# MONITORING AND MODELLING GROUNDWATER CONTRIBUTIONS TO DEPENDENT ECOYSTEMS
# THE CASE STUDY OF THE SANTO ANDRÉ COASTAL LAGOON

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## Abstract

When the Santo André coastal lagoon (SAL) is closed to the sea, and no surface runoff is generated, its water balance is mainly controlled by the hydraulic connection between the stream network discharging into the SAL and the top detritic layer of the multi-layer Sines aquifer system, allowing the classification of this lagoon as a groundwater dependent ecosystem (GDE). A monitoring plan has been implemented to continuously register stream flow discharges in order to estimate groundwater contributions to calibrate the developed numerical flow model of the top detritic Sines aquifer. Simultaneously, the monitoring network was also continuously recording the aquifer level variation, and manual measurement of the hydraulic head of several wells installed in the top detritic aquifer were also used for the numerical flow model calibration. This paper presents estimates of groundwater contributions to the SAL obtained through monitoring and modelling and stream flow estimates contributing to the SAL water balance.

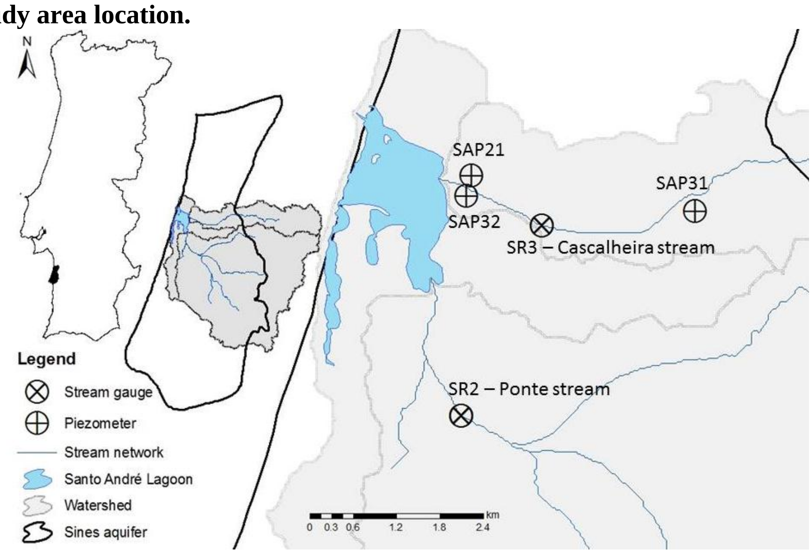
**Keywords: Stream discharge, water balance, numerical flow model, groundwater depending ecosystems**

## 1. Introduction

The Santo André lagoon (SAL) is a coastal lagoon located in the southwest of Portugal (see Figure 1 for location), subject to several conservation and wildlife protection statuses. The SAL has been defined as a mesotidal semi-enclosed coastal lagoon under the Water Frame Directive (WFD). Isolated from the ocean during most of the year by sand barriers, the lagoon is artificially opened to the sea on a regular basis in late winter, in order to promote water renewal and nutrients and organic matter transport, reducing the risk of eutrophication (Cancela da Fonseca et al., 1989; CEZH/RNLSAS, 2004). The SAL has two major tributaries, the Ponte and Cascalheira streams, which are fed by groundwater along their terminal reaches (Monteiro et al., 2008). The bottom of this lagoon is mainly composed of detritic sediments and organic matter layers that reach a maximum thickness of 40 m (Freitas et al., 2002), limiting the hydraulic connection between the lagoon and the top detritic layer of the multi-layer Sines aquifer system. Therefore, when the lagoon is closed to the sea, and no surface runoff is generated, its water balance is controlled by the hydraulic connection of the stream network with the top detritic aquifer, allowing the classification of this lagoon as groundwater dependent ecosystem (GDE). The alternation between seasonal inflows of fresh and marine water determines the salinity of this water mass, thus determining the local ecological characteristics. Therefore, groundwater exploitation may threaten this complex and fragile ecosystem. The WFD has set the objective of achieving good water status until 2015 for all aquatic and terrestrial ecosystems depending directly on water. The submitted river basin management plan has classified the SAL's status as unknown, due

to lack of monitoring data. Similarly, the volumes of water transfers from the aquifer to the stream network associated with this lagoon have not been quantified. Although, a numerical flow model of the Sines aquifer system has been developed (Chambel and Monteiro, 2007, Monteiro et al., 2008, Monteiro et al. 2010, Monteiro et al. accepted), the estimates of water transfers between the aquifer system and the stream network have not been validated and calibrated due to insufficient monitoring to allow real data to be compared with the model simulations. In this sense, a monitoring plan has been implemented to continuously register hydraulic head and stream discharges data, in order to produce estimates of groundwater contributions from the top detritic Sines aquifer to the streams discharging into the SAL, to calibrate a numerical flow model developed for the top detritic Sines aquifer.

**Figure 1 – Study area location.**




## 2. Methods

### 2.1. Monitoring

To estimate stream flow ($Q$) contributions to the water balance of the Santo André Coastal Lagoon (SAL), two automatic water level data-loggers (CTD) have been installed (see Figure 1 for location), since November 2011, close to the mouths of the two main streams (SR3 – Cascalheira stream; SR2 – Ponte stream). To construct the rating curves (i.e. discharge vs. water level curves) needed to convert streams water levels into discharge, several field campaigns were made at various times during almost two years. In discharge measurements flow is often estimated by determining the velocity at which water flows through a given cross-sectional area (equation 1):

$$Q = VA \quad (1)$$

Where: $Q$ is the volumetric flow rate passing the channel reach ($m^3/s$), $V$ is discharge velocity (m/s) and $A$ is the cross-sectional area ($m^2$) of flow normal to the flow direction. In a first approach, discharge measurements were made by gauging several vertical velocity profiles at the location of each installed CTD. Average vertical velocity ($V_i$) at CTD location was obtained after vertical velocities were integrated. Discharge velocity ($V$) of these shallow streams was obtained rewriting Manning's equation (equation 2) (Costa and Lança, 2001) into equation 3, considering (i) channel slope ($S$) and Manning's roughness coefficient ($n$) as constants and (ii) wetted perimeter of the channel ($Pw$) approximately equal to the width of the channel ($w$), as river channels are

commonly much wider than they are deep. As hydraulic radius (*Rh*) is the cross-sectional wetted area (*A*=*h*.*w*) divided by the wetted perimeter (*Pw*), when considering *Pw* approximately equal to *w*, the *Rh* will be approximately equal to *h*.

$$V = \frac{Rh^{2/3} S^{1/2}}{n} \qquad (2)$$

Where: $V$ is discharge velocity (m/s), $n$ is Manning's roughness coefficient, *Rh* is the hydraulic radius (m) and *S* is channel slope (m/m).

$$\frac{V}{Vi} = \left(\frac{Rh}{h}\right)^{2/3} \qquad (3)$$

Where: $V$ is discharge velocity (m/s), $V_i$ is average vertical velocity (m/s), *Rh* is the hydraulic radius (m) and *h* water height (m) at CTD location. To estimate *Aw* and *Pw*, a detailed map of the streams' cross-section and flooding areas, at each CTD location, was obtained using a high resolution Differential GPS (DGPS). Recorded DGPS data was processed in Surfer software and streams' cross-section at CTD location was obtained after kriging analysis. Both *A* and *Pw* for each stream were estimated intersecting streams' cross-section with water level elevation values in Grapher software. Two scenarios were considered to obtain water level elevation, (a) where water height was added to the CTD elevation value (as water height was measured at the CTD location) and (b) where water height was added to the lower elevation value of the cross-section. To validate *A* estimates, the width of the wetted surface (*w*) was also recorded obtaining a maximum wetted area. Comparing both scenarios with maximum wetted area it was possible to understand that scenario (a) was overestimating and scenario (b) was underestimating *A* values. Therefore, an intermediate scenario (c) for each stream was developed where an average elevation value was determined from interpolated elevation values for maximum wetted areas. To validate discharge scenarios, discharge measurements were made by gauging several vertical flow velocity profiles along the stream cross-section at the location of each installed CTD. This second approach to estimate discharge is based on the assumption that the average velocity measured at a vertical line is valid for a rectangle that extends half of the distance to the verticals on each side of it, as well as throughout the depth at the vertical. The area of each rectangle ($A_i$) is determined through equation 4 (Kuusisto, 1996).

$$A_i = \left[\frac{(b_i + b_{i+1})}{2} - \frac{(b_{i-1} + b_i)}{2}\right] \times d_i \qquad (4)$$

Where: *Ai* is the area of each rectangle ($m^2$), *bi* is the horizontal distance (m) from a reference point on one side of the shore to the point where the corresponding vertical velocity profile is being measured and *di* is the water depth (m) for the same vertical profile. Several methods have been proposed for determining rating curves and improve data fitting (Braca, 2008). In this study the Excel solver tool (*Q*solver) was used to build the rating curves.

Stream flow (*Q*) consist of the sum of direct surface runoff (*Qd*), the water flow generated within the drainage area of the measuring point after the initial demands of interception, infiltration, and surface storage have been satisfied, and base flow (*Qb*), the groundwater contributions occurring in effluent reaches and points. *Qb* was determined by hydrograph (*Q* graphical representation vs. time) separation techniques. Initially, the HYDATA software developed by the UK Institute of Hydrology was used for automatic base flow separation. The software calculates base flow index (*BFI*) i.e the ratio of base flow to total flow, but one cannot actually extract the base flow time series. Therefore, the same smoothed minima approach (Gustard et al., 1992) for base flow (*Qb*) separation was applied manually. This technique uses the minima of five-day non-overlapping consecutive periods from daily flow time series, subsequently

connecting turning points from this minima series. *Qb* estimates were then used for the calibration of the numerical flow model.

Simultaneously, the hydraulic head of 47 wells (observation points) installed in the upper aquifer were manually measured and three automatic water level data-loggers (SAP21, SAP31, SAP32) (see Figure 1 for location) were installed in three of the wells continuously recording the aquifer level variation, data was after used for the numerical flow model calibration.

### 2.2. Numerical groundwater flow model

In order to estimate the groundwater contributions from the top detritic Sines aquifer to the surface water streams leading to the SAL, a finite element numerical flow model was developed. The developed model only considers the top detrittic aquifer of Sines, once this is the only sector which contributes directly with water discharge to the streams. Hence, the numerical flow model limits were defined as the sea to the west and as the interception of the Sub-River Basins of interest (Ribeira das Fontaínhas, Ribeira da Cascalheira, Lagoa de Santo André, Ribeira de Melides and Ribeirda da Ponte) and the Plio-Quaternary layer of Sines, corresponding to the top detritic aquifer. The finite-element mesh was created with Feflow 6.0 (DHI-WASY HmbH) with support of Shewchuk (1996) tool for Mesh Generation and Delaunay Triangulation, taking into account the refining of model nodes at a) the 47 observation points; b) the streams of interest to the project; c) the Santo André and Melides Lagoons; and d) the coastline. The resulting model 2-D mesh consisted of a total area of 192.880 $km^2$, 13160 elements and 6785 nodes. Assuming the recharge rate, 29%, estimated by **Error! Reference source not found.**and considering an average rainfall of 530 mm/yr (obtained for the Sines weather station for 29 hydrological years, 1983/84 – 2012/13) with spatial and temporal distribution as proposed by Nicolau (2002), total annual recharge accounts to 29.9 hm3/yr. Water abstractions volumes from Public supply, Industry, private supply and irrigation, with locations provided by the local River Basin Administration (ARH Alentejo) are estimated by Monteiro et al. (accepted), and account a total of 13.96 hm3/yr for the Multi-Aquifer System of Sines. Yet, the same author considers only private supply and irrigation abstractions extract water from the top detritic aquifer, which sums 7.56 hm3/yr. The latter value was the reference volume considered in the model which was spatially distributed into the 133 abstractions locations provided by ARH Alentejo.

Two versions of the model were developed, a permanent-state and a transient-state based. The physical principles at the basis of the simulation of the hydraulic behavior of the aquifer system are expressed by equation (5).

$$T\ S\frac{\partial h}{\partial t}+\mathrm{div}(-[T]\cdot\overrightarrow{\mathrm{grad}}\cdot h)=Q \qquad (5)$$

Where: $T$ is transmissivity [$L^2T^{-1}$]; $h$ is the hydraulic head [L]; $Q$ is the volumetric flux per unit volume [$L^3T^{-1}L^{-3}$], representing sources and/or sinks; and $S$ is the storage coefficient [-]. The first stage of the model, the permanent-state model, was developed in order to define the best suited boundary conditions (BC) and Transmissivity (*T*). BC were defined as imposed constant hydraulic head equal to the mean sea level along the coastline, and as fluid-transfer BC, also known by 3rd type or Cauchy BC (Franke et al., 1987 and Reilly, 2001), with reference head equal to terrain elevation imposed along the streams and a varying transfer rate from 0.001 and 0.1 m/d. *T* was estimated through a

sensitivity analysis varying from 100 to 1000 $m^2/d$ considering 100 $m^2/d$ increment and assuming that Cascalheira and Ponte streams have effluent behavior (negative flow) and that Fontaínhas stream has an influent behavior (positive flow). The high seasonal variability of rainfall in semi-arid climates such as occurs in the Sines can lead to significant fluctuations in groundwater levels and flow rates. It is necessary to take into account the temporal variability of these systems when discussing available groundwater and its discharge, as single average annual values can give misleading results (Hugman et al., 2013). In order to analyze the seasonal variation of the groundwater discharge a transient analysis was developed for different gammas of storage coefficient (*S*) ranging from 0.001 to 0.1. The model was calibrated by comparing model simulations with field obtained data to define the best suited solution.

## 3. Results and Discussion

### 3.1. Monitoring

Comparing *A*, *V* and *Q* estimates from both discharges approaches, it was possible to understand that first approach scenario (c) was underestimating discharge flow, though more data from second approach is needed for a more detail analysis and to quantify miscalculations of streams' cross-section. For the first approach, adding to the fact that the DGPS has already an associated small vertical error that can be of great significance when water levels are smaller, it can accumulate with miscalculations of streams' cross-section through the kriging process.

Analysing and comparing CTD recorded water levels ($h_{CTD}$) and water height (*h*) of manual measurements it was possible to verify that for SR2 sometime during January 2013 the CTD started to record water levels higher than manual measurements. While SR3 maximum error ($h$- $h_{CTD}$) found was of 7.5cm, for SR2 until November/December 2012 the CTD was recording $h_{CTD}$ with a maximum error of 6.8cm and after January 2013 the error started to rise and reached a maximum of 74.2cm. These higher differences were associated with CTD siltation due to sediment dragged in the heavy rains that occurred in January 2013. For SR3, $h_{CTD}$ values were lower than *h* manual measurements, thus to adjust automatic data to manual data the error found between two measurements was interpolated and added to the CTD $h_{CTD}$ data. For SR2 the same approach as for SR3 was applied, adding the interpolated error to $h_{CTD}$ for the period where the errors were smaller and $h_{CTD}$ lower than *h*, and subtracting for the period where the errors were greater and $h_{CTD}$ higher than *h*.

Although it is still not possible to present estimates for one complete hydrological year, Table 1 presents *Q*, *Qb* and *BFI* moving annual estimates for the period from 15-11-2011 to 18-03-2013, and precipitation (*P*) data from Sines weather station managed by the Portuguese Institute of Ocean and Atmosphere (IPMA). Afterwards, exponential relations for moving annual estimates were establish for *Q* vs. *P* and *Qb* vs. *P*, while poor relations were found for monthly estimates. No relation was obtained for Q vs. Qb. From these relations *Q* and *Qb* were estimated for a 29 hydrological year (October 1983/September 2013) average *P* (530 mm), also presented in Table 1. Where total *Q* (sum of the two streams) contributing to the SAL water balance was estimated in about 8.3 $hm^3/yr$, of which about 21% (1.7 $hm^3/yr$) were aquifer contributions to the streams as base flow. The *BFI* index provides indication of the groundwater dependency degree of the streams and thus of the SAL. Streams with *BFI* values above 0.5 (50%

base flow) are generally considered to be significantly groundwater dependent (Environmental Agency, 2013).

**Table 1 - Surface runoff (*Q*), base flow (*Qb*) and *BFI* estimates for Cascalheira and Ponte streams.**

| Time period | Cascalheira Stream (SR3) | | | Ponte Stream (SR2) | | | Santo André Coastal Lagoon (SAL) | | | P (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Q ($hm^3$/yr) | Qb ($hm^3$/yr) | BFI | Q ($hm^3$/yr) | Qb ($hm^3$/yr) | BFI | Q ($hm^3$/yr) | Qb ($hm^3$/yr) | BFI | |
| Dec2011-Nov2012 | 1.96 | 0.88 | 0.45 | 1.83 | 1.15 | 0.63 | 3.79 | 2.03 | 0.53 | 413 |
| Jan2012-Dec2012 | 2.51 | 0.95 | 0.38 | 2.26 | 0.98 | 0.43 | 4.78 | 1.93 | 0.40 | 470 |
| Feb2012-Jan2013 | 3.53 | 1.04 | 0.29 | 3.34 | 0.78 | 0.23 | 6.87 | 1.81 | 0.26 | 498 |
| Mar2012-Feb2013 | 3.73 | 1.11 | 0.30 | 3.74 | 0.75 | 0.20 | 7.47 | 1.86 | 0.25 | 534 |
| Apr2012-Mar2013 | 4.47 | 1.16 | 0.26 | 5.04 | 0.79 | 0.16 | 9.51 | 1.95 | 0.20 | 526 |
| Oct1983-Sep2012 | 4.06 | 1.10 | 0.27 | 4.23 | 0.60 | 0.14 | 8.29 | 1.70 | 0.21 | 530 |

Even though stream monitoring data allowed estimating surface runoff (*Q*) and base flow (*Qb*) average annual contributions to the SAL water balance, these values are still only indicative of orders of magnitude, given the low density of stream flow monitoring data. The greater the number of sets of discharge and water height measurements, the greater the accuracy of the rating curve, and thus more accurate the estimates of stream water discharges into the lagoon. One must have in mind that the relations that allowed these estimates were not built on annual values of several complete hydrological years, thus still needing to be improved with more monitoring data. On the other hand, as previously mentioned, during January 2013 the CTD installed in Ponte stream (SR2) suffered siltation by sediments dragged in the heavy rains that occurred and data had to be readjusted. Apparently for this period some *Qb* data may have not been accounted, analysing Table 1 it is possible to realize that for similar *Q* for both streams, *Qb* decreases considerably in SR2 from the moment that January 2013 data is accounted. Although more monitoring data is needed for more accurate results these estimates were still used for the calibration of the numerical flow model.

## 3.2. Numerical groundwater flow model

For the first stage of the model, the permanent-state model, the sensitivity analysis performed to estimate the best suited transmissivity (*T*) suggested values of 600 $m^2$/d, and inflow and outflow transfer rates of 0.025 m/d to the Ponte stream river basin area and 0.25 m/d to the remaining area of the model, when comparing the model simulations with registered hydraulic head variation and base flow (*Qb*) estimates obtained from monitoring data. Achieving discharge rates in the same order of magnitude as the field data and hydraulic head average error of 3.19 m with a $R^2$ of 0.773.

For the transient-State model, the analysis of the seasonal variation of the groundwater discharge, for different gammas of storage coefficient (*S*), when comparing the model hydraulic level simulations with the registered hydraulic head variation indicates S values of 0.01 and 0.05. Table 2 presents the root mean square error (RMSE) and R2 calculated for the period recorded by the data-loggers (SAP 21, SAP 31, SAP 32).

**Table 2 - Coefficient of determination ($R^2$) and Root Mean Square Error (RMSE) for the data-logger recorded hydraulic head levels and the simulated hydraulic head for the same period of time.**

| S | SAP 21 | | SAP 31 | | SAP 32 | |
|---|---|---|---|---|---|---|
| | $R^2$ | RMSE ($m^2$) | $R^2$ | RMSE ($m^2$) | $R^2$ | RMSE ($m^2$) |
| 0.001 | 0.531 | 2.89 | 0.331 | 4.71 | 0.464 | 4.21 |
| 0.01 | 0.749 | 1.39 | 0.745 | 2.94 | 0.717 | 3.78 |
| 0.05 | 0.581 | 0.92 | 0.919 | 2.39 | 0.777 | 4.14 |
| 0.1 | 0.581 | 0.97 | 0.916 | 2.49 | 0.759 | 4.11 |

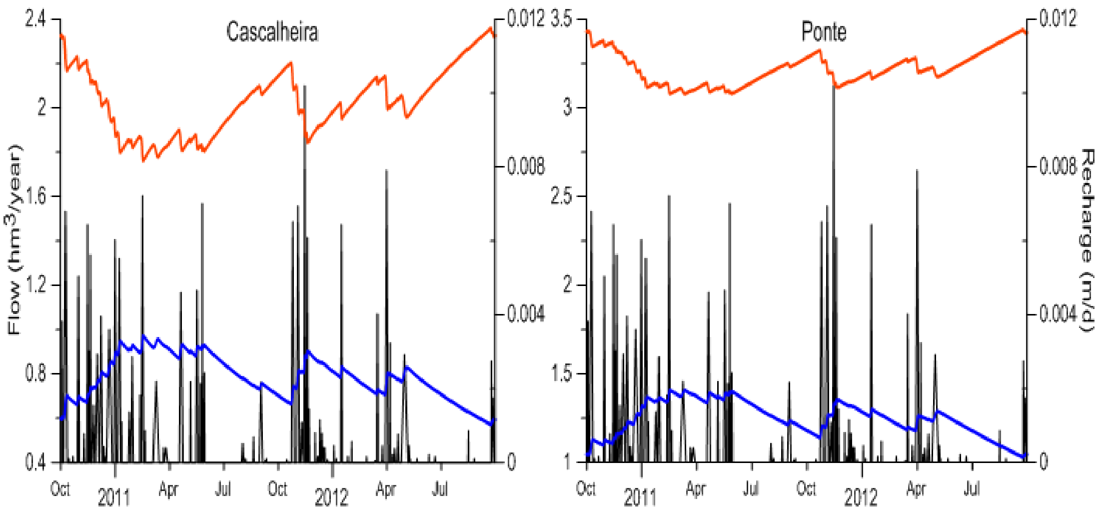
Comparing simulated base flow estimates (${}_{m}Qb$) for S values of 0.01 and 0.05, presented in Table 3, with base flow ($Qb$) estimates obtained from monitoring data presented in Table 1, suggests an S value of 0.05 as the most indicated choice, as error is continuously lower for S values of 0.05 than for 0.01. Therefore, an S value of 0.05 was assumed for the transient model simulations.

**Table 3 - Cascalheira and Ponte stream base flow model simulations for S = 0.05 and for S = 0.01 and errors between model estimates and base flow estimates obtained from monitoring data.**

| Time period | Cascalheira Stream | | | | Ponte Stream | | | |
|---|---|---|---|---|---|---|---|---|
| | ${}_{m}Qb$ S=0.05 ($hm^3$/yr) | S=0.05 error ($hm^3$/yr) | ${}_{m}Qb$ S=0.01 ($hm^3$/yr) | S=0.01 error ($hm^3$/yr) | ${}_{m}Qb$ S=0.05 ($hm^3$/yr) | S=0.05 error ($hm^3$/yr) | ${}_{m}Qb$ S=0.01 ($hm^3$/yr) | S=0.01 error ($hm^3$/yr) |
| Dec2011-Nov2012 | 0.723 | 0.155 | 0.591 | 0.287 | 1.19 | 0.040 | 1.29 | 0.140 |
| Jan2012-Dec2012 | 0.719 | 0.231 | 0.598 | 0.352 | 1.18 | 0.202 | 1.29 | 0.313 |
| Feb2012-Jan2013 | 0.717 | 0.319 | 0.618 | 0.418 | 1.17 | 0.398 | 1.31 | 0.537 |
| Mar2012-Feb2013 | 0.717 | 0.397 | 0.642 | 0.472 | 1.17 | 0.425 | 1.35 | 0.599 |
| Apr2012-Mar2013 | 0.727 | 0.431 | 0.699 | 0.459 | 1.18 | 0.390 | 1.43 | 0.638 |

A more detailed transient analysis was performed for 2 hydrological years, 2010/2011 – 2011/2012, that includes the period of field data collection. It suggests a significant seasonality regarding the aquifer discharge to the streams, as can be seen on**Error! Reference source not found.** Figure 1Figure 2, whereas discharge decreases substantially in dry periods, but with quick recoveries after recharge episodes. For the given period, the estimated base flow reaching the SAL was 2.19 $hm^3$/yr and 1.72 $hm^3$/yr for the Cascalheira and Ponte respectively, accounting a total of 3.92 $hm^3$/yr of groundwater contribution to the SAL.

**Figure 2 - Aquifer discharge (blue) and recharge (orange) to and from streams.**




## 4. Conclusions

Even though stream flow estimates are more indicative of orders of magnitude, as more monitoring data is need for more accurate results given the low density of stream flow measurements and all the mischances that occurred, these estimates were still useful for the numerical flow model calibration. The proposed model may be a great tool to support decision making regarding groundwater exploitation for human consumption while protecting wildlife, being possible to predict changes in groundwater contributions to the SAL for prospective exploitation and climate change scenarios.

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