Assessment of groundwater resources in an intensively irrigated area in Golegã, Portugal

Analysis of the impact of climate change and adaptation measures

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Abstract: Surface water has always been the main source of water for irrigated croplands in the proximity of big rivers, yet the security of the surface water supply is compromised by climate variability, human intervention by building reservoirs and contamination through anthropogenic or natural pollutants. Thus, dependency on groundwater as a safer source of irrigation water has been increasing significantly especially during drought years. The Tagus river holds a great socio-economic importance to Portugal. In the area of Golegã, the Tejo-Sado Alluvial aquifer system is used to secure water needs by urban as well as intensive agricultural lands. Maize as the main crop in the area has a very high consumption and the area has been going through a series of drought periods that compromises the water balance between the aquifer system and the adjacent rivers.

The results of this study confirm the strong connection between the recharge of the Tejo-Sado alluvial aquifer and the decrease in precipitation amounts in future climate change scenarios. This decrease in recharge rates directly increases the drawdown due to extraction in the area with dense well distribution. Extraction wells distribution and spacing plays a very important role in the groundwater flow regime and intensifies the effect locally. Changing crop types to vegetables instead of maize, as an adaptation scenario, was not conclusive in terms of groundwater depletion although it has shown a good contribution in decreasing the river flow depletion into the alluvial aquifer system.

Keywords: Groundwater Modeling, River-Groundwater Interaction, MODFLOW, Groundwater Recharge, Tejo-Sado Alluvial Aquifer, Climate Change

I. **Introduction**:

The fluctuation in climate conditions and the increase of awareness regarding climate change influences on the future of our planet have made it clear to all nations that there is an urge to better understand and manage our resources to guarantee the sustainability of life on Earth. Scientific evidence has prominently proved that anthropogenic emissions of GHGs are having a noticeable effect on Earth's climate. This implies the urge to act upon and work on adaptation schemes for a more sustainably managed resource such as water resource.

Groundwater safe yield depends not only on hydrogeological factors but also on physical geographical and human-induced factors that are dependent on changes in water consumption and the resulting changes in groundwater recharge, quality and abstraction rates (Zektser and Everett, 2004).

The EU Water Framework Directive adopted in October 2000, aimed at providing "good status" for surface water bodies and groundwater by 2015. A Groundwater daughter directive recognizes that groundwater is a valuable natural resource and as such should be protected from deterioration and chemical pollution, taking in consideration the qualitative as well as the quantitative aspects (European Union, 2006).

This study was carried out in Portugal, specifically on the shallow alluvial aquifer of the Tagus river basin. The Tagus river runs through Spain and Portugal with an average discharge of 600 m^3/s and average annual volume of 19 km^3. Around 66% of the water is generated in Spain "upstream", while only 34% is generated in Portugal (Cordovil *et al.*, 2018). Although there are a lot of agreements and management cooperation of the river basin between the two countries, yet the increased intensity of droughts over the years have made it a difficult management task.

II. **Objectives**:

The objectives of this study are:

- Calculate recharge of the area of interest and its spatial distribution
- Groundwater-surface water interaction characterization
- Groundwater flow modeling at present and future climate change projections
- Assessment of adaptation measures to climate change

III. **Study Area**:

The area of interest in this study is in the heart of Portugal in the former Ribatejo plain, Figure 1, which translates to Upper Tagus; in relation to Lisbon that lies at the mouth of the Tagus river. Since 1976 it has been associated with the district of Santarém. At the center of the study area lies the city of Golegã, which has a population of 3,845 inhabitants as of 2011 (INE). Agriculture as the main economic driver of the settlement of this population and some agri-dependent industries associated. The total surface area of the study area is 66 km^2.

As seen in the topographic map in Figure 1, the area is mostly flat at the central and southern part and with higher gradients in the north and a very steep gradient in the arm in the northwestern part representing the valley where the river Almonda runs all the way until reaching the Tagus river. The highest elevation point within the study area is 62.6 masl, meters above sea level, while the lowest is 6.5 masl, yet the median value of the DEM is 17.5 masl, which means a very low elevation and a very low gradient in most of the area. The area is bounded by two main water bodies, the Almonda river from the west and the Tagus river from the east. This naturally water bounded system makes it very interesting to study the interactions between the different water bodies and the groundwater resource as well since the whole socio-economic setting of the area is mainly dependent on the water resources. Hence, a well-designed water resource management program and a sustainability plan of such important economic asset is a necessity.

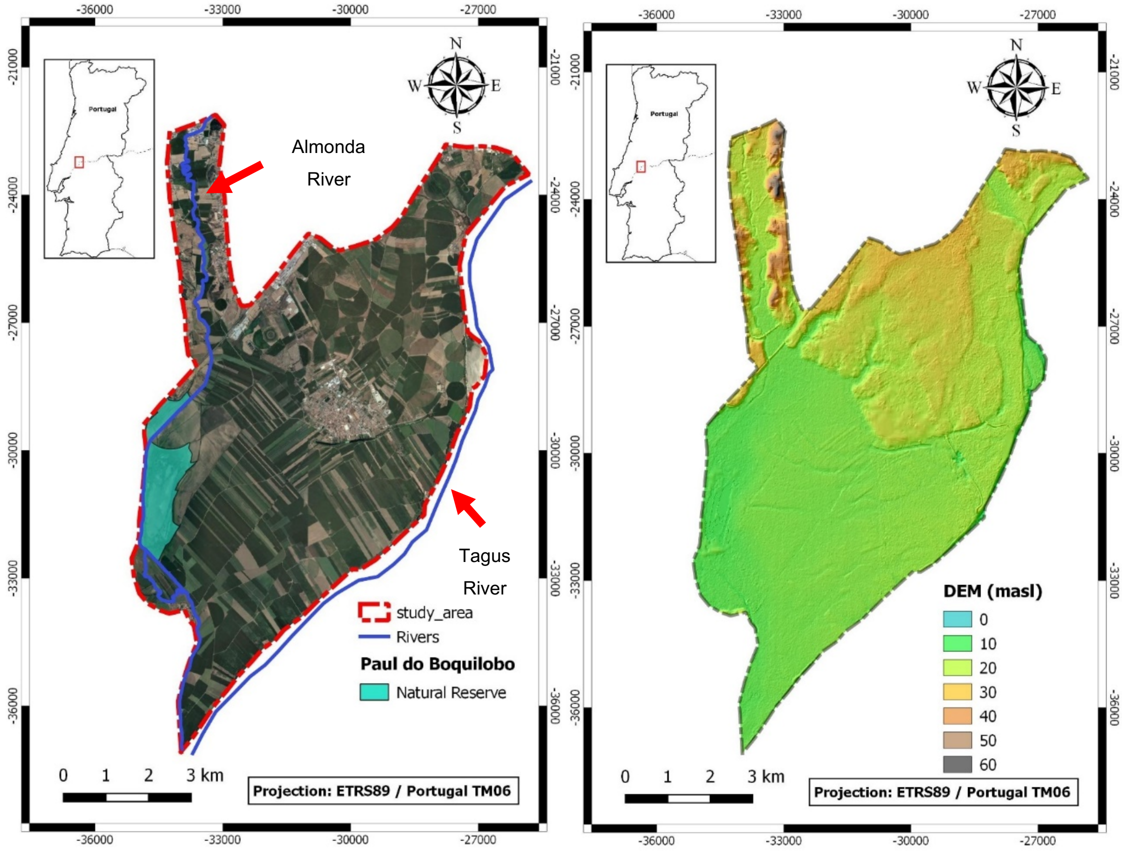


Figure 1: Location Map (Left) & Topographic Map (Right)

This study area was suggested and requested to be studied by the local agriculture association in the area which is called AGROTEJO. This is the agricultural union of the north of the Tagus valley region. They have shown interest in the study as there has not been an attempt before to model the groundwater resource on such small scale in the area.

a. **Geological Setting**:

The Tagus river originates at an elevation of about 1,500 meters in Spain and with a length of 1,000 meters and a catchment area of 80,630 km^2. Average discharge near the mouth is 400 m^3/s, but the river is characterized by extreme seasonal and annual variability. The evolution of the Lower Tagus Valley in the late Quaternary is determined by a narrow continental shelf and a deep glacial incision, rapid post-glacial relative sea-level rise, a wave-protected setting, and a large fluvial sediment supply. Since the Pliocene–Early Pleistocene the area was lifted up to 200 m above present sea level, which resulted in a staircase of Pleistocene fluvial terraces, mainly located east of the river up to a 100 m above the Holocene floodplain (Vis and Kasse, 2009).

Figure 2 shows the regional geology map of the area. The lithological units' origin is fluvial, alluvium (Holocene) and terraces (Pleistocene) and are characterized by irregularity and complexity of stratification. Alluvium deposits are generally sand and clays with intercalations of coarse sand and pebbles with thickness up to 40 meters. While terraces are composed of basal deposits of gravel and pebble followed by an interglacial complex of sand and clay.

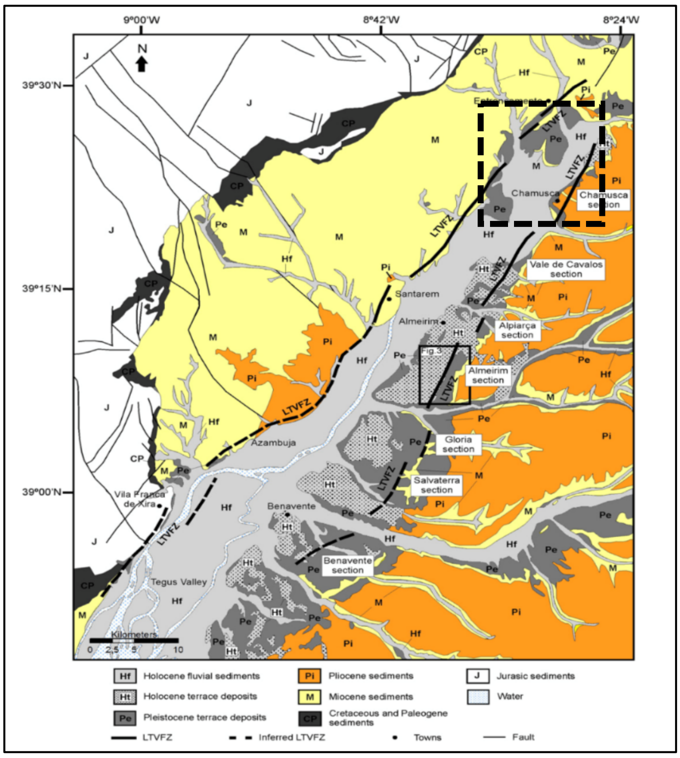


Figure 2: Regional Geology & Controlling Fault System (Study area in dotted square) (Canora *et al.*, 2015)

b. **Hydrogeological Setting**:

The Tejo-Sado alluvial aquifer system belongs to one of the most productive hydrogeological units of Portugal mainland; Tejo-Sado Miopliocenic multi-later aquifer system. The aquifer consists of alternating layers of fine and coarse sand or silty sandstone, clays, and silts. Sometimes intercalated with gravel. The base layer is composed of a layer of sand with gravel. The Almonda & Alviela tributaries can either recharge or discharge the alluvial aquifer system depending on the hydraulic potential (Mendes and Ribeiro, 2010).

The Tejo-Sado aquifer system is divided into three different sub-systems; the shallow and most recent alluvial aquifer subsystem, the right bank aquifer subsystem and the left bank aquifer subsystem. This study is concerned with the alluvial system as the agricultural sector in the area is mainly dependent on this system as it is the most economically efficient system for utilization.

Within the study area and surrounding, twelve borehole log data points were provided by the Administração da Região Hidrografica Do Tejo (ARH Tejo). Figure 3 shows the spatial distribution of those borehole logs, indicating a higher density in the northern and southern parts of the study area and lower density in the central part with 3 to 5 meters separation.

The borehole records in Figure 3, provided by ARH Tejo, show that the main capture zone is in the sands and gravel layers of the alluvium and terraces as they have the highest transmissivity values. Generally, transmissivity increases from the margins towards the central part of the aquifer.

Figure 3: Borehole Logs location map (Z magnification of 20 times)

c. **Agriculture**:

Agriculture is the primary economic sector in the region of Golegã as it is in a region of fertile soil, irrigated by two rivers, Tagus and Almonda. Agri-business is developed in the transition zone of the Paul do Boquilobo biosphere reserve according to the good agriculture practice. Agriculture lands cover 95% of the study area. The main crop type in the area is maize, occupying 90% of the land followed by 6% of vegetable production and 4% of vineyards, olive trees and some sunflower in the south near Azinhaga as shown in Figure 4.

In 2007, a study in an unpublished report on an area of 11,713 ha that lies on the left bank of the Tagus river opposite to the study area, specifically in Pinheiro Grande and Carregueira, concludes that the annual agricultural crops occupy 66.6% in which maize occupies 80% and other vegetables like tomato, potato, and bell pepper occupy the other 20%. By including the efficiency of the irrigation systems, assuming 60% efficiency by furrow irrigation, 90% by drip irrigation and 85% by sprinklers, the total annual consumption was 1099 mm and 1204 mm by furrow irrigation of maize in an average year and critical year respectively.

To calculate the present actual consumption of the irrigated area, it was assumed that in the year 2007, the time when the report was made, 70% of the annual cultivated maize was irrigated by furrow irrigation systems. For calculating present time consumption, it was assumed that only 10% of the total annual cultivated maize is irrigated by furrow irrigation systems and the rest is irrigated by sprinkler systems. This results in a total annual consumption of 7,399,843 m3 of water by maize and 1,517,542 m^3 my other crops in an average year. Thus, the total annual consumption in an average year is 8,917,385 m^3 of water for an area of 11,713 ha.

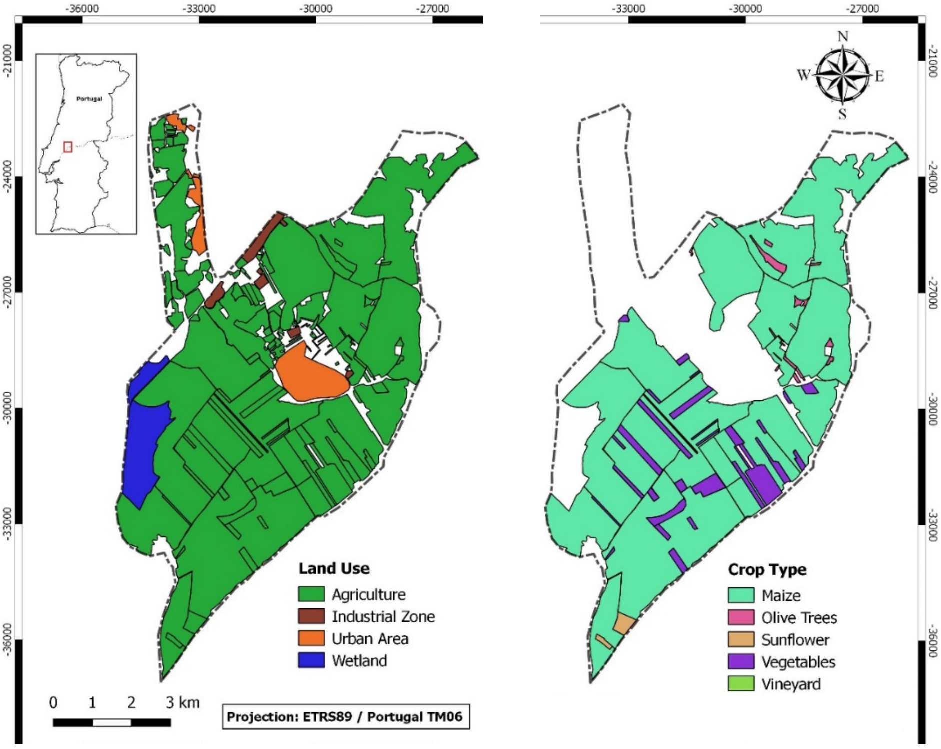


Figure 4: Land Use & Crop Type Maps

IV. Methodology

a. Recharge Estimation

Drought Index

According to Vicente-Serrano, Beguería and López-Moreno, 2010, SPEI is based on precipitation and temperature data and has the advantage of being multi-scalar in comparison to PDI, which is crucial in drought analysis. SPEI is like SPI calculation but includes the role of temperature variability effect on drought assessment. Thus, SPEI was decided to be the best drought index to be used to choose a normal year within the past decade so that normal conditions would be modeled. A freely available software has been developed by Vicente-Serrano, Beguería and López-Moreno, 2010 to calculate the SPEI. SPEI was calculated using monthly precipitation and the potential evapotranspiration from the Thornthwaite method as input data. A simple water balance is then calculated as the difference between the precipitation and PET on a monthly time scale from the year 1989 till 2017. An accumulated time difference is calculated for a time series of 6 months. This measure the anomalies in the PT-PET values based on a comparison of observed total difference for an accumulated period of interest, 6-months in this case, with the long-term historical record of difference.

Real Evapotranspiration

Remotely sensed MODIS Global Terrestrial Evapotranspiration (ET) Product (NASA MOD16A2) was used. The MOD16 algorithm is based on the logic of the Penman-Monteith equation, which includes inputs of daily meteorological reanalysis data along with MODIS remotely sensed data products such as vegetation property dynamics, albedo, and land cover. This dataset is available in 0.5 km spatial resolution.

The pixel value of evapotranspiration is the sum of all eight days within the composite period. Due to the size of the raster datasets and for time constraints, only one raster was decided to be used as a representation of each month of the model time period. Initially, the accumulative raster of the first 8 days of the month was downloaded and processed for further calculation of the monthly evapotranspiration. But it was noticed that in some months, pixels of NODATA started appearing and it is associated with cloud cover at the time of remote sensing, especially that they coincided with the rainy season. Thus, all raster datasets of these months were downloaded and compared and the raster with the least number of NODATA available was used as a representative for the month.

The unit of evapotranspiration is given in kg/m^2 for an accumulation of 8 days, thus on a GIS-based platform, namely QGIS, calculations were done to transform the units from kg/m^2 to monthly cumulative in mm/day as in equation [1].

$$ETR_{Monthly\ Cumulative} = \frac{ETR_i * 1000}{1000 * 8} \times Number\ of\ days\ in\ the\ month \qquad [1]$$

Recharge Calculation

Finally, the recharge was calculated by subtracting the real evapotranspiration from the mean monthly precipitation values for each month and then added all together to give the total annual recharge in the study area.

b. Groundwater Flow Modeling

Groundwater flow models have been widely used for studying regional steady-state flow in aquifer systems; regional changes in the hydraulic head caused by changes in discharge or recharge (Fetter, 2001). Groundwater flow is controlled by the laws of physics and thermodynamics, and thus it can be described by differential equations. Flow is a function of variables described in partial differential equations in which x, y, and z represent the spatial coordinates and t as the time, all are independent variables.

From the law of mass conservation, partial differential equations of the groundwater flow are derived. This law states that there can be no change in the net mass of the fluid in a small aquifer volume and that any change in this mass has to be compensated by a change in the mass flux out of that volume or a change in the mass stored in it, or both (Fetter, 2001). This equation in the steady state condition is as in equation [2]:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \qquad [2]$$

For isotropic aquifers, where K is constant in all directions, Laplace equation becomes as in equation [3] and it is the governing equation for groundwater flow in homogeneous and isotropic aquifer system under steady-state conditions.

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad [3]$$

In unconfined aquifers, water is derived from the storage by vertical drainage of water in the pore spaces resulting in a decline in the water table at extractions wells fields where water is pumped out for different water uses. Thus, the saturated thickness of the aquifer is subject to change with time and hence the ability of the aquifer to transmit water. Transmissivity, T, is the product of the hydraulic conductivity, K, and the saturated thickness, b, which is measured from the bottom of the aquifer to the water table level (T=Kb).

Significant advances in the regional flow system analysis were driven by the application of 3D groundwater flow models. The most widely used industrial groundwater modeling tool is MODFLOW since its release in 1988 (Zhou and Li, 2011). MODFLOW is a block centered finite difference groundwater flow model. It only simulates saturated flow in a porous medium with uniform temperature and density. Modeled layers can be confined, unconfined or combined and it simulates recharge, evapotranspiration, areal recharge, flow to wells, flow to drains and flows through river beds (Fetter, 2001).

The following section describes in more detail the 3D groundwater flow model inputs and development setup. For this study, Ground Water Modeling Software (GMS 10.3) was used to simulate the groundwater flow system to better understand the flow system performance under current conditions as well as interaction with surrounding surface water bodies. And then running several global change scenarios to be able to come up with adaptive solutions for the sustainability of water use in the area.

V. Model Setup

a. Conceptual Model

The conceptual model describes the hydrogeological framework, groundwater flow, recharge, evapotranspiration, discharge to streams, water use and hydraulic properties of the alluvial aquifer system of the Tagus around the city of Golegã. The hydrogeological framework describes the physical dimensions and location of the aquifer. The boundaries of the alluvial aquifer within the study area were defined according to the limits defined by the Portuguese Environmental Agency (APA). This indicates a lateral contact between the alluvial aquifer and the deeper confined aquifer of the right bank of the Tagus river in the western part of the study area. According to Almeida et al., 2000, there is an interaction between the two aquifer subsystems.

From the east and the south-western limits, the aquifer is bounded by the Tagus river and the Almonda river respectively. The interaction between both rivers and the aquifer system is among the most important aspects of this study. It is assumed that the groundwater flows toward the east from the high lands on the northwestern part and discharges in the Tagus river. Recharge to the Tejo-Sado alluvial aquifer is mainly through infiltration of precipitation especially that most of the study area has a very low relief which makes runoff negligible. It is also believed that the Almonda river contributes to the aquifer from the west following the terrain relief. Finally, extraction wells primarily are for irrigation and domestic water supplies and they act as the main external pressure on the aquifer system that needs to be well explored.

b. Hydrogeological Model

Twelve borehole logs descriptions provided by the local Portuguese environmental body, ARH Tejo, were used to build the geological model. A software called GMS, Groundwater Modeling System was used for building the geological model. The software is developed by a US based company called AQUAVEO and a license provided by Instituto Superior Técnico was used.

The preliminary lithology correlation on cross sections showed a thick sequence of coarse sand and gravel layers intercalated with thin clay layers in the northern part of the area. This layer decreases in thickness in all directions and pinches out towards a finer sediment of sand closer to the river bank and towards the western edge of the aquifer. In the northern part, this layer’s thickness ranges between 70 meters in the west and 20 meters at the river bank. In the southernmost part of the area, the same coarse gravel sediment appears with a much less thickness, around 20 meters, and pinches out towards the central south part into coarse gravel.

Furthermore, the model was more simplified to match the level of detail of the groundwater characteristics in the aquifer. All sand and gravel layers were combined in one aquifer layer topped by a thin layer of soil in some areas and bounded by a clay layer at the bottom. Finally, a 3D model of the extent of the geological units was build using the function Solids in GMS software as shown in Figure 5.

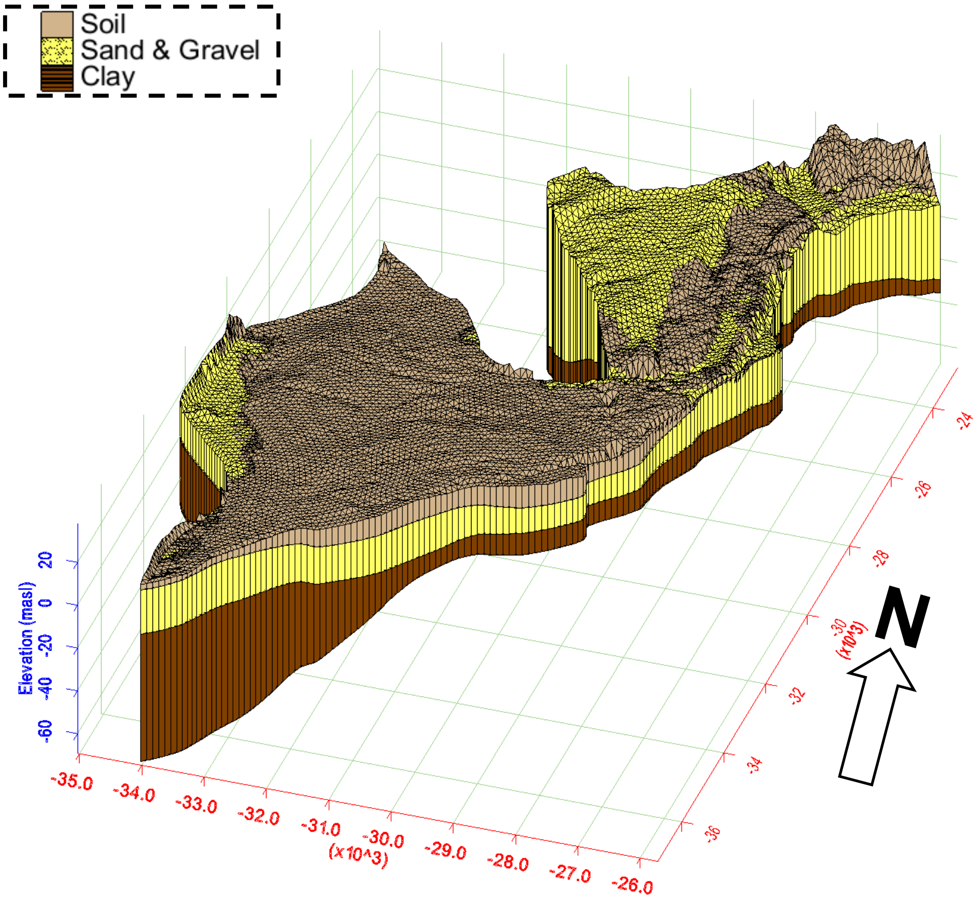


Figure 5: Hydrogeological Model

c. Groundwater Flow Model

Boundary Conditions

The two rivers, Tagus and Almonda, were defined as a river package as well as a small stream that cuts through the north part of the study area. Due to the lack of data on the river stage in the national database (SNIRH), the river stage at the stations Barquinha, Chamusca, Ponte Chamusca, and Quinta da Cardiga was used. From the data available at the station Ponte Chamusca, an average depth of 5 meters in the Tagus river was deducted and used in the river package. For the Almonda river as well as the small stream in the north, the DEM was used to assign river stage and an average depth of 1 meter was assumed, based on field observation, and a calculated raster was used to assign for the bottom elevation.

The way the river package works in GMS works as follow: by defining river stage and river bottom at specified locations along the river, the elevation and stage are assumed to vary linearly between the points. Thus, the arc defining the river is interpolated linearly between the points. The initial riverbed conductance that was used for the model was calculated using the equation [4]

$$\textbf{Riverbed Leakage} = k \times \mathrm{w} \times \frac{1}{b} \qquad [4]$$

Where k is the riverbed hydraulic conductivity, w is the river width, b is the riverbed thickness over the river segment. The average width of the Tagus river in this area is 250 meters and the thickness of the riverbed material was estimated to be 0.4 meters, thus a riverbed conductance of 40 m^2/d/m was used. And since there is no literature mentioning the Almonda riverbed conductance, the same value was used for the initial model setup as well and then tested for sensitivity.

Hydraulic Conductivity

According to the report of the aquifer systems of Portugal, Almeida et al., 2000, the following statistical values of the most important hydraulic characteristics of the Tejo-Sado alluvial aquifer subsystem are provided as shown in Table 1:

Table 1: Aquifer Hydraulic Parameters

Parameter	*Average*	*Median*	*Maximum*
Productivity (l/s)	19.9	12	80
Transmissivity (m2/d)	1585	1493	5575
Hydraulic Conductivity (m/d)	140	122	464

Where transmissivity is calculated using the formula T=Kh, where T is transmissivity, K is the hydraulic conductivity and h is the saturated aquifer thickness. Based on these values, an initial value of 120 m/day was used. Further optimization was done for this parameter and will be discussed in a later section.

Extraction Wells

Pumping rates were calculated according to the water needs of the crop type and the area of irrigated land based on the statistical study presented in the study area section.

By calculating the area of each pivot in the study area and multiplying by the consumption rate, a pumping value was computed for each well inside a pivot. Since there is no way to assign every other well to a specific plot of land, the remaining of the total water need by all the irrigated area was divided by the number of wells outside of the pivots and a constant value was given (1,238 m^3/day).

Water Budget Zoning

To be able to analyze the individual interaction between each of the Tagus river and Almonda river with the groundwater aquifer system, the study area was divided into three different zones as shown in Figure 6.

Zone One: Covers the northern part of the study area where the Tagus river bounds from the east, the specified head, representing the interaction with the Tejo-Sado right bank aquifer subsystem, bounds from the west and a small stream that flows into the Tagus. Also, 60 % of the pivot extraction wells are in this zone.

Zone Two: Covers the south-east part of the study area where the Tagus river bounds from the west and the less dense area of the extraction wells in the south are.

Zone Three: Covers the southeastern part of the study area where the Almonda river bounds from the west and the specified head bounds from the north. The highly dense extraction wells are in this zone.

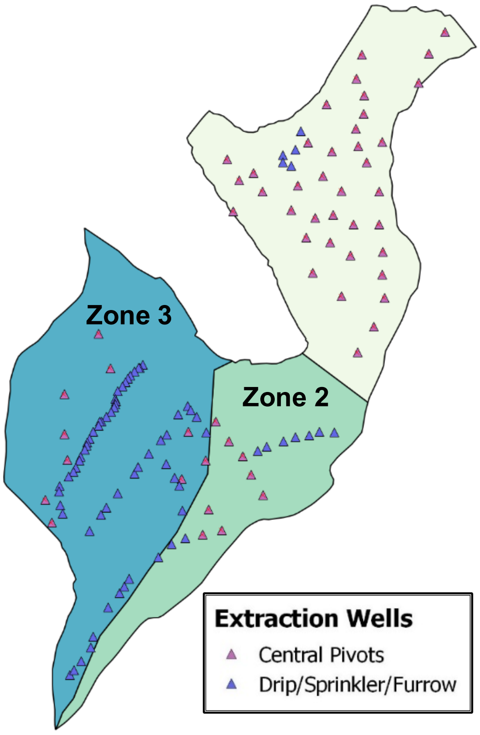


Figure 6: Water Budget Zones

Model Calibration

Calibration is the process of systematically altering certain model parameters and the model is repeatedly run until the computed solution matches the observed values within an acceptable confidence level. During the field visit, 4 wells were found accessible to measure water level in them. These wells along with one piezometer available in the national monitoring network (SNIRH) were used as calibration points for the model.

Aquifer hydraulic conductivity and river conductance where systematically changed in the model input packages and the results were noted. To quantify the model sensitivity and performance several indicators were used. First, the sum of squared differences between the observed and modeled head values at the observation points was calculated and correlated to the initial run.

The Nash Sutcliffe coefficient, NSE, by Nash and Sutcliffe, 1970 was used to measure the model efficiency and performance. The NSE is a way to measure the fit between predicted and measured values. It measures the sum of deviations of the observations of the observations from a linear regression line with a slope of one. If the observed values are equal to the predicted values, a NSE value of one is obtained. The equation to calculate the NSE is as follows:

$$\mathbf{NSE} = \frac{\sum_{i-1}^{n}(Q_m - \overline{Q_m})^2 - \sum_{i-1}^{n}(Q_m - Q_p)^2}{\sum_{i-1}^{n}(Q_m - \overline{Q_m})^2} \qquad [5]$$

Where; Q_m is the measure value, Q_p is the predicted value and the $\overline{Q_m}$ is the arithmetic mean of the measured value.

Using an automatic parameter estimation method (PEST) on GMS software, the spatial distribution of the hydraulic conductivity was estimated aiming for a better fit model. PEST is an inverse modeling technique that iteratively adjusts a one or several parameters and repeatedly launches the model until the computed output is equal to the observed values or until the error is minimized. A pilot point guided inverse model estimates the parameter at the pilot points to minimize the objective function. A 2D scatter point grid was created with a spacing of 500 meters in the x and y directions to guide the automatic estimation inverse model. A total number of 213 pilot points were used as shown in Figure 7.

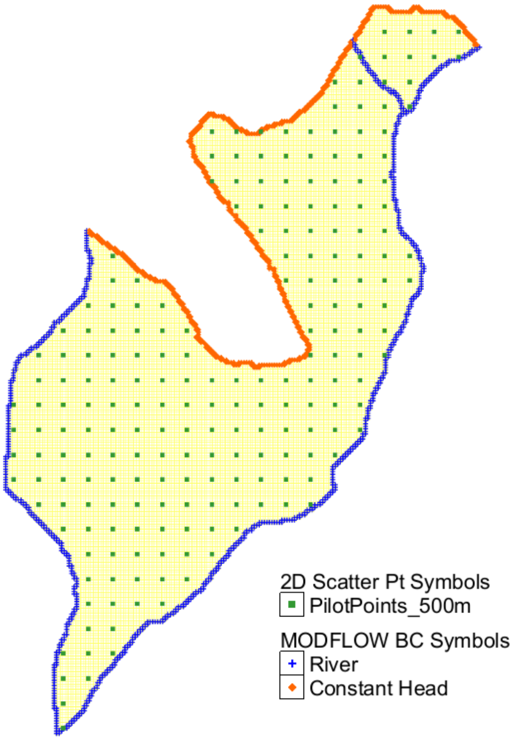


Figure 7: Pilot Points

VI. Results & Discussion

a. Recharge Estimation

The first objective of this research is to estimate the recharge rate as well as the total recharge volume of the shallow Tejo-Sado alluvial aquifer in the proximity of the city of Golegã. The SPEI index was chosen to identify a normal year, where the SPEI value is lowest, to be used as the modeled period. Results obtained are shown in Figure 8 for the past 27 years. The hydrologic year of 2015/2016 shows the lowest overall SPEI values since 2010 and thus was chosen for the modeling period.

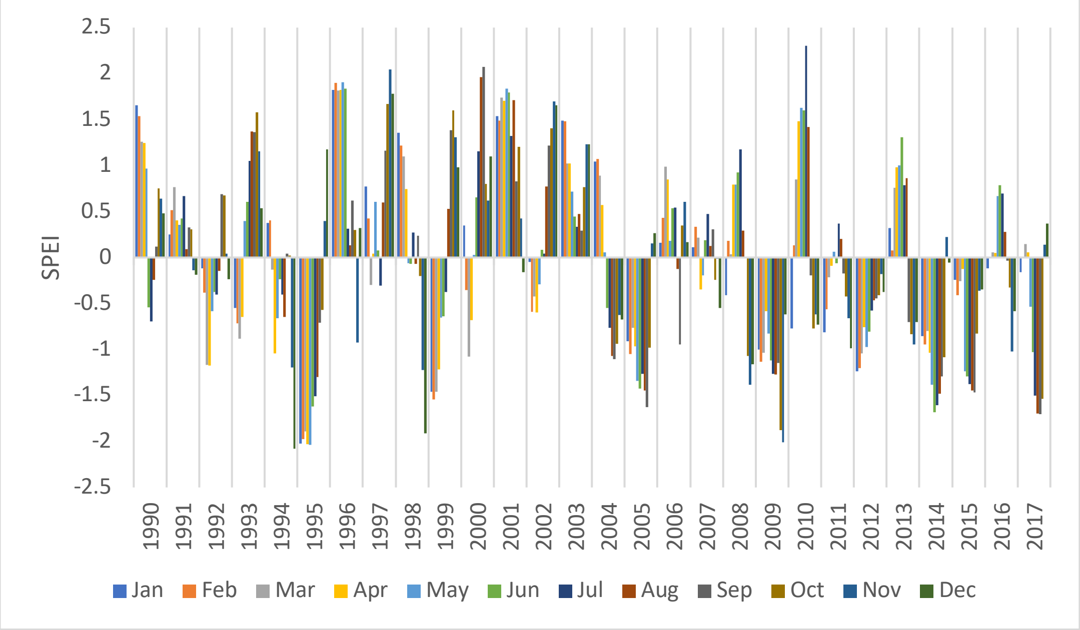


Figure 8: SPEI Drought Index

After processing the raster maps of real evapotranspiration and monthly precipitation and subtracting them to obtain monthly recharge, they were summed up to give the spatial distribution of the total annual real evapotranspiration, shown in Figure 9. The resulting raster has the same resolution of the original MODIS layers, 500 m resolution. The map shows a wide range of recharge values from a maximum of 0.00082 m/day and a median of 0.0007 m/day. There is no specific spatial trend or focal points in terms of recharge noticed from the results, yet, a high recharge area exists in the central part of the study area, south west of the city of Golegã. Another high recharge area is in the northern high relief area which does not make sense in terms of water flow as the water is expected to run on the surface towards the eastern low lands into the river.

Relatively low recharge is noticed in the southwestern part of the study area where the Paul do Boquilobo biosphere reserve exists. This is due to the high evapotranspiration rates in this area because of the dense vegetation in the reserve area as well as the evaporation from the wetland within.

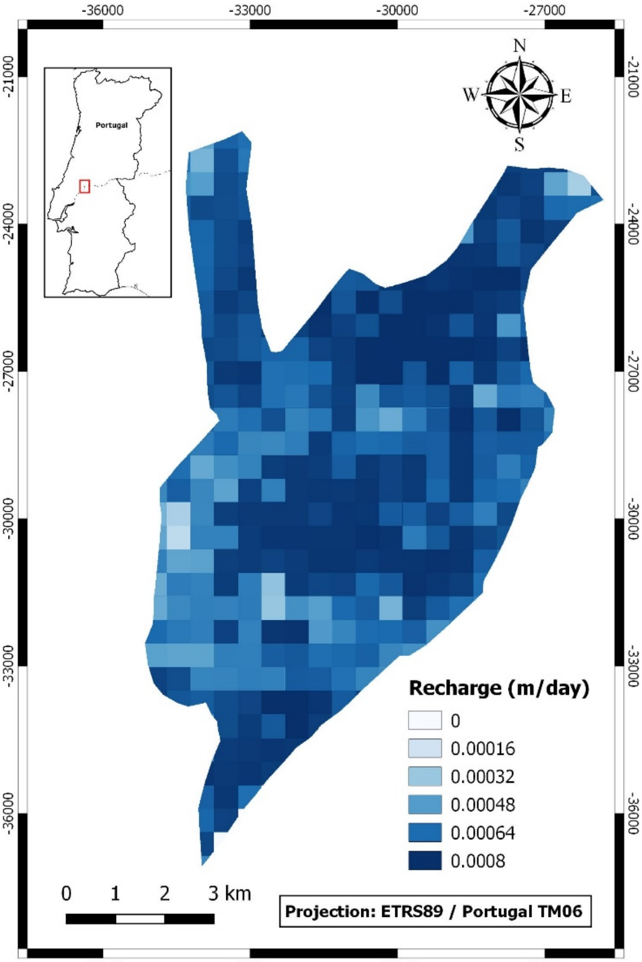


Figure 9: Total Annual Recharge (m/day)

b. **Pre-calibrated Model**

The total volumetric in/outflow balance is 901,018 m^3 with a percentage of discrepancy between In and outflow volumes of 9×10^{-6}. This is the first indication of the good performance of the model. To further check the model performance, the sum of squared difference of the observation wells is calculated and it is 5.176 m^2, which is minimal and indicates good model performance as well. The last model performance indicator used is the Nash–Sutcliffe model efficiency coefficient (NSE), which was 0.91. The closer NSE value to one, the better the model performance is. Thus, the overall performance of the model so far is good.

Figure 10 shows the global water budget of the initial groundwater flow model. Results indicate that the constant head and river leakage have the highest contribution to the water budget. On the inflow side of the budget, the constant head has the highest contribution with 84% of the total inflow volume into the aquifer system while river leakage and recharge contribute by 12% and 4% respectively. In absolute values, the constant head boundary inflows 756,098 m^3/day while all rivers inflow 109,831 m^3/day into the aquifer system. On the outflow side of the budget, constant and river leakage contribution are very close to each other with 46% and 42% of the outflow is contributed respectively, while extraction wells for agriculture use consume 12% of the total outflow with a total extraction rate of 109,290 m^3/day. Total outflow from the aquifer system to the contact head boundary is 411,553 m^3/day and 380,175 m^3/day outflows towards the rivers.

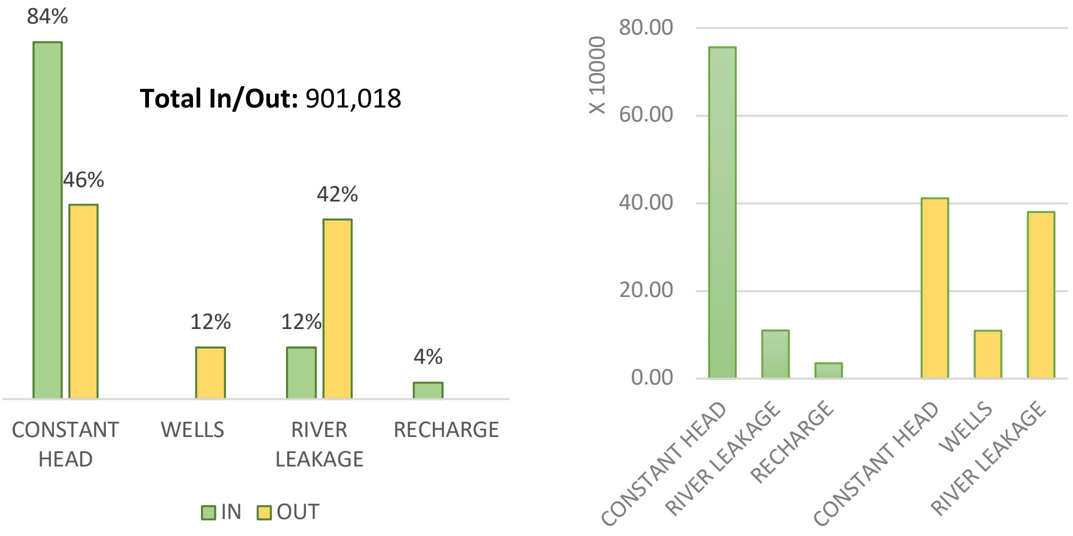


Figure 10: Global Water Budget of Initial Model (Left: Percentage from the total in/out, Right: Total flow in m^3/day)

By calculating the difference between the total inflow and total outflow of zones one and two together, the relationship between the aquifer system and the Tagus river can be analyzed. After subtracting the total outflow from the total inflow from river leakage a deficit of 314,301 m^3/day was found. Knowing that the Tagus boundary on the east is 17 km long, this gives a discharge of 18,488 m^3/day/km into the river. This concludes that the aquifer contributes to the Tagus river discharge especially in the northern part, zone one, where the high gradient induces the flow towards the river and a widely distributed extraction wells distribution does not put too much pressure on the groundwater resource as it is compensated from the constant head boundary. As for the Almonda river, a surplus of 43,957 m^3/day is calculated, meaning that the river contributes to the aquifer much more than the aquifer contribution to the river discharge. Almonda river boundary is 11 km long, which concludes a total discharge of 3,996 m^3/day/km into the aquifer.

c. Model Calibration

Sensitivity Analysis

The first step into model calibration was performing a sensitivity analysis to define the hydrological parameters which the model is sensitive to. A systematic trial and error method was used and resulted in the following results presented in Table 2. Change in SSD is the difference between the initial model SSD and the sensitivity simulation SSD. The change % is the ratio between the change in SSD and the initial SSD.

Table 2 :Qualitative sensitivity analysis indicators (RC: Riverbed Conductance, HK: Hydraulic Conductivity)

PARAMETER	RC (M/DAY)	HK (M/DAY)	MULTIPLIER	SSD	CHANGE IN SSD	CHANGE %	NSE
INITIAL CONDITIONS	40	120		5.176			0.914
RC 1	20	120	0.5	5.454	-0.278	-5%	0.910
RC 2	80	120	2	5.028	0.148	3%	0.917
RC 3	160	120	4	4.930	0.246	5%	0.918
HK 1	40	60	0.5	59.665	-54.488	-1053%	0.013
HK 2	40	240	2	8.466	-3.290	-64%	0.860
HK 3	40	180	1.5	5.581	-0.404	-8%	0.908
HK 4	40	150	1.25	4.539	0.636	12%	0.925

Further on, one simulation was run with zero recharge input to test the model performance and sensitivity toward recharge and this resulted in a 48% decrease in the SSD which indicates sensitivity to recharge and indicates good recharge estimation. Overall, using the qualitative indicators of model performance, it was proved that the model is significantly sensitive towards the hydraulic conductivity and less or even slightly sensitive towards riverbed conductance.

To quantitatively assess the model, absolute water budget components were tested during the sensitivity analysis process. Changing the river bed conductance showed significant changes in river leakage in both Inflow and outflow with a maximum change of 110% and 48% of the initial model respectively. While constant head contributions had minimal changes of a maximum of 6%.

Conclusively, the optimal values for the two variables after sensitivity analysis and manual calibration were 160 m/day hydraulic conductivity and 150 m/day riverbed conductance. These values have resulted in a 15% improvement in the model performance in the SSD and 2% in the NSE.

Automatic Parameter Estimation

The second step in model calibration is using an automatic parameter estimation method called PEST that is embedded in the GMS software and can be applied to MODFLOW as an inverse modeling technique. Pilot points were used with a spacing of 500 m in both x and y directions as in Figure 7. The main reason behind this method is not only to try to better fit the model but also to estimate the special distribution of the hydraulic conductivity of the aquifer to better understand the hydrodynamics of the aquifer system.

An initial value of 150 m/day of hydraulic conductivity was given to the points to guide the inverse model iteration process. A minimum of 80 m/day and a maximum of 200 m/day were used as the limiting values of hydraulic conductivity as described in the previous literature.

Figure 11 shows the computed groundwater flow heads overlain by arrows of the vector direction of the groundwater flow. The scale of the flow vectors is proportional to the magnitude, thus longer arrows indicate higher flow velocity. In relation to the initial model, both plotted in Figure 11, there is no significant change in the magnitude of the groundwater flow. By comparing the groundwater flow direction, a minor change in the flow direction is noticed at the west with the constant head boundary, which will affect the absolute water budget values, but the general direction is maintained flowing from the west to the east and flowing into the Tagus river. In the southern part, a change in the computed head is noticed especially closer to the Tagus river. The drawdown is reduced by around one meter, contour ten indicates the change and the direction of the flow close to the river reversed from going towards the river to be more parallel to or towards the Tagus river.

The analysis of the computed hydraulic conductivity from the automatic parameter estimation method was made and correlated to observed aquifer properties. Figure 12 shows the spatial distribution map of the computed aquifer hydraulic conductivity. The map shows an increasing trend in the hydraulic conductivity from west to east. Zone one shows a very significant high gradient in hydraulic conductivity. In the south, zones two and three, show a gentle gradient from north to south increasing toward the riverside.

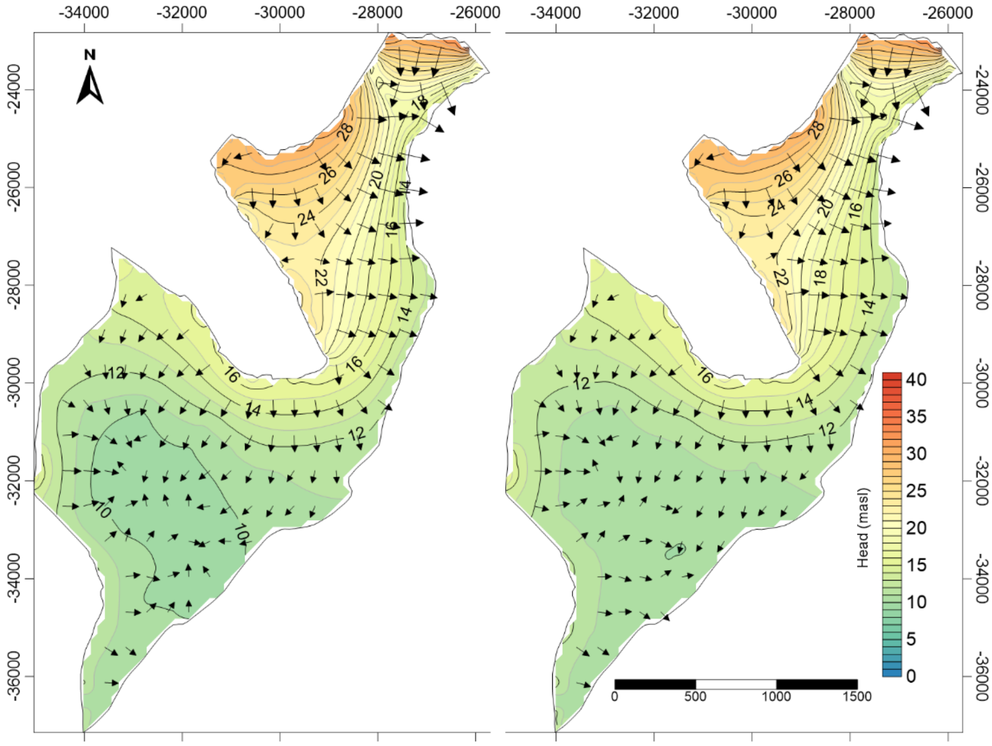


Figure 11: Groundwater Flow in the Pre-Calibrated Model (Left) and the PEST Calibrated Model (Right)

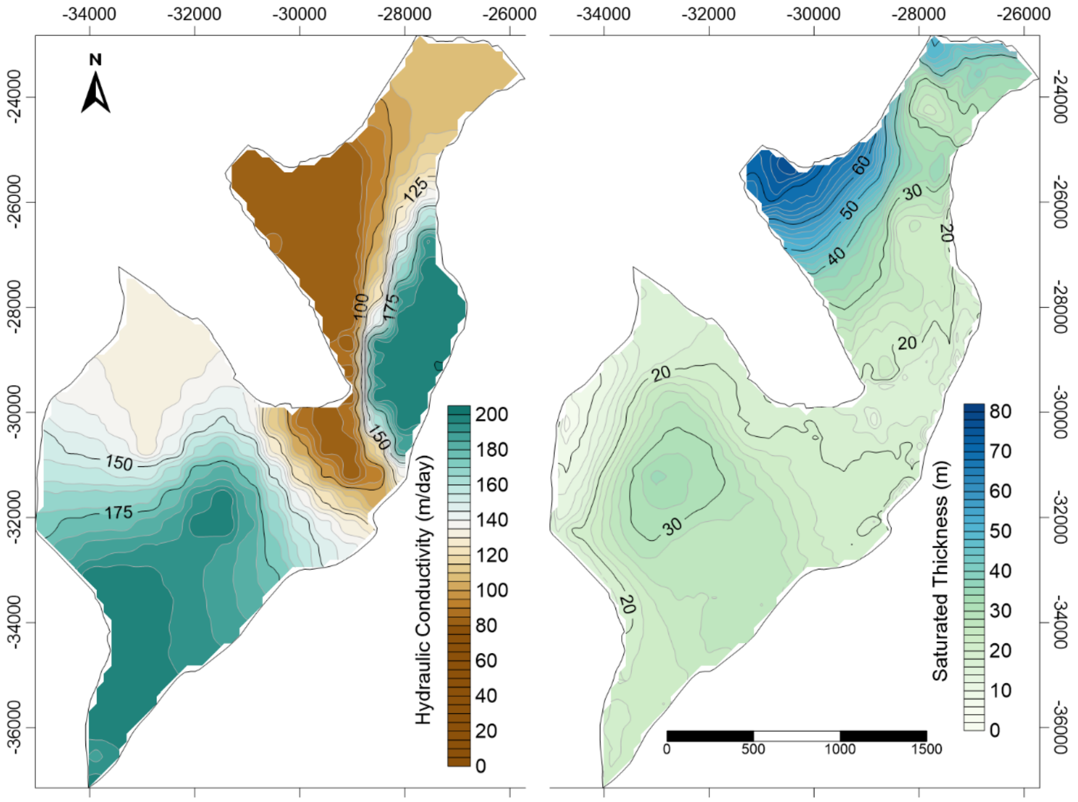


Figure 12: Estimated Hydraulic Conductivity (Left) and Aquifer Thickness (Right)

Considering h as the fully saturated part of the aquifer, bounded between the bottom and the water table level which is considered as the surface level in this study as the initial head, the transmissivity, T, of the aquifer follows the law T=Kh, and thus hydraulic conductivity is inversely proportional to the saturated thickness of the aquifer. And since the thickness decreases in the northern part from west to east, the hydraulic conductivity should be increasing accordingly.

To emphasize the effect of the extraction wells and analyze the response of the groundwater head and water table toward the extraction for agricultural lands in the study area, a simulation was run using the output hydraulic conductivity from the PEST simulation and with zero extractions. By subtracting the computed head of the simulation with extraction from the computed head with no extraction, a drawdown map was produced as shown in Figure 13. Significant drawdown, up to 3.5 meters, is shown because of the groundwater extraction.

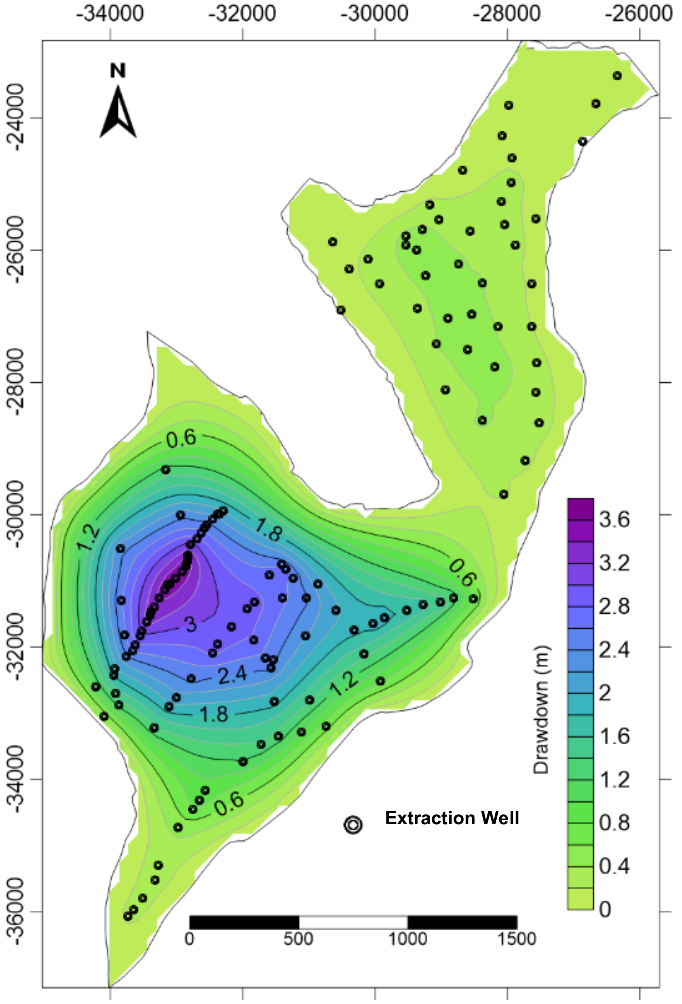


Figure 13: Drawdown in PEST calibrated model

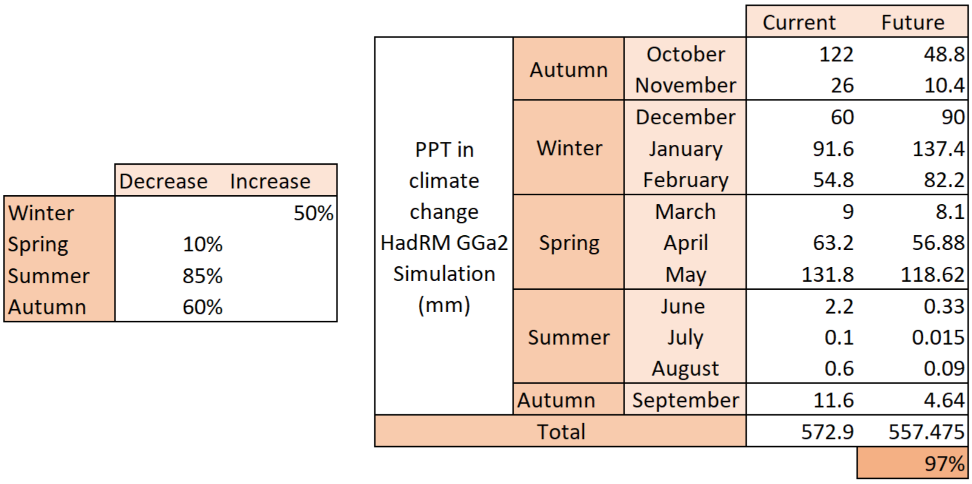
d. **Climate Change & Adaptation Scenarios**

Decrease in recharge

The report of climate change scenarios of Portugal by Miranda *et al.*, 2002, shows the relative change in accumulated precipitation under climate warming scenario, HadRM GGa2 simulation.

Table 3 shows the actual seasonal precipitation values of the hydrological year of 2015/2016 along with the estimated seasonal precipitation values for the future climate change scenario. An increase of 50% in precipitation during winter time and a decrease of 10%, 85% and 60% during spring, summer, and autumn respectively. The total annual precipitation decreases from 573 mm to 558 mm by a percentage of 3%. Recharge was recalculated with the future precipitation and temperature values and MODFLOW simulation was run.

Table 3: Current & future seasonal precipitation



	Decrease	Increase
Winter		50%
Spring	10%	
Summer	85%	
Autumn	60%	

			Current	Future
PPT in climate change HadRM GGa2 Simulation (mm)	Autumn	October	122	48.8
		November	26	10.4
	Winter	December	60	90
		January	91.6	137.4
		February	54.8	82.2
	Spring	March	9	8.1
		April	63.2	56.88
		May	131.8	118.62
	Summer	June	2.2	0.33
		July	0.1	0.015
		August	0.6	0.09
	Autumn	September	11.6	4.64
Total			572.9	557.475
				97%

A constant recharge value is given to all MODFLOW cells in the groundwater flow model. This simplification to the model is due to the unpredictability of the spatial distribution of the potential evapotranspiration in the study area in a time interval of 80 years. The results of the groundwater flow model are presented in Figure 14. Groundwater heads don't show a significant change from the reference scenario throughout the study area, except at the southern part where extraction wells exist that induce local drawdown areas. One of these local areas is close to the Tagus river, which divers the groundwater flow direction toward the extractions wells increasing the flow from the river to the aquifer system.

By calculating the difference in head between the reference scenario and this scenario, the plot on the right in Figure 14 is produced, where the head of the reference scenario is subtracted from this scenario's head result. The result shows a negative difference indicating an increase in the drawdown due to the decrease in total recharge from precipitation. The maximum decrease in drawdown noticed is 0.22 m, which is considered non-significant with respect to the scale of extraction in the study area. This small increase in drawdown is probably due to the compensation from the inflow of groundwater from the western boundaries, the constant head, and the Almonda river. Due to the steady state conditions of the model, the decrease in recharge would induce more water to inflow from the boundaries, especially the constant head boundary, to compensate and stabilize the groundwater flow budget. Thus, the water budget was analyzed to test the validity of this hypothesis.

In terms of water budget, the zonal classification helped in isolating the water budget of each of the bounding rivers to be able to analyze the individual interaction between the groundwater aquifer and the rivers separately. Results indicate that the Almonda river in both scenarios has higher inflow than outflow from the aquifer, which means that Almonda river is contributing to the aquifer as expected from the flow direction map. The difference in the net flows between the two scenarios shows an increase in the inflow from the Almonda river under climate change scenario by 3,026 m^3/day and a total volume of 1.1 hm^3 flows into the aquifer in this scenario than the reference scenario. The decrease in recharge was partially compensated by more inflow from the river towards the extraction wells. In percentage, the net difference between the scenarios shows a 5% increase in river contribution under climate change scenario.

The outflow from the aquifer into the Tagus river exceeds the inflow from the river into the aquifer system, yet the comparing between scenarios, the river inflow decreases, and the outflow increases under the climate change scenario. This indicates that the decrease in recharge has the same effect on the Tagus river as it induces more inflow to compensate for the volume needed to feed the extraction wells stabilize the steady state of the model. A total volume of 2.5 hm^3/day is reduced from flowing from the aquifer to the Tagus river.

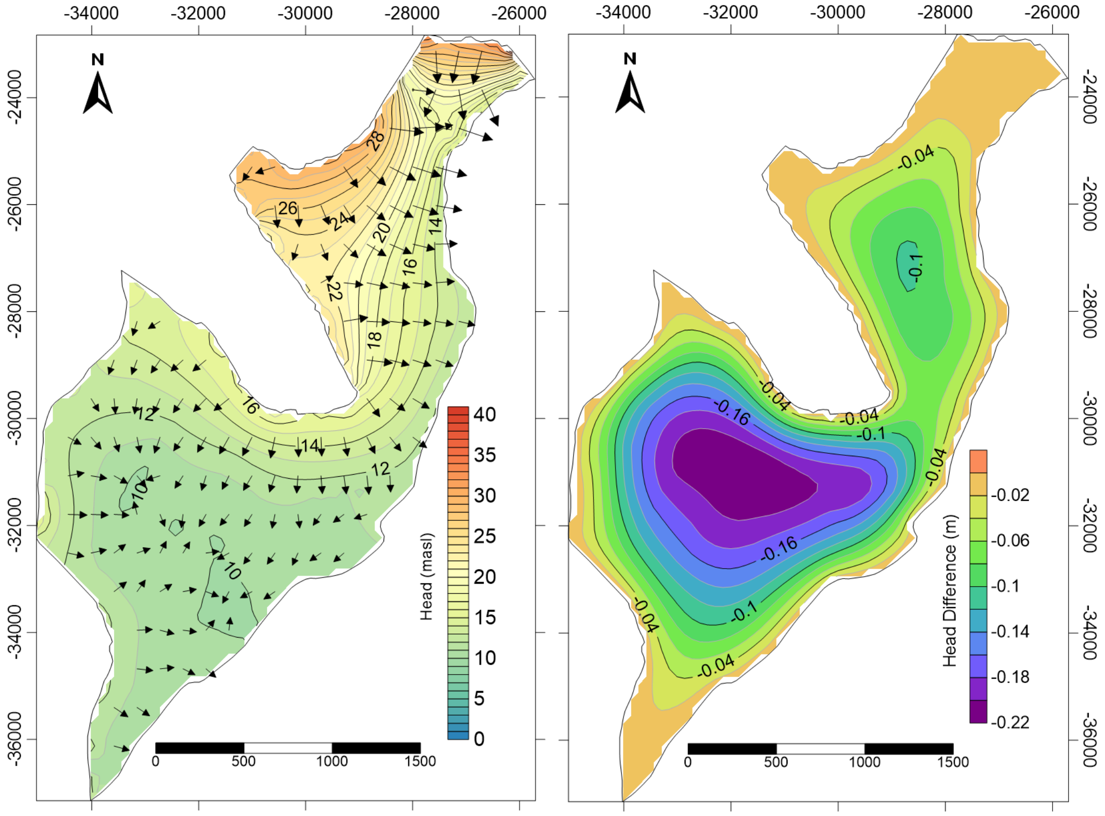


Figure 14: Groundwater head and flow direction (Left) and Difference in head from reference scenario (Right)

Adaptation Measure

As an adaptation scenario to the future changes in climate patterns, this scenario suggests that all maize cultivated croplands would also cultivate vegetables that would consume less water. It is also assumed that the drip irrigation system has an efficiency of 90%. This assumption leads to a total annual water consumption of 34,546,601 m3 and a total daily consumption of 94,648 m3 for irrigation use. The new scenario would decrease the total groundwater extraction by 14%.

Figure 15 shows the results of the groundwater heads and flow direction on the left. In terms of groundwater flow direction patterns and velocity, no significant changes were noticed. Thus, to see the effect on the groundwater drawdown from the reference scenario, the difference in computed head between this scenario and the reference scenario, the PEST calibrated model, is plotted in Figure 15 on the right. The results show a maximum decrease in the drawdown by 0.6 meters at the central south part of the study area, where dense extraction wells exist. This suggests a decrease in the volume of water flowing into the aquifer from the surface water bodies surrounding it, the Tagus and Almonda rivers.

Quantitatively, results show that the total volumetric interaction between the aquifer system and the two rivers, Almonda and the Tagus, for each scenario separately and then the difference between the inflow to and outflow from the aquifer. The net calculation indicates that river Almonda's inflow to the aquifer is greater than the outflow from the aquifer to the river. The net inflow from Almonda decreases by 5,417 m^3/day, saving 8% of the river natural inflow into the aquifer system with a total annual saving of 1.977 hm^3.

As for the Tagus river, the aquifer outflows into it around 4 dm^3 on daily bases in both scenarios with a slight increase in the crop change scenario. At the same time, the inflow from the river to the aquifers system decreases by around 185 m3/day. The net water balance shows a total annual saving of 2.13 hm^3 from the groundwater from the aquifer system that outflows towards the Tagus river.

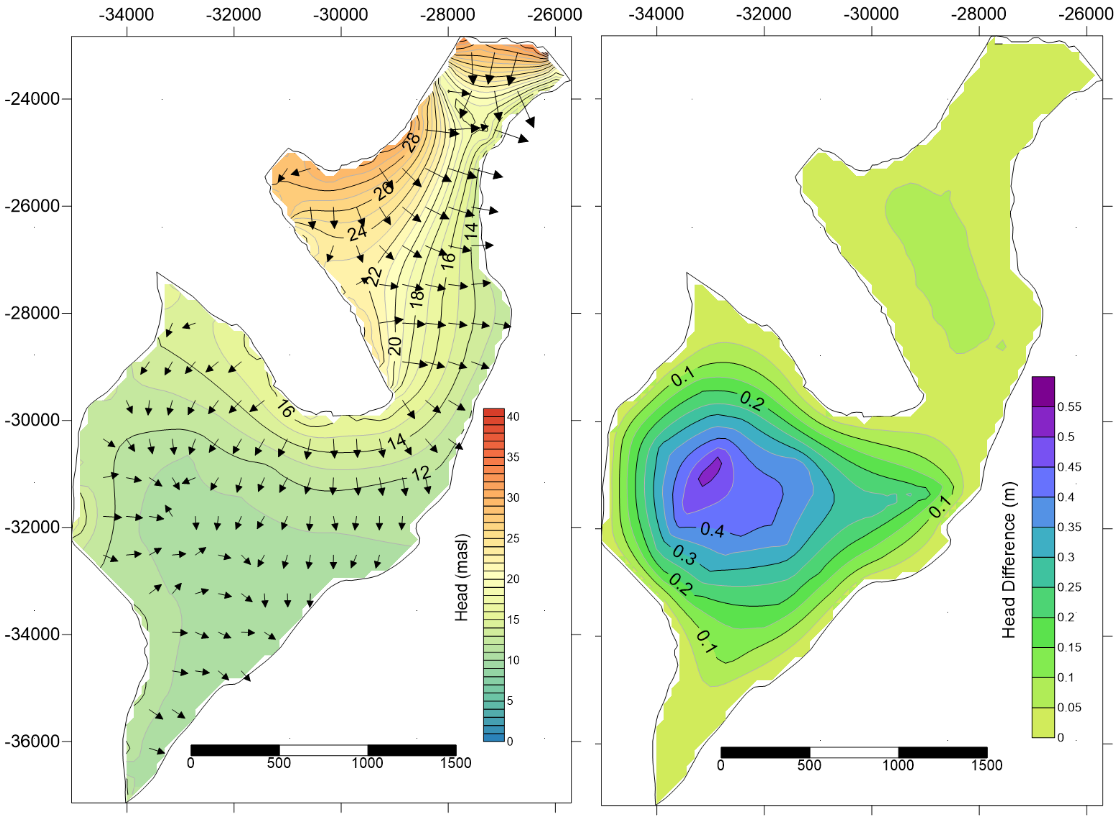


Figure 15: Groundwater Flow (Left) and Difference in the head from the Reference Scenario (Right)

VII. Conclusion & Recommendations

This study investigated the potential depletion in the groundwater levels in the Tejo-Sado alluvial aquifer of the Tagus-Sado basin in an intensively irrigated land under uncertain drought conditions, namely the decrease in total precipitation and increase in temperature.

Climate data from the past three decades show an increase in the duration and the frequency of extreme weather events in terms of dry and wet years. Since 2004 droughts have been predominating the extreme events with only one, significant but short, wet event in the year 2010. Because of the very low relief in the topography of the study area, surface runoff is minimal, and infiltration is promoted. Groundwater recharge connection to precipitation is emphasized by the fact that the Tejo-Sado alluvial aquifer is an unconfined aquifer.

Remotely sensed real evapotranspiration data from MODIS proved to be a good tool to use in limited data availability as it gives good estimation compared to values of potential evapotranspiration calculated using local climate data. Although MODIS real evapotranspiration data has a resolution of 500 meters, it proved to be reliable to use for studying a small sty area like the one in hand. The only limitation to the MODIS data is that cloud cover results in areas with no data that must be further corrected before being used in calculating recharge.

The spatial distribution of recharge produced from precipitation and real evapotranspiration data was not conclusive to deduct a correlation between land use and recharge distribution within the study area. That said, only the effect of the Paul Boquilobo natural reserve area could be detected in the recharge distribution, where the evapotranspiration is high due to high vegetation all year long and the existence of a wetland that results in an area of low local recharge.

The southern part of the study area, namely zones two & three, show a significant change in the groundwater flow direction toward the center, where the high density of extraction wells exists. The extraction wells induce the flow to go diverge from all directions towards the center, resulting inflows from the Tagus river, Almonda river, and the constant boundary into the aquifer system. A maximum drawdown of 3.6 meters is produced due to this intense extraction backed by the high density of wells in this area. This concludes that the density of the extraction wells is highly influential on the change groundwater depletion.

The steady state condition of the groundwater flow model implies a minimal discrepancy between the total inflow and outflow of the system. This ensures that the water is forced to outflow from the system in the form of extraction wells would be compensated by inflows from the boundaries if sufficient. Since the western boundary is defined as a constant head, it acts as an unlimited source of inflow if needed and that explains the predominance of contribution by this boundary.

Under the climate change scenario, the inflow from the Almonda river increases while the outflow from the aquifer to the river decrease. Both changes result in an overall change in net balance by 5%. The same effect on the inflow/outflow interaction with the aquifer is noticed but with only 2% change in the total net flow exchange. This supports the assumption that under extremely dry conditions, the groundwater extraction activity induces more inflow from the rivers toward the aquifer compromising the river natural flows.

The suggestion of changing the maize field with other existing vegetables cultivated in the study area, as it indicates market demand, shows a decrease of 14% in the total water demand for agriculture. This scenario implies a recovery in the groundwater heads by a maximum recovery of 0.6 meters in the central south part of the study area. Although the recovery in groundwater head is not significant, this shows that further scenarios of changing crops and decreasing the water demand can be an effective adaptation measure to minimize the effect of coming extreme dry events in the future.

Finally, recommendations for future studies in this study area would be:

- Getting more detailed information about the real groundwater extraction rates from each well from the landowners or local authorities.
- Studying the short-term climate variability and the effect of the change in the frequency and magnitude of extreme climate conditions is highly recommended for a more substantial motivation for farmers to take actions in a shorter time period and to help local decision-makers on having a proper management plan for the water resources in the area.
- A transient state model for the period of 2016 to 2018 is highly recommended to be studied if the necessary datasets are available from the monitoring network as 2017 was a drought year and studying the transient condition from a normal year to a drought year to a year with significant rainfall events like 2018 would give a complete insight of the various components of the water balance. This can indicate the lag time between precipitation and change in groundwater heads as an effect of the vadose zone.

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