Q0-RA2	Q0-RA3	Q0-RP0	Q0-RP1	Q0-RP2	Q0-RP3
Q1	Decrease up to 90% in 2035	Q1-RA0	-	-	Q1-RA3	-	-	-	-
Q2	Increase by 110% in 2035	Q2-RA0	-	-	-	-	-	-	-
Q3	Increase by 120% in 2035	Q3-RA0	Q3-RA1	-	-	-	-	-	-
Sea level	Increase	Q0-RA0 -SR	-	-	-	-	-	-	-
Development of new wells	Cuenca Sur	Q0-RA0 -CS	-	-	-	-	-	-	-
	Cuenca Sur and San Felipe	Q0-RA0 -CS+SF	-	-	-	-	-	-	-

Base year: 2015
A: Average of the 1986-2015 periods, repetition of the average monthly value
P: Past recharge values for the 1996-2015 period, repetition every ten years

Changes in salt concentration and groundwater levels for the next 20 years (2016 ~ 2035) were estimated on the basis of 2015 results for each future prediction scenario shown below.

5.2 Conditions of Analysis of Each Scenario

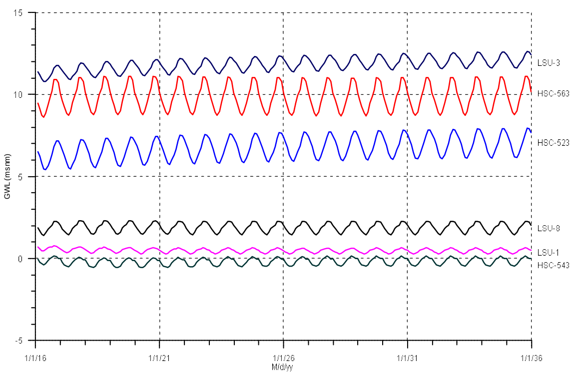
a. Basic scenario

Two cases were assumed for the model in which the current conditions were maintained.

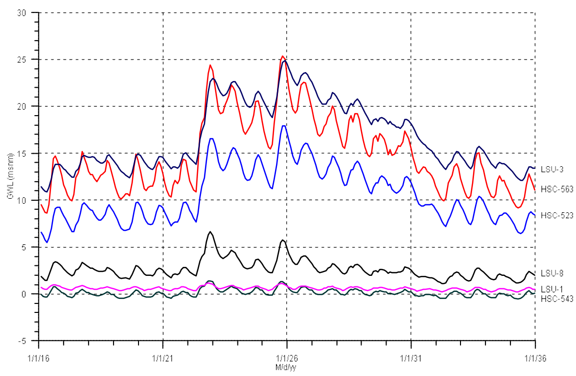
① Basic Scenario 1 (Q0-RA0 Model)
- Pumpage volume: The pumpage volume of 2015 is maintained.
- Volume of groundwater recharge: The average monthly volume of groundwater recharge of the last 30 years (1986-2015) is repeated. (E.g.: average volume of January from 1986 to 2015 = recharge volume for January 2016, 2017, ..., 2035)

② Basic Scenario 2 (Q0-RP0 Model)
- Pumpage volume: The pumpage volume of 2015 is maintained.
- Volume of groundwater recharge: The groundwater recharge of the last 20 years (1996-2015) is repeated over the next 20 years (2016-2035). (E.g.: recharge volume 1996 = recharge volume for 2016, recharge volume of 1997 = recharge volume for 2017, ..., recharge volume for 2015 = recharge volume for 2035)

The transition of calculated groundwater level for both scenarios is shown in the figure below.



(Model Q0-RA0)



(Model Q0-RP0)

Figure 5-7: Fluctuation of the calculated groundwater level ([Q0-RA0 Model] and [Q0-RP0 Model])

b. Scenario of groundwater recharge rate fluctuation

b.1 Basic model 1 (Q0-RA0 Model)

Three cases of the assumption for groundwater recharge transition were undertaken while the pumpage volume is maintained as 2015.

① Q0-RA1 Model
- Volume of groundwater recharge: The volume was reduced at the same rate so the recharge volume in 2035 will be 80% of the recharge volume of Q0-RA0 model.

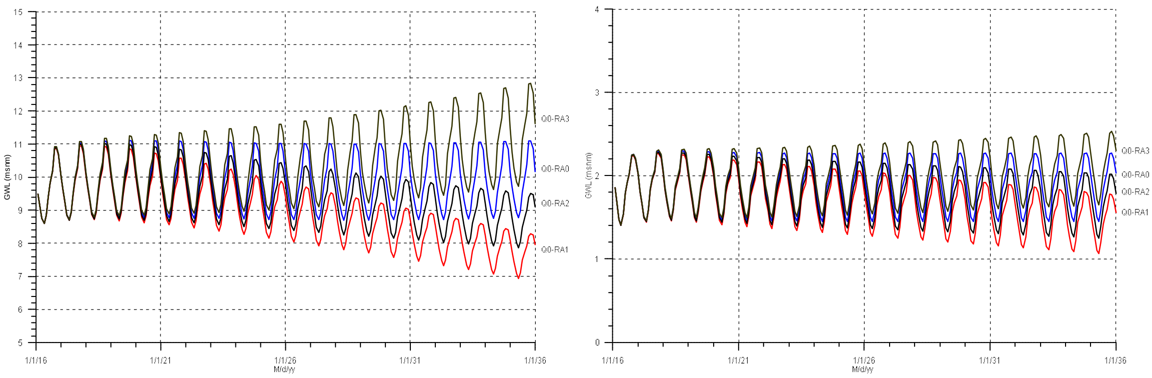
② Q0-RA2 Model
- Volume of groundwater recharge: The volume was reduced at the same rate so the

recharge volume in 2035 will be 90% of the recharge volume of Q0-RA0 model.

③ Q0-RA3 Model

- Volume of groundwater recharge: The volume was increased at the same rate so the recharge volume in 2035 will be 110% of the recharge volume of Q0-RA0 model.

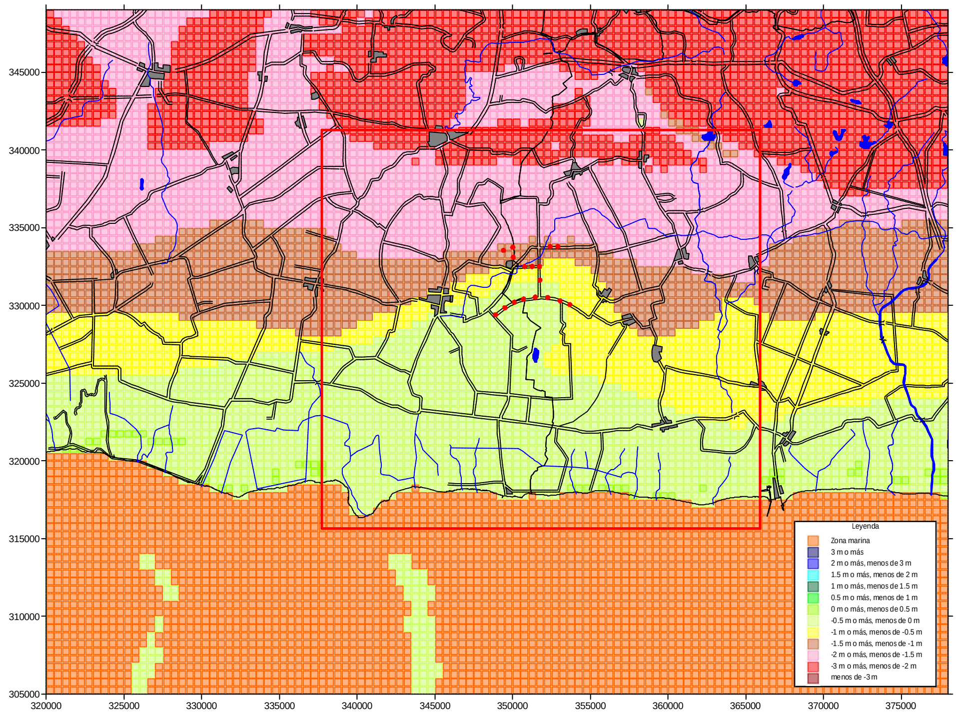
The transition result of the calculated groundwater level of the Basic Model 1 and the three cases are shown in the figure below.



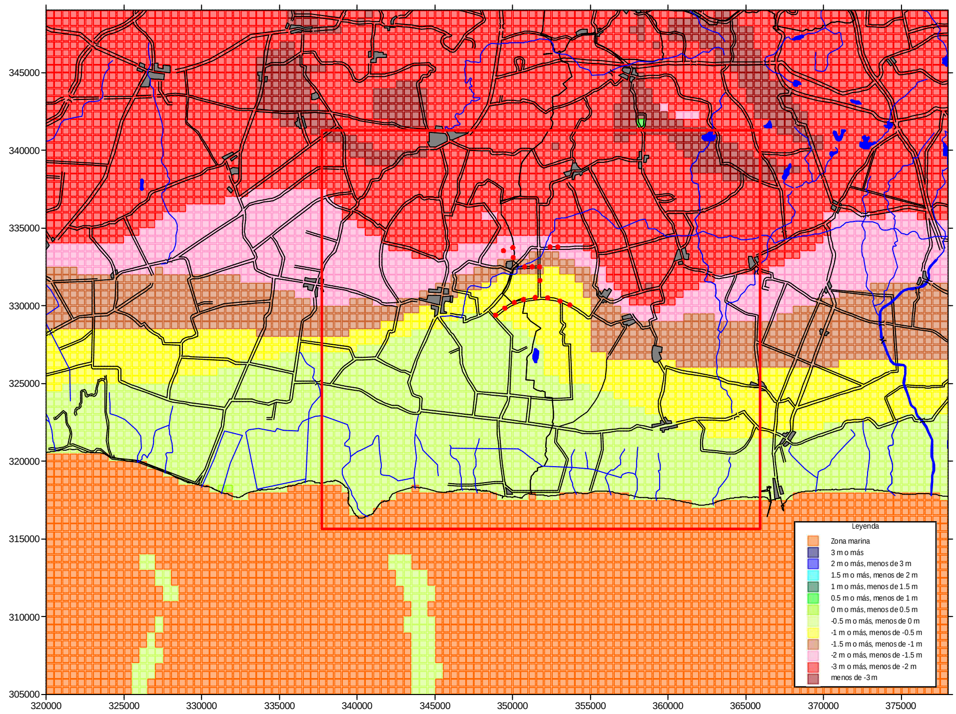
(HS-563) (LSU-8)

Figure 5-8: Fluctuation of the calculated groundwater levels ([Q0-RA0 Model], [Q0-RA1 Model], [Q0-RA2 Model] and [Q0-RA3 Model])

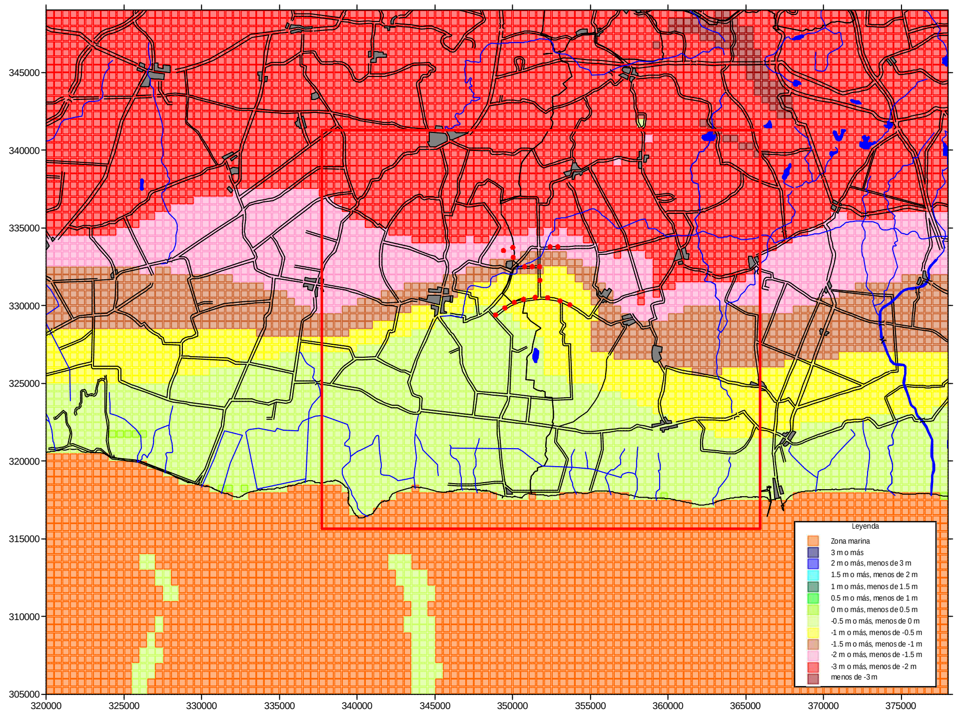
The comparison figures of the calculated groundwater level distribution between Basic Model 1 and the three cases (17th layer) are shown below. The comparison was made for the end of the dry season (April 2035), end of rainy season (October 2035), and last month (December 2035).



(End of the dry period (April 2035))

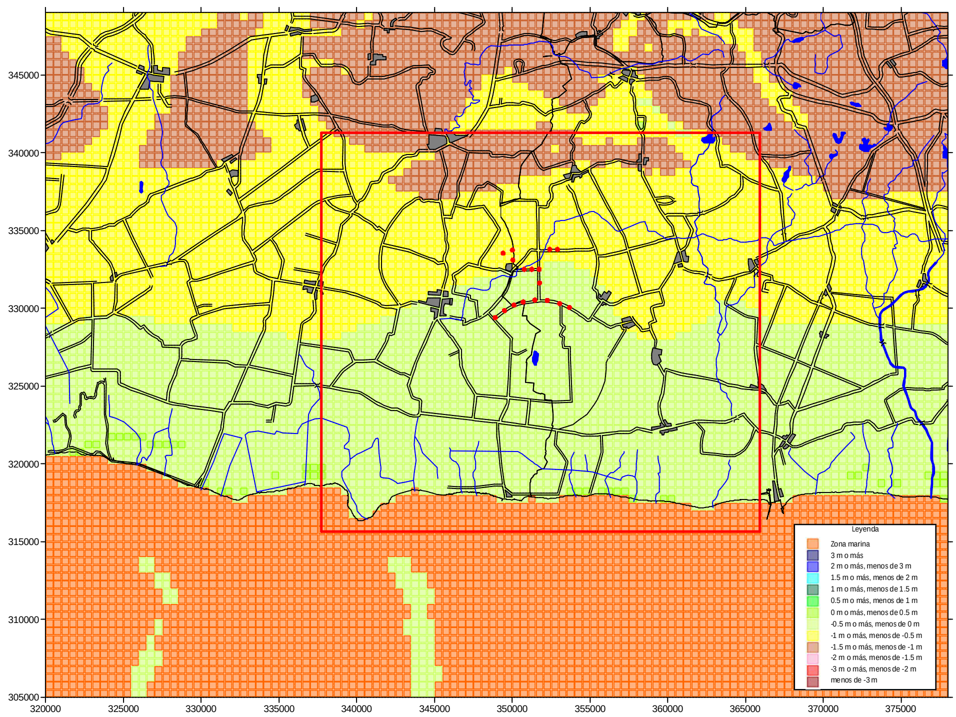


(End of the rainy period (October 2035))

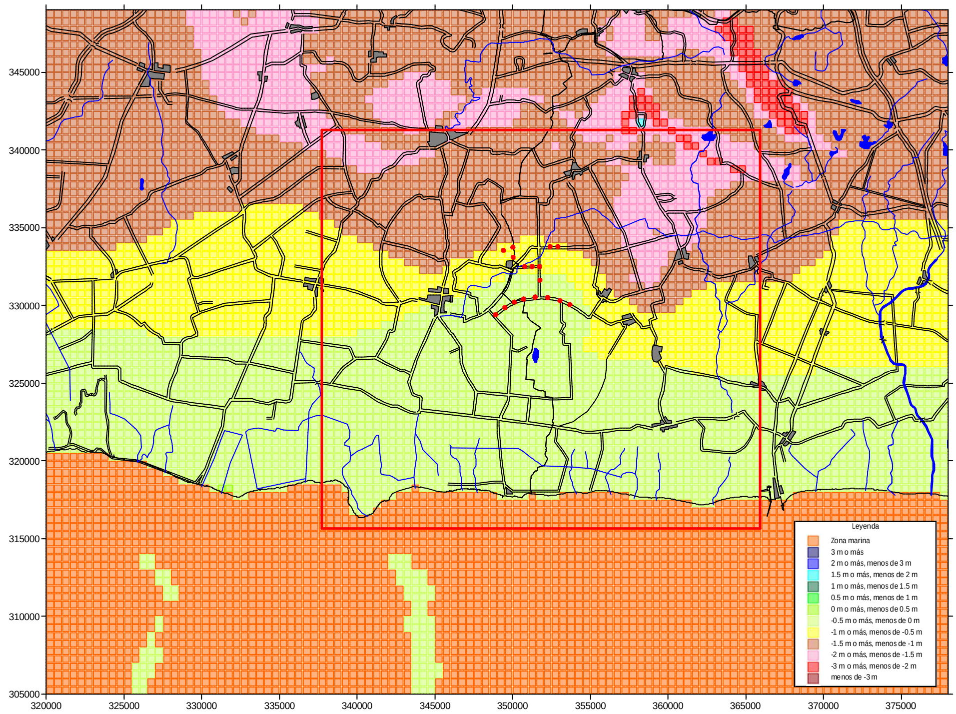


(Last month (December 2035))

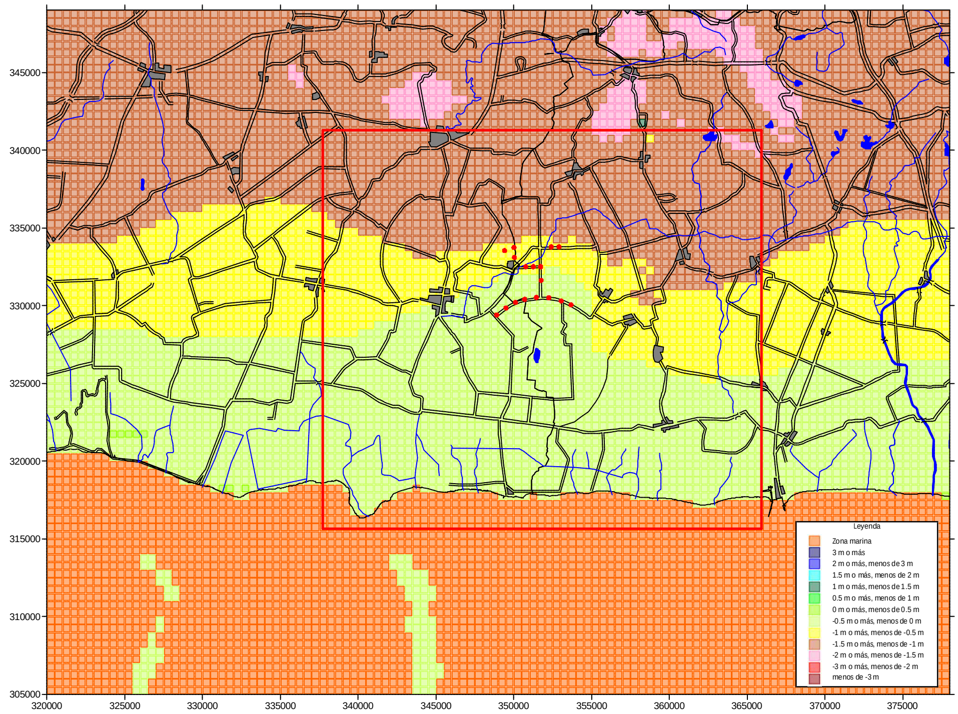
Figure 5-9: Comparison of calculated groundwater level distribution (17th layer) of [Q0-RA0 Model] and [Q0-RA1 Model]



(End of the dry period (April 2035))

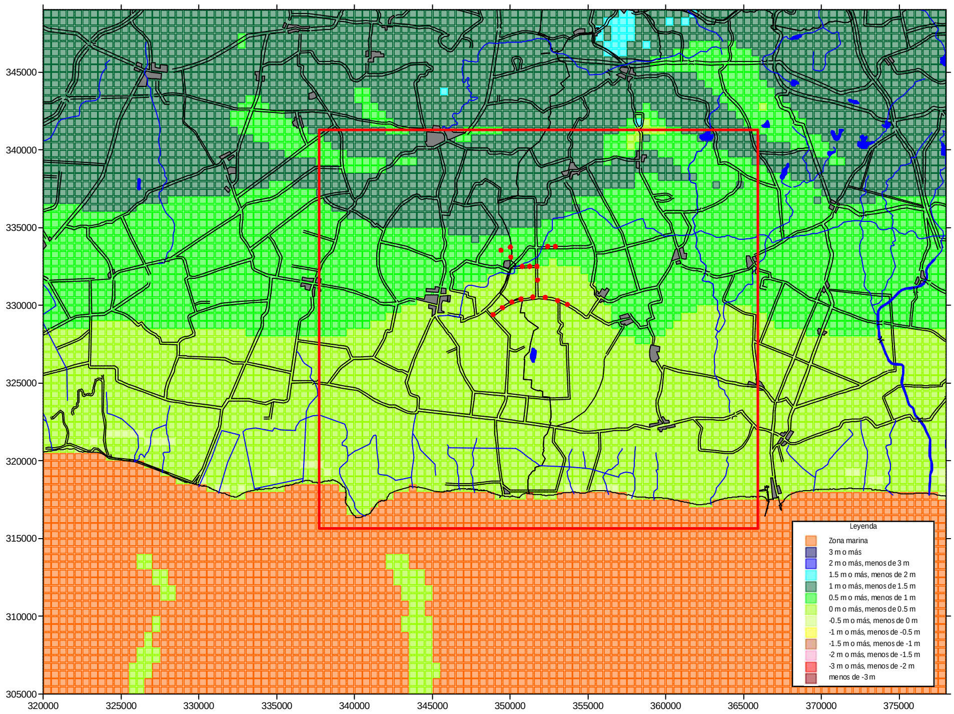


(End of the rainy period (October 2035))

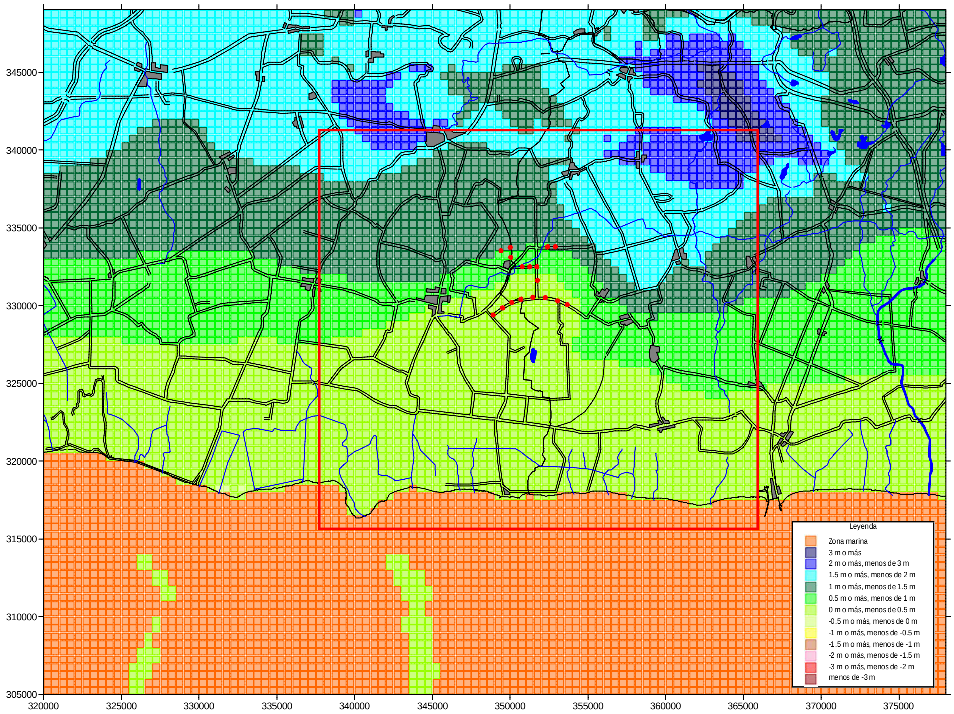


(Last month (December 2035))

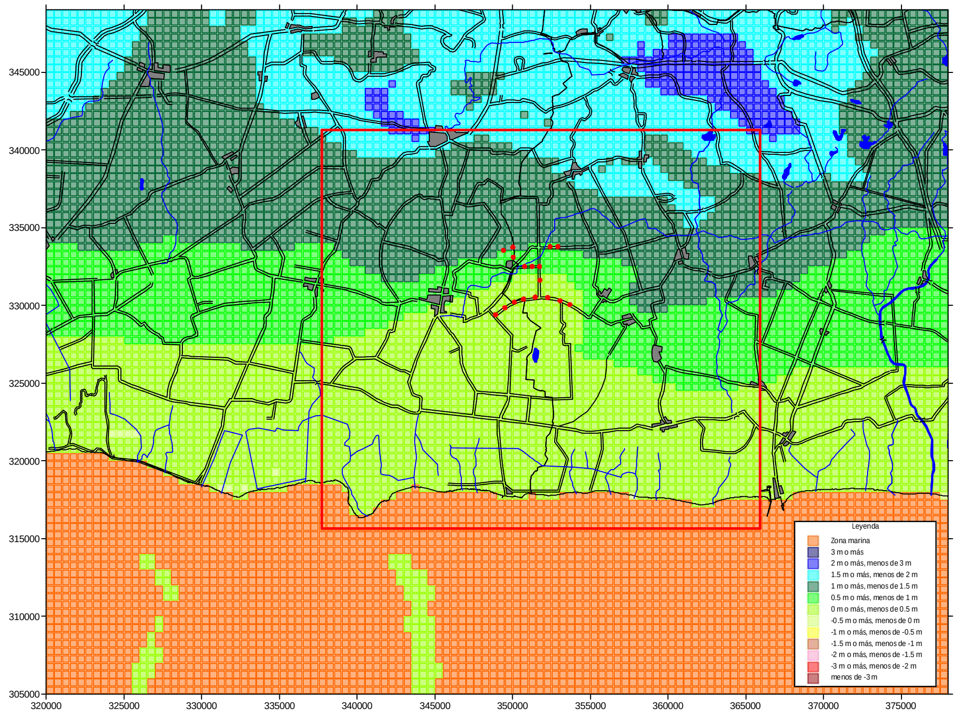
Figure 5-10: Comparison of calculated groundwater level distribution (17th layer) of [Q0-RA0 Model] and [Q0-RA2 Model]



(End of the dry period (April 2035))



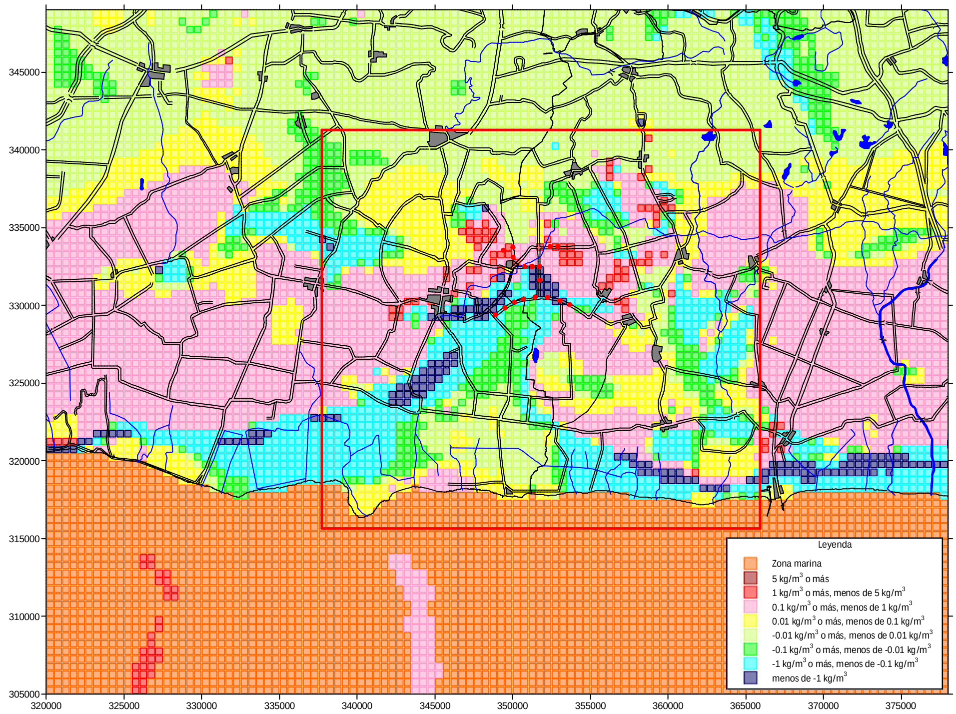
(End of the rainy period (October 2035))



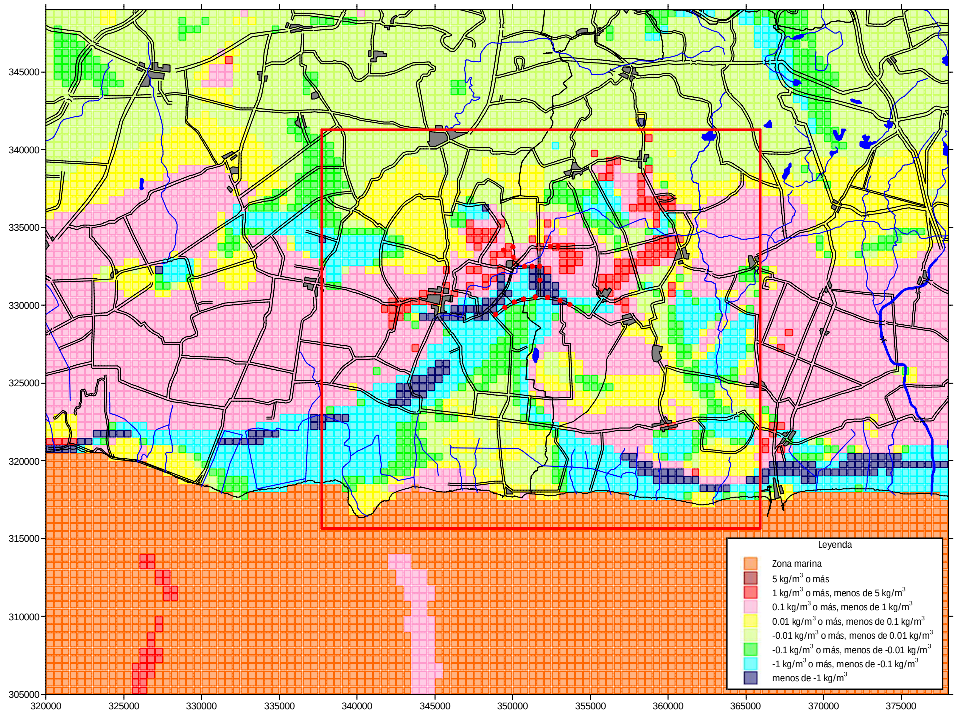
(Last month (December 2035))

Figure 5-11: Comparison of calculated groundwater level distribution (17th layer) of [Q0-RA0 Model] and [Q0-RA3 Model]

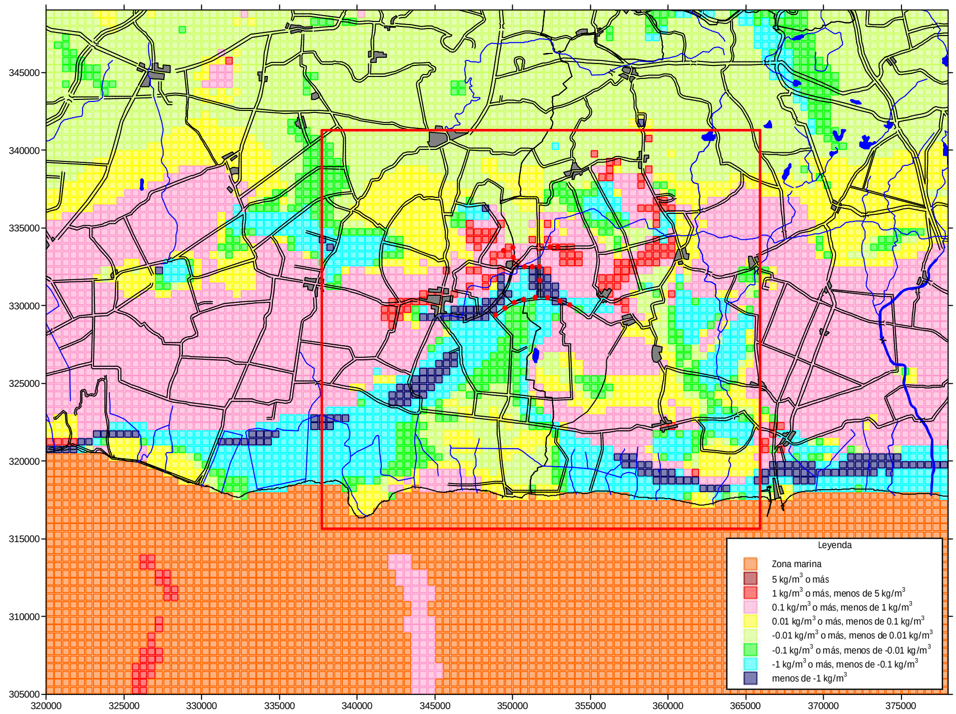
The comparison figures of the calculated salt concentrations (17th layer) between Basic Model 1 and the three described cases are also shown below. The period of comparison is the same as that of the groundwater level distribution.



(End of the dry period (April 2035))

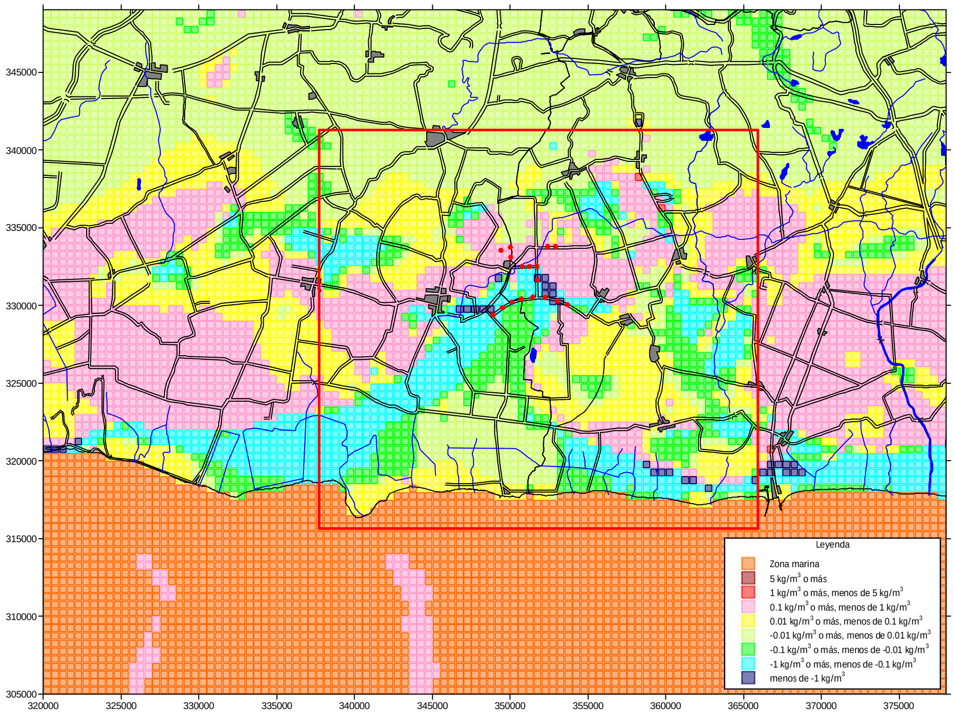


(End of the rainy period (October 2035))

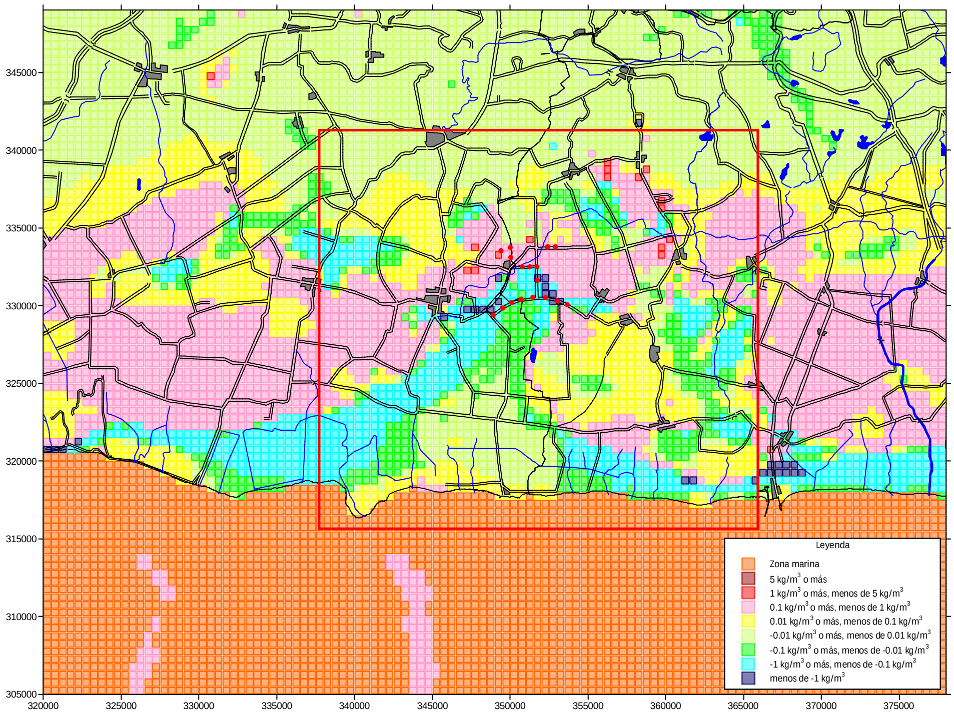


(Last month (December 2035))

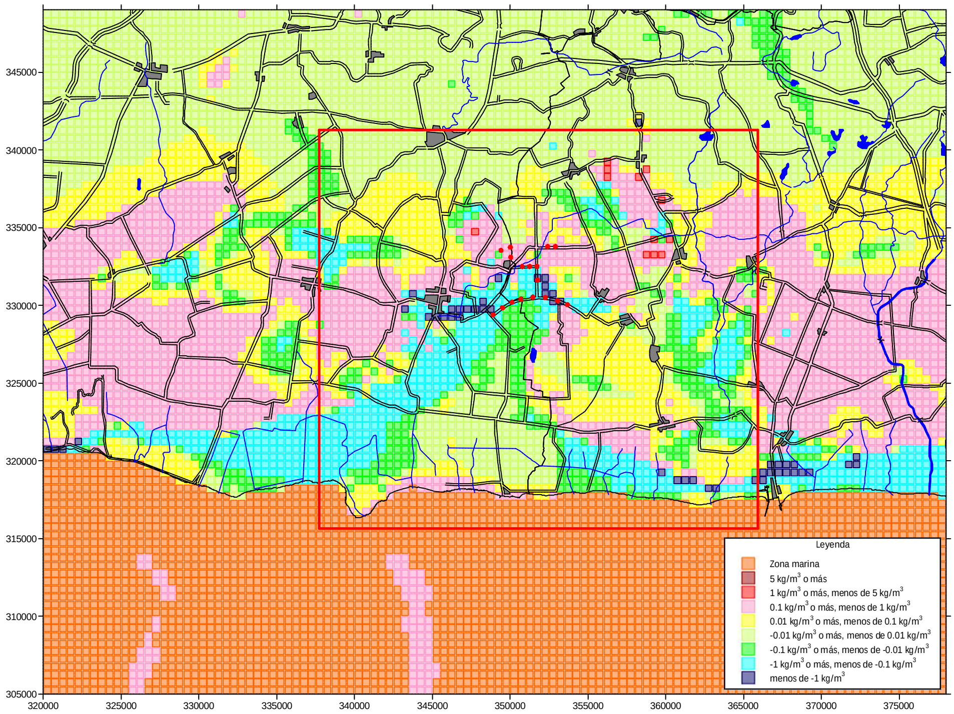
Figure 5-12: Comparison of calculated groundwater salt concentration distribution (17th layer) of [Q0-RA0 Model] and [Q0-RA1 Model]



(End of the dry period (April 2035))

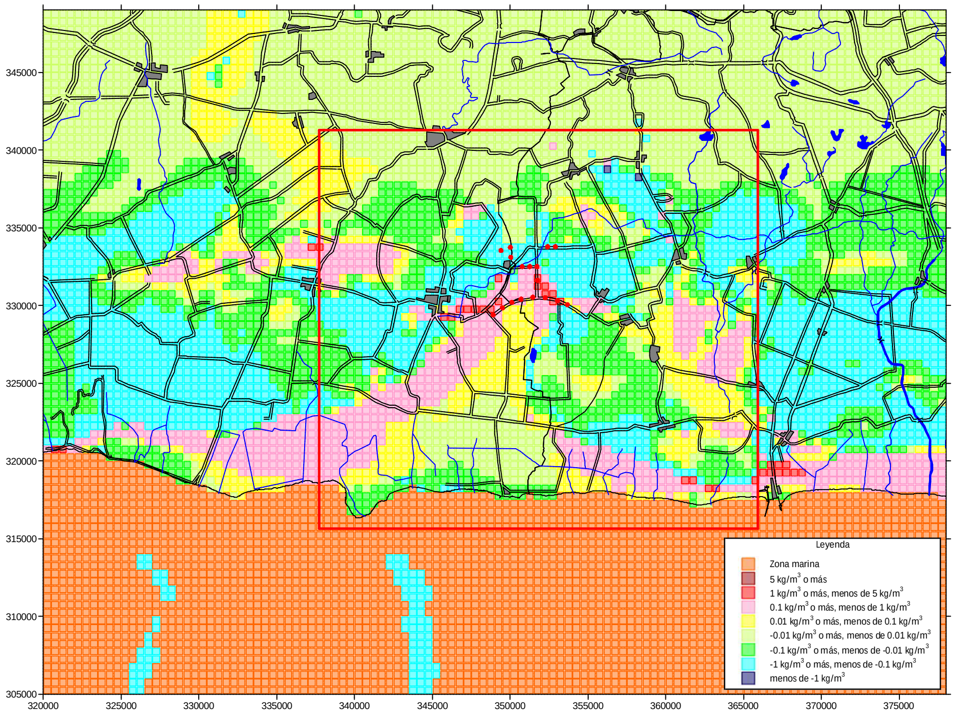


(End of the rainy period (October 2035))



(Last month (December 2035))

Figure 5-13: Comparison of calculated groundwater salt concentration distribution (17th layer) of [Q0-RA0 Model] and [Q0-RA2 Model]



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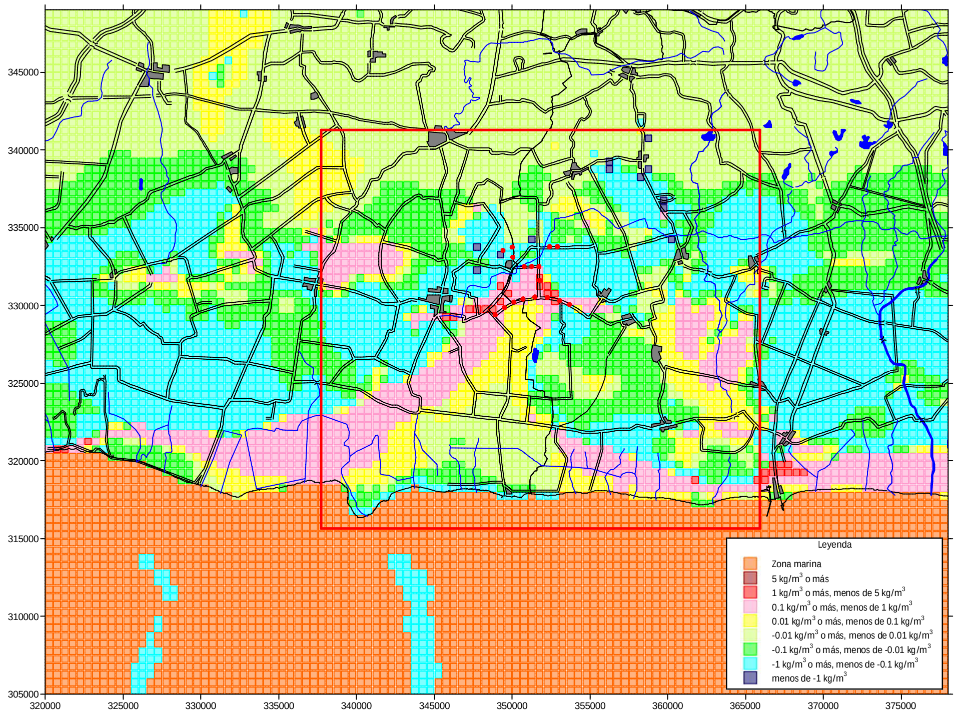
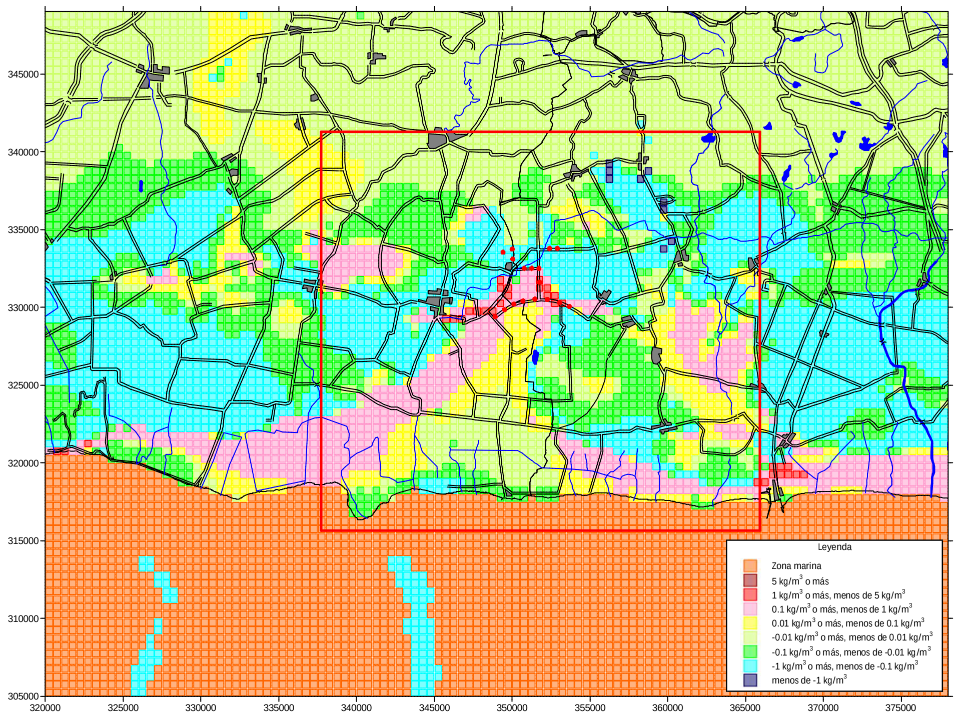


(End of the rainy period (October 2035)



(Last month (December 2035))

Figure 5-14: Comparison of calculated groundwater salt concentration distribution (17th layer) of [Q0-RA0 Model] and [Q0-RA2 Model]

b.2 Basic model 2 (Q0-RP0 Model)

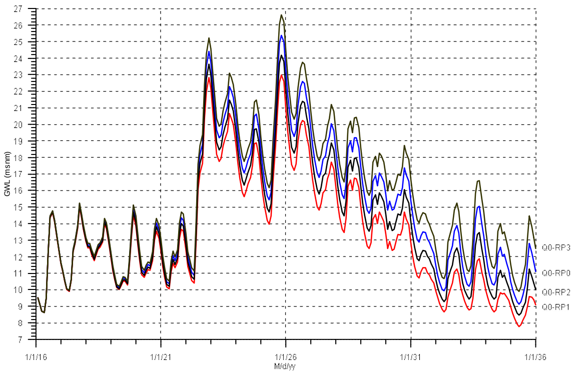
Three cases of the assumption for groundwater recharge transition were undertaken while the pumpage volume is maintained as 2015.

① Q0-RP1 Model
- Volume of groundwater recharge: The volume was reduced annually at the same rate so the recharge volume in 2035 will be 80% of the recharge volume of Q0-RP0 model.

② Q0-RP2 Model
- Volume of groundwater recharge: The volume was reduced annually at the same rate so the recharge volume in 2035 will be 90% of the recharge volume of Q0-RP0 model.

③ Q0-RP3 Model
- Volume of groundwater recharge: The volume was increased annually at the same rate so the recharge volume in 2035 will be 110% of the recharge volume of Q0-RP0 model.

The transition result of the calculated groundwater level of the Basic Model 2 and the three cases are shown in the figure below.



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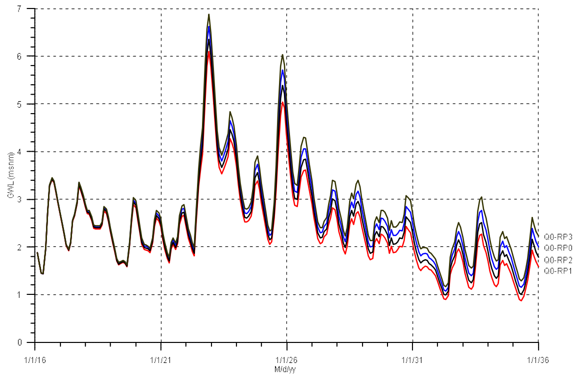
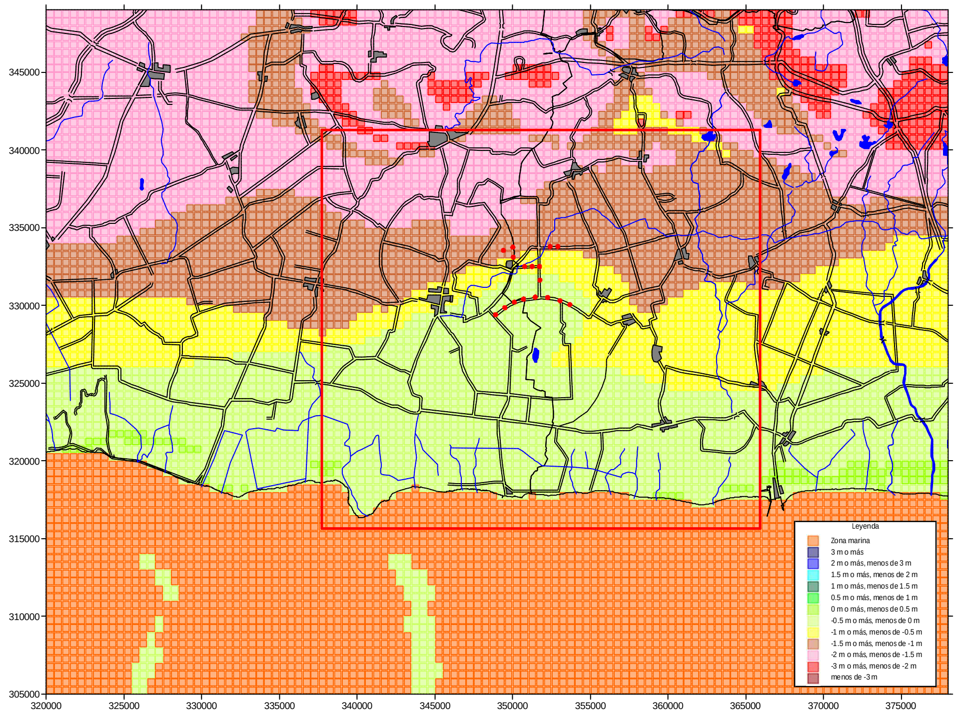


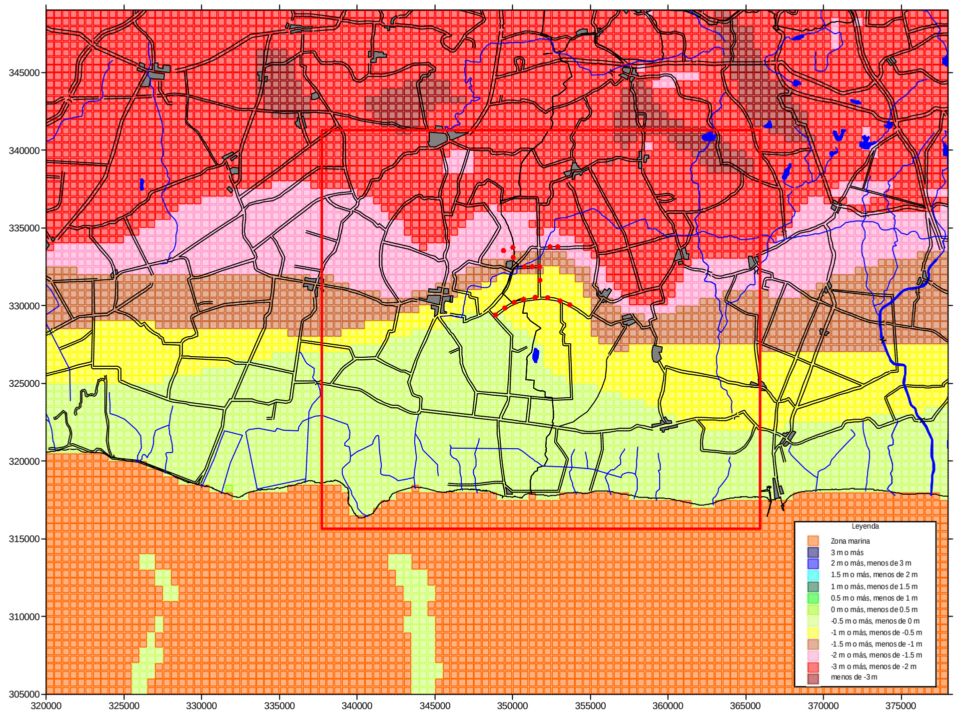
(LSU-8)

Figure 5-15: Fluctuation of the calculated groundwater levels ([Q0-RP0 Model], [Q0-RP1 Model], [Q0-RP2 Model] and [Q0-RP3 Model])

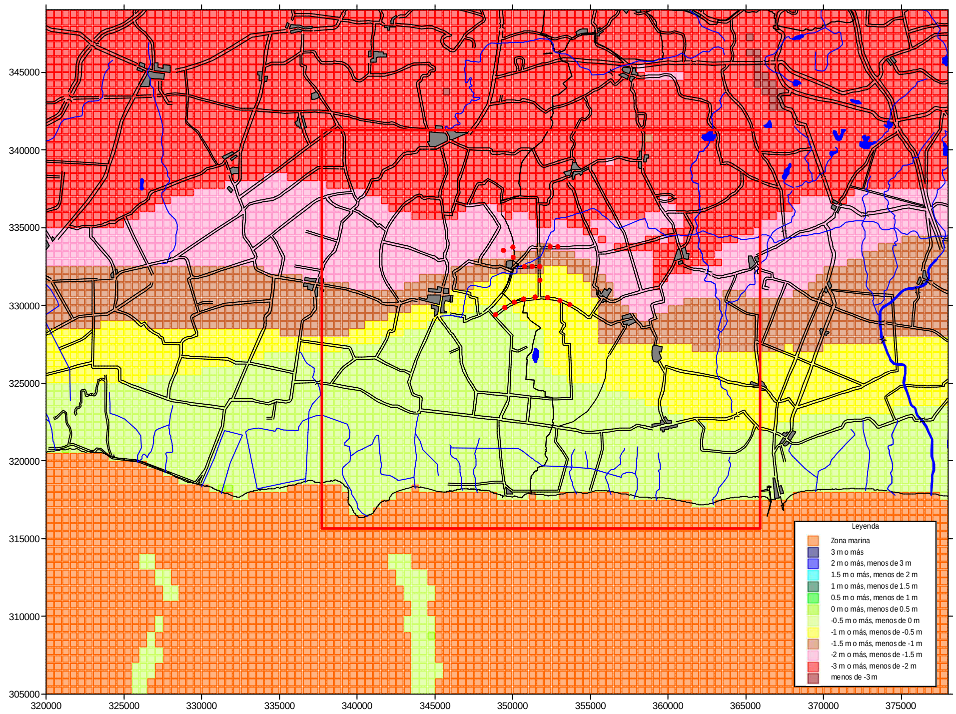
The comparison figures of the calculated groundwater level distribution between Basic Model 2 and the three cases (17th layer) are shown below. The comparison period is the same as that of basic model 1.



(End of the dry period (April 2035))

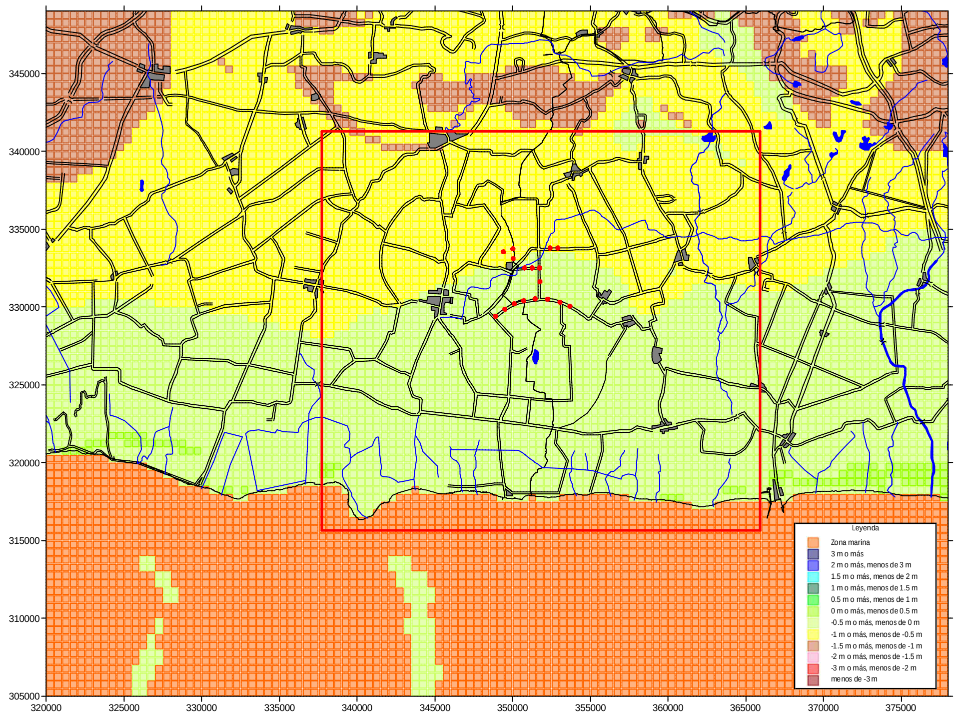


(End of the rainy period (October 2035))



(Last month (December 2035))

Figure 5-16: Comparison of calculated groundwater level distribution (17th layer) of [Q0-RP0 Model] and [Q0-RP1 Model]



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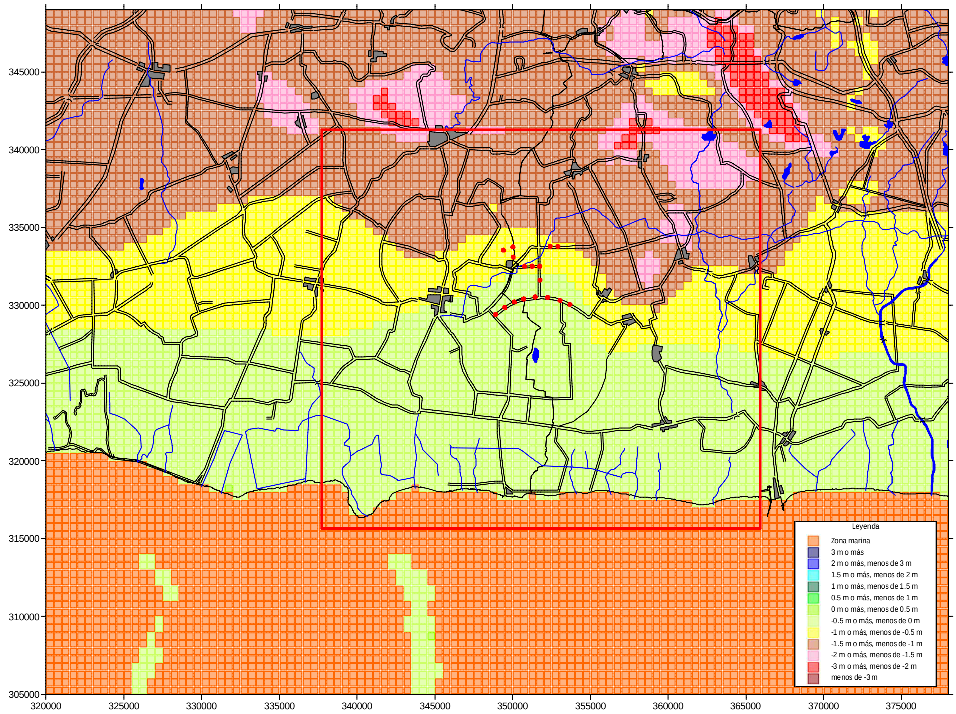
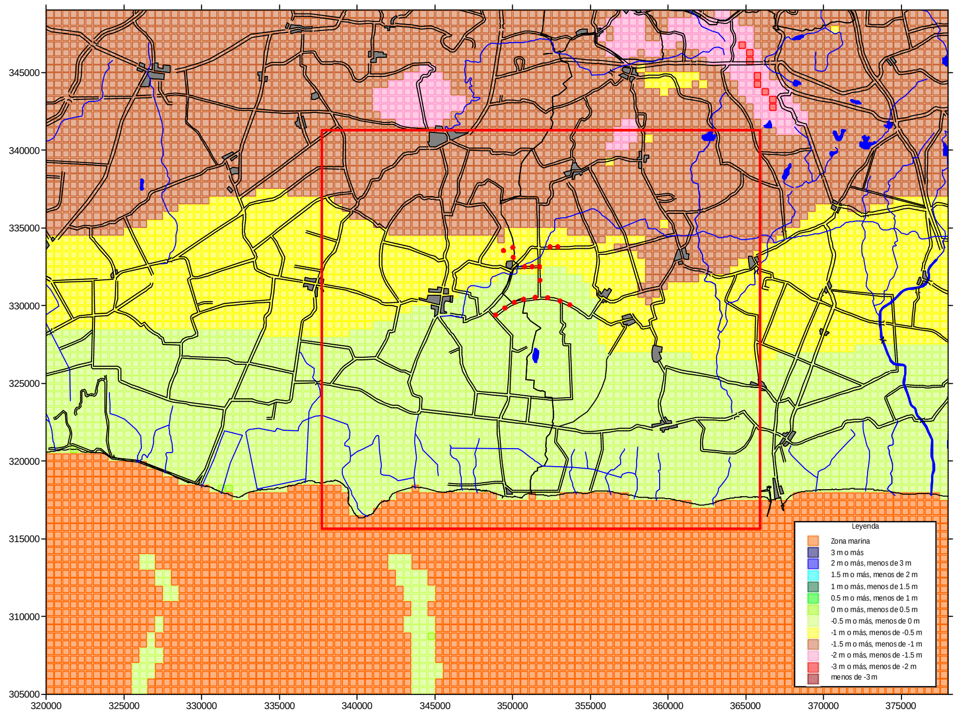
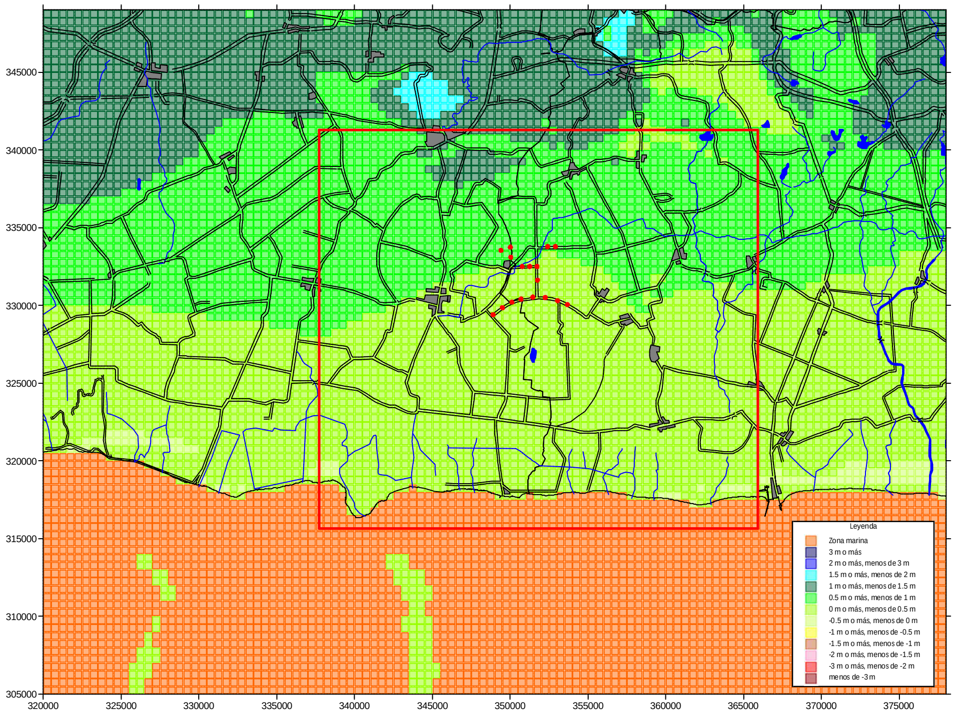


(End of the rainy period (October 2035))



(Last month (December 2035))

Figure 5-17: Comparison of calculated groundwater level distribution (17th layer) of [Q0-RP0 Model] and [Q0-RP2 Model]



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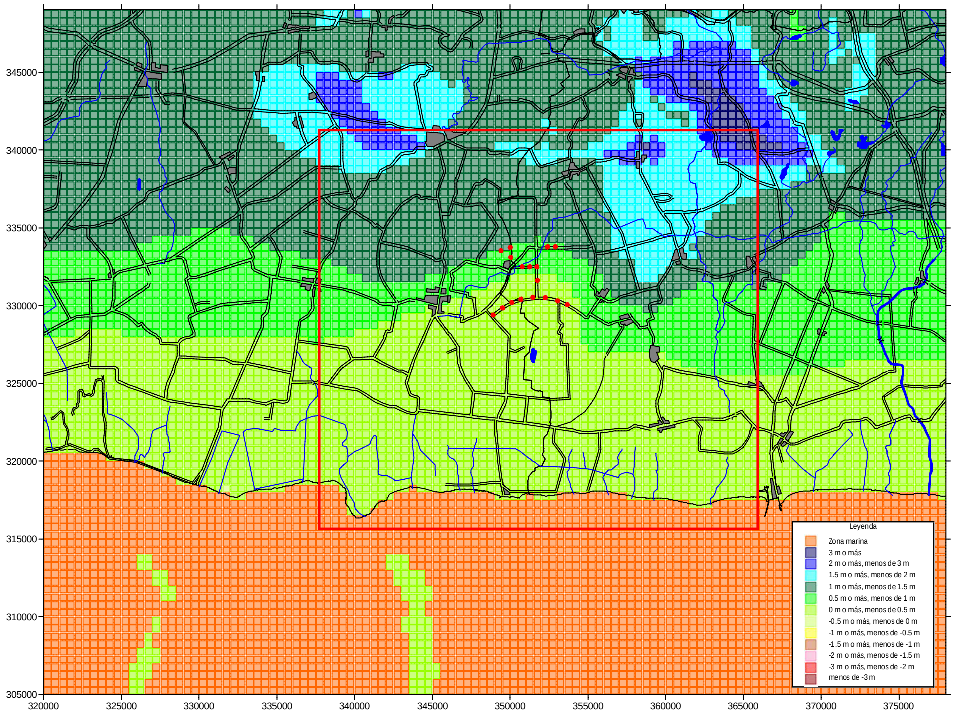

(End of the rainy period (October 2035))