Improving Groundwater Model Reliability by Coupling Unsaturated and Saturated Models

A case study of Sardon catchment, Spain

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by

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Dedicated

To

My father: Tseggai Berhe & My mother: Tsigge Beraki

My Brothers:

Yohannes , Yossief , Henok, Mussie & Aron

My Sisters:

Saba, Yodit, Elsa & Eyorusalem

My first cousin:

Hidat T. Berhe

Abstract

Groundwater flow models are capable to represent and predict the regional flow system in the saturated zone; however, they suffer with problem of non-uniqueness due to the combination of uncertainty in the parameter and fluxes estimation, model assumptions, model development. Fully-transient models are more reliable solution than steady state models because of their spatial and temporal fluxes input. The accurate representation of vadose zone flow processes (fluxes) in groundwater models enables to simulate the effect of near- and sub-surface hydrologic processes which improve their prediction. The main objective of this study was to improve the reliability of groundwater model by coupling unsaturated and saturated zone models. The developed unsaturated zone model called pyEARTH-2D, provide spatially distributed recharge. The methodology was composed of; (i) subdivision of Sardon catchment into soil zones based on soil hydraulic parameters; (ii) preparation of input data for the distributed recharge model; (iii) coupling of pyEARTH-2D and MODFLOW using PEST. The proposed methodology was tested on Sardon catchment, Spain.

The subdivision of catchment in to zone was a pre-requisite for the application of the distributed recharge model which calculate recharge at cell-by-cell basis. Based on the fracture outcrop map the Sardon catchment was subdivided into four zones (massive outcrop, fractured outcrop, regolith/soil cover, and valley/drainage). The soil hydraulic parameters derived from the laboratory analysis of collected soil samples and field tests were assigned to each zone. Input of daily driving forces (rainfall and potential evapotranspiration) and state variables (soil moisture and hydraulic head. The upscaling of PET and interception loss to catchment scale was done based on classified vegetation map into three attributes: *Q.ilex*, *Q.pyrenaica*, and grass/shrub.

The semi-distributed recharge model pyEARTH-2D was applied to estimate of spatially distributed recharge. The simulated heads by coupled pyEARTH-MODFLOW show trend more similar to the observed heads than the simulated heads by standard (non-coupled) MODFLOW. The water balances of the two, show that the latter model considers high recharge to simulate heads while the former model simulates minimal recharges which closely show the real groundwater conditions. The main objective of this study was to improve groundwater model reliability by coupling pyEARTH-2D recharge model with MODFLOW using PEST. The RMSE and the similar trend of simulated heads by coupled pyEARTH-MODFLOW show the improvement of MODFLOW simulation due to the accurate recharge input from pyEARTH-2D.

The coupling and calibration of pyEARTH-2D using PEST with optimized parameter field capacity show good improvement in the output of the model, therefore optimization of the other parameters hydraulic conductivity, porosity, wilting point etc could improve the performance and the output of the models.

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1. Introduction

Groundwater demand is continuously increasing water demand due to rapid population growth and extensive economic developments in the whole world particularly in arid and semi- arid regions. Therefore, evaluation and accurate quantification of the available groundwater resources is a basic requirement for effective management particularly in these regions where such resource is scarce but important for economic development.

Groundwater modelling is the best tool that supports management of groundwater resources in evaluation and quantification of the available groundwater resources. Groundwater models are being increasingly used in order to simulate scenarios in groundwater resources to fully understand the hydrological processes and predict future challenges in the available resources due to various factors such as abstractions, land cover and climate change. However, they suffer with problem of non-uniqueness due to the combination of uncertainty in the parameter estimation, model assumptions, model development. Furthermore, the spatio-temporal variability of recharge also affects the uncertainty of the model output. Groundwater recharge in arid and semi-arid regions represents an essential component in the management of the groundwater resources and quantifying its rate is crucial. The use of accurate estimate of spatio-temporal recharge in to the groundwater flow model would constrain the model and minimize the non-uniqueness solution.

The main focus of this research was on improvement of the groundwater flow model reliability by coupling unsaturated zone model with fully-transient flow model. The unsaturated zone model provides distributed recharge which input to the groundwater flow model. The linking of the two models enables to represent the complete flow process and improve the model output.

The methodology that was followed in this research include sub-division of the Sardon catchment in to recharge soil zones based on unsaturated zone parameterization; processing and computation of the main driving forces and state variables (soil moisture and hydraulic heads) for the recharge model ; laboratory analysis of the soil samples and derive the soil hydraulic parameters; estimation of interception loss as percentage of gross precipitation, and finally calibrating the recharge model and fully transient flow model by coupling with PEST.

The study area, Sardon catchment, is located in the lower part of the Rio-Tormes basin of Salamanca province, central-western part of Spain. The area is characterized by semi-arid climatic conditions, gently undulating topography, and granitic area, and with limited human influence.

1.1. Research Setup

This sub chapter discusses the main setup of the research starting by identifying the research problem setting objectives which can be addressed by the research questions that are based on the hypothesis and assumptions.

1.1.1. Problem definition

Groundwater modeling is recognized nowadays as the best tool to support management of groundwater resources. Despite their sophisticated and data intensive nature numerical models have been able to address the water-related problems. The unavailability of appropriate data for reliable models calibration hampers, however, their wide application in many circumstances. The required knowledge for reliable data acquisition, data integration and data extrapolation, particularly the spatial data up scaling and spatio-temporal data integration is far less developed than the modeling techniques (Lubczynski and Gurwin, 2005).

Groundwater flow models are capable to represent and predict the regional flow system in the saturated zone; however, they suffer with problem of non-uniqueness due to the combination of uncertainty in the parameter estimation, model assumptions, model development. The non-uniqueness occurs when identical objective function values are produced from corresponding changes in parameter values and generate identical simulated equivalents; and this shows that the available observation data are insufficient to uniquely estimate each parameter value (Hill and Tiedeman, 2007) .The applications of numerical groundwater modeling for groundwater water recourses assessment in fractured rocks suffer with problem of non-continuity, anisotropy and heterogeneity of the medium (Sanchez-Vila et al., 1996, in (Lubczynski and Gurwin, 2005)).The extrapolation of fluxes such as recharge (R) and groundwater evapotranspiration is complex because of their spatio-temporal variability nature. The most common ways of distributing fluxes spatially is kriging interpolation (geostatical analysis) and spatial extrapolation (e.g. by GIS zonation). Both techniques have inaccuracies. These inaccuracies, particularly when dealing with spatio-temporal variable fluxes cause the non-unique, therefore unreliable solutions of groundwater flow models (Cherkauer, 2004; Lubczynski and Gurwin, 2005).
This problem can be mitigated by using distributed, spatio-temporally variable models, coupled with groundwater flow models. Such fully transient solution was proposed in this study and involved coupling of the pyEARTH-2D lumped parameter recharge model with MODFLOW groundwater model proposed.

1.1.2. Research objectives

The general objective of this research is to improve the reliability of groundwater model by coupling a semi-distributed unsaturated zone model with fully-transient groundwater flow model.

In order to achieve the main objective the following specific objectives will be addressed:

- To sub-divide the Sardon catchment into recharge zones based on unsaturated zone parameterization.
- To assess the temporal variability of recharge.

- To calibrate the semi-distributed unsaturated model (pyEARTH-2D) coupled with MODFLOW using PEST.

1.1.3. Research questions

- How to integrate the spatial and temporal variability of recharge?
- How to couple and calibrate the semi-distributed unsaturated model (pyEARTH-2D) with fully-transient flow model (MODFLOW)?
- Does the above mentioned coupled model system improve the consistency of model results?

1.1.4. Research hypotheses

- Lumped parametric models (such as pyEARTH-2D) can provide groundwater recharge estimate efficiently.
- Coupling of pyEARTH-2D with fully transient flow model (MODFLOW) using PEST and its calibration by soil moisture and hydraulic head will provide reliable groundwater flow model.

1.1.5. Research assumptions

The assumptions considered in the present study include

- The actual evapotranspiration (ET_a) in the dry season is taken as the evapotranspiration from groundwater (ET_g).
- The actual evapotranspiration (ET_a) in the wet season is taken as the sum of evapotranspiration from the unsaturated zone (ET_u) and from the surface (ET_s).

1.2. Literature Review

1.2.1. Unsaturated zone model

The unsaturated zone models are mainly designed to compute recharge from precipitation. The main part of these models consists of a "root zone part", but a part simulating the unsaturated flow in the intermediate zone between the roots and the water table may have been added. One of these models is a so-called "lumped parameter" EARTH model (van der Lee and Gehrels, 1990) .

The water movement in the unsaturated zone plays important role in determining the conditions in surface and subsurface, however, modelling of vadose zone flow processes is a complex, computationally demanding and data intensive, i.e. data necessary to characterize the hydraulic properties of the subsurface environments. Hence vadose zone flow processes have rarely been properly represented in hydrologic models (Sanford, 2002; Scanlon et al., 2002) . Models that simulate surface and near-surface hydrology usually oversimplify the impact of vadose zone flow processes and similarly regional-scale groundwater models often simplify vadose zone flow processes by calculating groundwater recharge externally without proper consideration of changes in groundwater levels. Thus, to overcome this simplification, there is a need for methods that can effectively simulate water flow through the vadose zone in large-scale hydrologic models (Tawarakavi et al., 2008) .

Hydrological modelling approaches are usually applied in simulation of groundwater recharge from the water movement in the unsaturated zone. Physically based models are hydrologic models which solve the unsaturated water flow equation, i.e. Richards's equation such as SWAP(Kroes et al., 2008) or Hydrus-1D (Tawarakavi et al., 2008).These models are complex in data input requirements and in their structure. Simpler solutions are lumped parametric models which use a numerical or analytical relationship between precipitation and recharge to solve water balance. The distributed lumped parameteric models use a holistic approach to water distribution, i.e. precipitation on the modelled area is distributed among evapotranspiration, runoff, and infiltration according the set of formulas (Cherkauer, 2004) ; for example BEACH (Sheikh et al., 2009) ; DREAM (Mandfreda et al., 2005) ; a catchment water-balance model (Khazaei et al., 2003); a tank model (He et al., 2008) ; a PRMS and GIS approach (Cherkauer, 2004) .

1.2.2. Saturated zone model

The saturated zone modelling consists of two different model conditions namely a steady state and unsteady (transient) state. In steady state models the condition of change of storage with time is not considered while in transient models the storage changes with time are taken in to account. Among the transient models, quasi-transient models do not consider the temporal variability of fluxes (R and ETg) whereas in fully-transient models, the fluxes are considered as temporally variable. Fully-transient models are able to take into consideration the effect of temporal variability of fluxes and aquifer storage which cause the temporal variability of hydraulic heads. The transient models with temporally variable fluxes (fully-transient) are more reliable solution than steady state models, because calibration of such models with temporal data (such as fluxes) reduces more degrees of freedom so that the model solution is less non-unique. The groundwater fluxes are dependent on the processes occurring at the ground surface and in the vadose zone and thus integration of saturated and unsaturated zone fluxes by coupling the two zones, improves reliability of the models (Lubczynski and Gurwin, 2005).

1.2.3. Coupling of unsaturated and saturated model

The strong interactions between surface-water and groundwater regimes require coupled simulation of the surface and subsurface flow regimes. The characterization of flow processes within the individual regimes cannot fully represent the complete flow behaviour; however, linking of the two regimes is necessary. The promising approach to accurately represent vadose zone flow processes in groundwater models involves coupling of groundwater and vadose zone models where a coupled model simulates the effects of near-surface hydrologic processes on groundwater flow by linking a groundwater model with the vadose zone model in space and time, such as Hydrus-Based flow package for MODFLOW (Tawarakavi et al., 2008); Unsaturated Zone Flow (UZF1) Package for MODFLOW (Niswonger, 2006 in (Tawarakavi et al., 2008)); Variably saturated Flow (VSF) Package for MODFLOW (Thoms, 2006 in (Tawarakavi et al., 2008)); a deterministic , fully distributed physically based model MIKE-SHE which integrates the land phase of hydrological cycle (Refsgaard and Storm, 1995 in (Tawarakavi et al., 2008). Panday and Huyakorn (2004) developed a fully coupled physically-based spatially-distributed model to represent the flow interactions between the surface and subsurface regimes, and (Batelaan and De Smedt, 2007) also develop a GIS –based spatially distributed and coupled model to estimate areal recharge. The characterization of flow processes within the individual regimes cannot fully represent the hydrologic cycle but rather requires linking of the two regimes to represent the complete flow behaviour which is an important issue for efficient and accurate modelling solution (Lubczynski and Gurwin, 2005; Tawarakavi et al., 2008).

1.3. Study area

In this sub chapter, the main information based on the existing data and previous works is presented.

1.3.1. Sources of previous studies

There are several previous studies conducted in Sardon catchment since 90’s which include the geological, hydrogeological and geophysical investigations. These scientific research studies were basically aimed at subsurface hydrology that focused generally on the improvement of input data to the groundwater modelling. The structural and subsurface characterization of the granitic basement was done by Tesfai (2000); and the geological and hydrogeological study done by Attanayke (1999) enable to identify the three layers of Sardon. The assessment of groundwater recharge using remote sensing and GIS applications by Duah (1999) and using EARTH model by Uria Cornejo (2000). The spatial and temporal integration of groundwater modelling with remote sensing and GIS done by Shakya (2001); Lubczynski and Gurwin (2005) present a means of integration of various data sources for transient groundwater modelling with spatio- temporally variable fluxes.The recent study conducted in Sardon by Rajapakse (2009) was aimed at improvement of the numerical groundwater flow model by coupling with solute transport model.

All the studies conducted in the study area have played important role in the advancement of the scientific research as a whole and in the detailed characterization of the sub-surface hydrologic conditions of Sardon catchment.

The soil hydraulic parameters for the core soil samples in the study area were collected and analyzed by Alain Frances and Rajapakse (2009) This secondary data were used in the parameterization of the unsaturated zone (Table 1).

Table 1 Soil hydraulic properties of secondary soil data (Rajapakse , 2009) , location in Fig 2.1

CODE	Soil type	ID	Depth	ρ (mg/cm^3)	n (%)	S_r (%)	S_y (%)	K (mm/d)
S1	Silty soil	C_25_ILEX_0A	25	1.66	37	29	9	4229
S2	Silty soil	outC_25_ILEX_2A	25	1.48	40	31	9	6122
S3	Silty soil	C_25_PYR	25	1.40	43	37	6	3596
S4	Weathered granite	C_50_ILEX_0B	50	1.48	30	24	6	5158
S5	Weathered granite	outC_50_ILEX_2B	50	1.70	30	25	5	3650
S6	Dark clayey soil	Ptrab6_50	50	1.63	32	26	6	1889
S7	Weathered granite	C_50_PYR	50	1.42	38	30	8	4014
S8	Sandy-silty	Pmu1_T1_65	65	1.43	37	34	3	6920
S9	Sandy soil	Pcl4_70	70	1.47	32	28	5	15173
S10	Sandy-silty soil	Pcl5_70Kh	70	1.56	36	34	2	133
S11	Weathered granite	C_75_ILEX_3A	75	1.70	27	23	4	3903
S12	Weathered granite	outC_75_ILEX_5A	75	1.86	24	22	2	448
S13	Weathered granite	C_75_PYR	75	1.70	27	21	6	5368
S14	Silty-sandy soil	Pcl5_80Kv	80	1.66	32	32	1	671
S15	Compacted weathered granite	outC_110_ILEX_5B	110	1.84	25	20	4	9
S16	Sandy soil	Pcl4_120	120	1.74	32	30	2	22800
S17	Sandy soil	Pcl6_140	140	1.52	31	28	4	53404
S18	Sandy soil	Pcl5_150	150	1.66	34	32	2	11669
S19	Soil, transition with weathered granite	Ptrab6_150	150	1.80	25	21	5	2398
S20	Sandy soil	Pmu1_T1_170	170	1.37	35	30	5	8732
S21	Sandy soil	Pcl5_230	230	1.47	31	27	4	31603
S22	Silty gravelly soil	Ptrab7_230	230	1.51	37	36	2	5
S23	Silty soil	Pcl6_292Kv	292	1.90	28	27	1	45

* ρ-density (mg/cm^3), n-porosity, S_r – field capacity, S_y – specific yield, K -Hydraulic conductivity (mm/d)

1.3.2. General setup of the study area

The Sardon catchment is situated in the lower part of the Rio-Tormes basin of Salamanca province, central-western part of Spain. The area covers about 80 sq. km with elongation to North-South direction and is located between 6°07’- 6°13’ W longitudes and 41°01’ - 41° 08’ N latitudes (Fig.1). The study area is linked to the surrounding towns and cities by a good road network system and it can be accessed via Ledesma, in east, and Villaseco de los Reyes, in north. The study area has limited human influence because of the very low population in the surrounding villages (Rajapakse 2009).

1.3.3. Topography and Geomorphology

The study area is characterized by a gently undulating topography with series of valleys and ridges which are evidences of tectonic and weathering processes. The higher relief is comprised of quartzite dykes, massive or fractured granitic outcrop with large boulders and covered with thin in-situ soil overburden in certain parts. The maximum thickness of alluvial and colluvial materials is found in the valleys. The elevation of the area varies from 730 to 870 meters above mean sea level where the elevation decreases from south to north of the catchment (Attanayake, 1999).

The catchment landscape is dominantly characterized by semi-arid woody shrubs of deciduous broad-leafed vegetation. The weathered granitic outcrops are exposed more in the western side than in the eastern side of the catchment. The drainage patterns in most parts of the area are poorly defined in which the surface runoff could only be observed in wet seasons. The Sardon brittle shear zone seems to control the morphology of the catchment (Tesfai, 2000).

1.3.4. Climate and hydrology

The study area has a semi-arid climatic conditions with mean annual rainfall of approximately 480 mm/yr analyzed for a period of 1962 to 1996 (Duah, 1999) . The wettest months are November and December with average temperature 5 ^{0}C, potential evapotranspiration of 0.5 mm/d and rainfall of 100 mm/month; while July and August are the warmest and driest months with average temperature of 22^0 C, potential evapotranspiration of 5 mm/d and rainfall 20 mm/month. The long term precipitation and potential evapotranspiration at Trabadillo ADAS for period Septemeber 2003 –October2009 is presented in Figure 1.1.

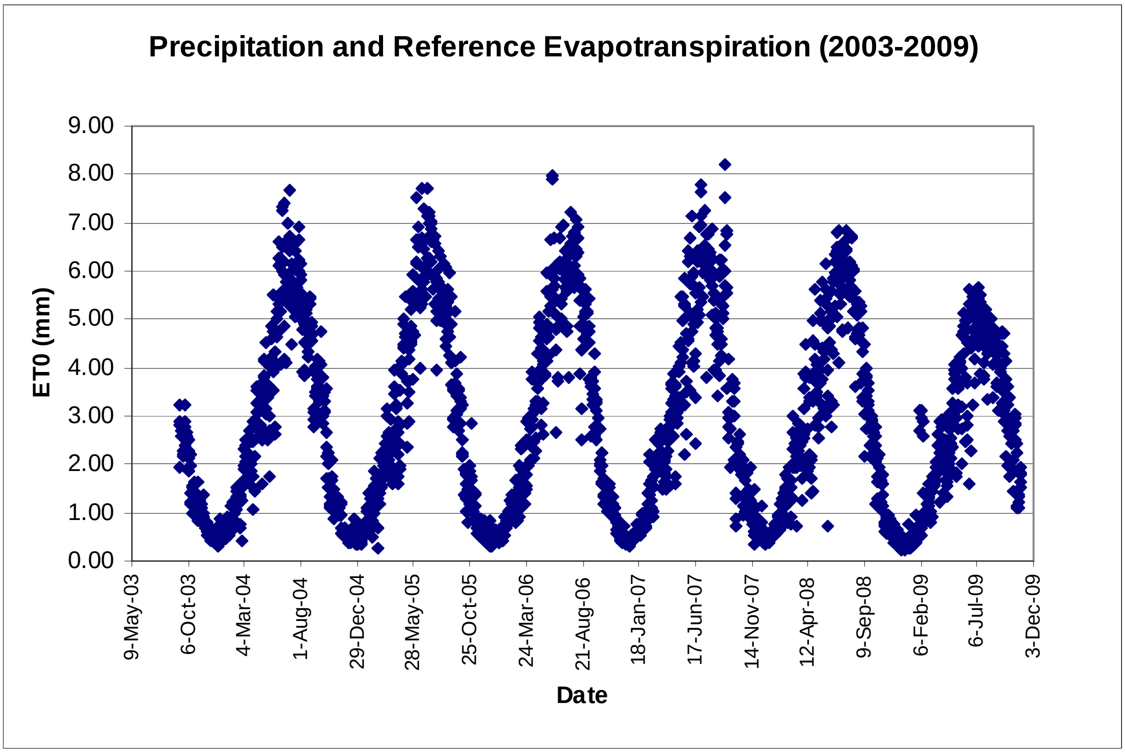


Figure 1-1 Daily precipitation and ET_0 at Trabadillo station (September 2003 –October 2009)

1.3.5. Land cover and land use

The study area has minor human influence and the agricultural activities are very limited. The area is dominantly covered with natural vegetation that include mainly two tree species named *Quercus pyrenaica* and *Quercus ilex*. The area under the sparsely distributed trees is covered with *Cytisus scoparius* shrub and short grass (Shakya, 2001) .

1.3.6. Soil and geology

The Study area lies in the Central Iberian Zone (CIZ) of the Iberian Massif in Moncorvo-Vitigudino metamorphic belt. The granitic rocks of the study area belong to the CIZ. The main lithological sections identified are megacrystic granite, microgranite and mica rich granites. The lithological units are highly affected by the tectonic processes which play major role in the modification of porosity and permeability of geologic materials. The area consists of highly fractured, weathered and massive granites with variable thickness (Attanayake, 1999) .

1.3.7. Hydrogeology

The hydrogeology of Sardon, which is influenced by the weathering and fracturing of granitic basement rock, strongly controls the groundwater recharge to the aquifer. The hydrogeology of Sardon consists of three layers namely a top layer, which consists of alluvial deposits and weathered granite; the second layer is fractured granite ; and a bottom layer of massive granite basement rock with gneiss inclusions. The groundwater flow pattern is towards the major (Fig 1.2, Attanayake, 1999) representing also main drainage channel of the study area aligned S-N and matching main, intermittent Sardon River which dries up from June to October. In wet season, the groundwater runoff occurs mainly as direct runoff.

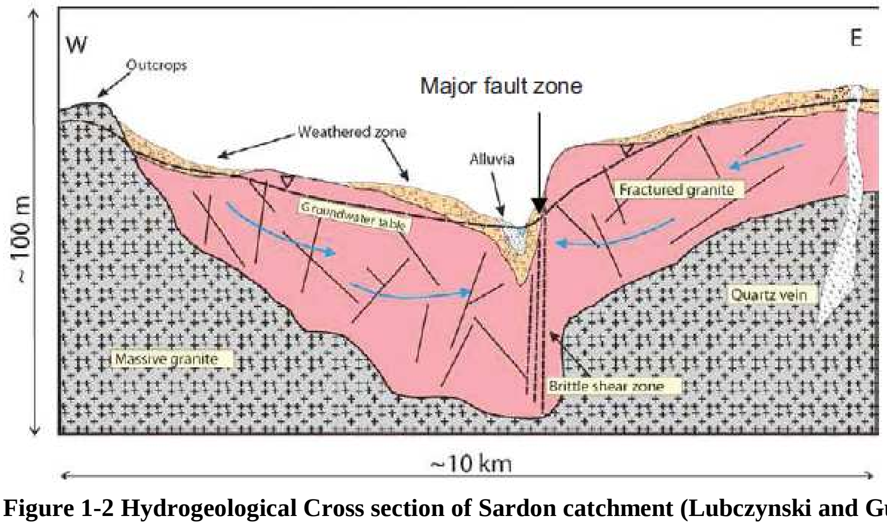


Figure 1-2 Hydrogeological Cross section of Sardon catchment (Lubczynski and Gurwin, 2005)

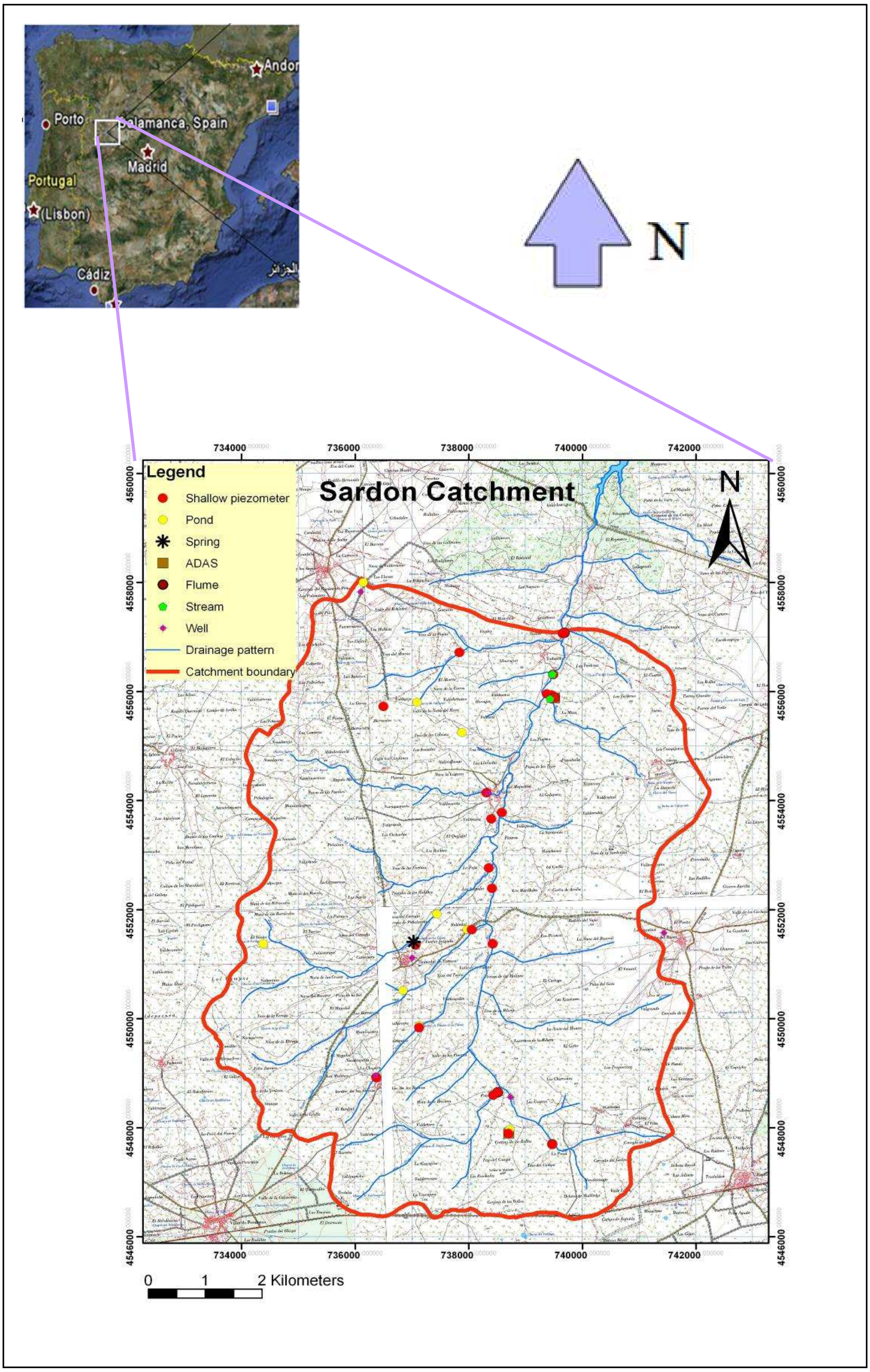


Figure 1-3 Location of Sardon Catchment

2. Material and methods

In this chapter the materials and methods which are used and applied to accomplish the research are presented. The materials that are used for the acquisition of field data and laboratory works are discussed. The two main models, pyEARTH-2D recharge model and transient model (MODFLOW), are dealt in the following sub chapters.

2.1. Data acquisition and integration

The data required for the characterization of the unsaturated zone are mainly acquired from field work and laboratory analysis. The field data acquisition, soil laboratory analysis, data processing and compilation for the period of June 2008 to October 2009 are presented in this part. The data for this study are acquired in two ways i.e. (i) data from field and laboratory work and (ii) secondary data from previous studies. The data required for the input to the unsaturated zone model (pyEARTH-2D) can be categorized in to spatial, spatio-temporal and temporal data.

Spatial data: These data types are spatially distributed but considered as constant over time periods. The soil hydraulic parameters or properties that show variation in space are due to soil type, geomorphology, topography, climate and other related factors. These parameters are very important to parameterize the unsaturated soil in to different hydrological zones. These soil properties are spatially re-distributed in to a larger area by assigning them in to zones of same characteristics. In this case, they are assigned to the three geomorphologic zones on which the recharge is to be estimated spatially.

Spatio-temporal data: These data types have spatial and temporal variation. The parameters which are considered in this study to have a spatio-temporal variable nature are Interception and PET. Their variation in space and time is mainly due to land cover change, i.e. vegetation type, and precipitation. Which are spatially and temporally variable across the catchment depending on the variation of type vegetation cover, in this case they will have different values for Q. ilex, Q. pyrenaica and Shrub/bush/grass.

Temporal data: The precipitation in the study area is assumed to be spatially uniform at catchment scale but temporally variable. The correlation made between rainfall records of the two ADAS stations shows that they are highly correlated and thus measurement from one station, in this case Trabadillo ADAS is representative of the rainfall pattern of Sardon catchment (Rajapakse 2009) .

2.1.1. Monitoring network

The monitoring network of the study area consists of two ADAS (Automated Digital Acquisition System) stations in Mulledes and Trabadillo, and several automated groundwater level recorders installed in piezometers. These meteorological stations equipped with multi-sensors record the climatic data such rainfall, short wave incoming radiation, wind speed, humidity, and temperature hourly. The hydraulic head variation in the piezometers was measured by the automated groundwater head monitoring loggers at each piezometer (Fig.2.1). The soil moisture was measured by TDR-based

Hydraprobe sensors (Keith, 2007) installed at the two ADAS stations. The soil moisture data is available from two locations Trabadillo and Mulledes. The hydraulic head is for the 12 piezometers existing in the Sardon catchment.

2.1.2. Driving forces

The driving forces, precipitation (P) and potential evapotranspiration (PET), for the pyEARTH-2D recharge model were calculated from wind speed, humidity, air temperature and solar radiation, by processing the micro-climatic time series data downloaded from ADAS stations (Trabadilo and Mulledes).The hourly recorded precipitation was averaged to daily to fit with input data for the recharge model. The ET_0 was calculated from the radiation, wind speed, temperature and humidity measured at the stations using the modified FAO 56 Penman-Monteith and PET was calculated using Penman-Monteith equation (combination equation) from the meteorological data and tree based parameters such as LAI and stomatal conductance (Allen et al., 1998).

2.1.2.1. Rainfall

The rainfall measurements taken in the two ADAS (Trabadillo and Mulledes) stations show that the rainfall in the study area is uniform at catchment scale. Therefore, rainfall is considered in this study spatially uniform but temporally variable. The hourly recorded data is averaged to daily.The rainfall data compiled from 2003-2008 by Rajapakse (2009) was updated till October 2009. For this study only 2008-2009 data was used for simulation in the pyEARTH-2D model.

2.1.2.2. Potential and reference evapotranspiration (PET/ET0)

Evapotranspiration is a combined term for all processes by which water in the liquid or solid phase at or near the earth’s land surfaces becomes atmospheric vapour. It is used to express the combined effect of transpiration by plants and evaporation from land surfaces

Potential evapotranspiration (PET)

Potential evapotranspiration (PET) is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water, and without advection or heat storage effects (Dingman, 2002).

The potential evapotranspiration, which is one of the driving forces of the unsaturated model, was spatially distributed over the Sardon catchment based on the vegetation cover map. In that respect three different PET attributes were assigned on the classified QuickBird image with help of Penman-Monteith equation 1, depending on the vegetation type: (i) *Quercus ilex*; (ii) *Quercus pyrenaica* (iii) grass and short bush.

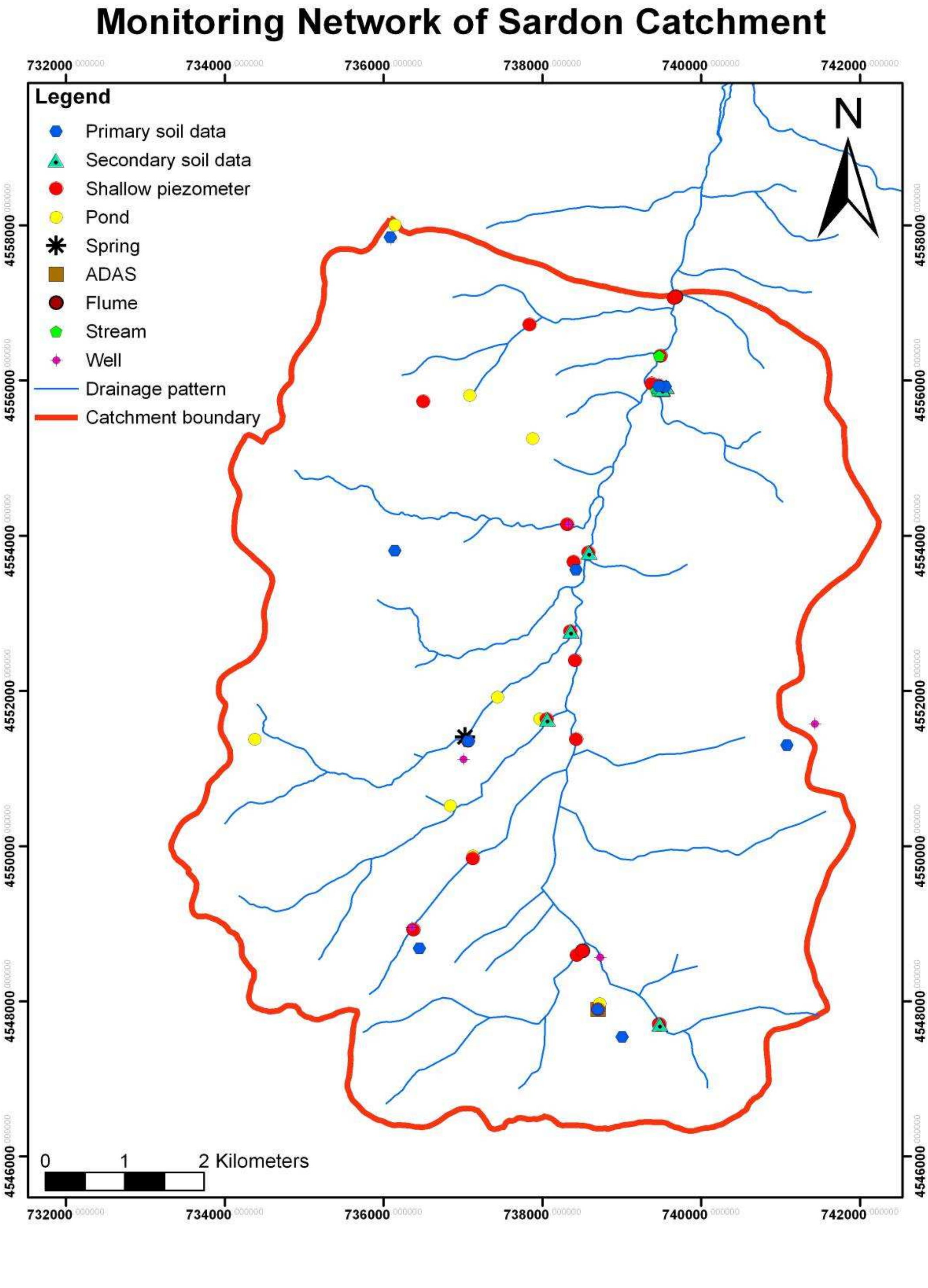


Figure 2-1 Monitoring Network of Sardon Catchment

The Penman-Monteith equation:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (1)$$

where R_n is the net radiation (MJ/m^{2}d), G is the soil heat flux (MJ/m^{2}d), (e_s - e_a) represents the vapour pressure deficit of the air (kPa), ρ_a is the mean air density at constant pressure (Kg/m^3), c_p is the specific heat of the air (MJ/kg^{0}C), Δ represents the slope of the saturation vapour pressure temperature relationship (kPa/°C) , γ is the psychrometric constant (kPa/^{0}C), r_s surface resistance (s/m) and r_a aerodynamic resistance (s/ m).

The Penman-Monteith approach as formulated above includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters are measured or can be readily calculated from weather data. The equation can be utilized for the direct calculation of any vegetation evapotranspiration as the surface and aerodynamic resistances are vegetation specific.

Aerodynamic resistance (r_a) which is the transfer of heat and water vapour from the evaporating surface into the air above the canopy varies with respect to the vegetation height. For instance the aerodynamic resistance for the two tree species (*Q. ilex* and *Q. pyrenaica*) is different as they have different mean height.

The zero displacement heights and roughness lengths have to be considered when the surface is covered by vegetation. The factors depend upon the vegetation height and architecture. The tree zero plane displacement height, d (m), and the roughness length governing momentum transfer, z_{om} (m) were calculated with the vegetation h (m) by the following equations:

$$d = \frac{2}{3} * h \qquad (2)$$

$$z_{om} = 0.123 * h \qquad (3)$$

The roughness length governing transfer of heat and vapour, z_{oh} (m), can be approximated by:

$$z_{oh} = 0.1 * z_{om} \qquad (4)$$

Assuming a constant tree height, i.e. mean tree height, and the height for wind speed and humidity measurement is adjusted to 10 m in order to be above the tree height using equation(6). Thus, z_m = z_h =10 m when calculating aerodynamic resistance for the tree species using equation 5.

$$u_z = \frac{u_2 * \ln(67.8 * z - 5.42)}{4.87 * u_z}. \tag{5}$$

Then, the aerodynamic resistance r_a (s /m) for the tree reference was calculated using (Equation 6), where u_z is the wind speed (m /s) at 10 m.

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right] - \ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z} \tag{6}$$

where r_a is the aerodynamic resistance (s/m), z_m height of wind measurements (m), z_h height of humidity measurements (m), d is zero plane displacement height [m], z_{om} roughness length governing momentum transfer(m), z_{oh} is roughness length governing transfer of heat and vapour (m), k is von Karman's constant, 0.41 (-), u_z is wind speed at height z (m/s).

The surface resistance (r_s) of the well watered Quercus ilex and Quercus pyrenaica trees were calculated using stomata resistance and LAI values from literatures and field measurements using equation (7).

$$r_s = \frac{r_l}{LAI_{active}} \tag{7}$$

Where: r_s is surface resistance (s/m), r_l stomatal resistance (s/m), *LAIactive*: LAI of active leaf (-).

Table 2.Tree stomatal conductance and resistances

Vegetation Type	C_stomata (mm/s)	r_l (s/m)	*f*	LAI	h (m)	LAI	r_s (s/m)
Grass	10	100*	0.5	24	0.12*	2.88	69
Ilex	2	500**	0.5	0.375	6.4[f]	2.4[f]	417
Pyrenica	5***	200	0.5	0.214	8.4[f]	1.8[f]	222

Sources: * FAO-56 (Allen et al., 1998); ** ; ***(Dingman, 2002); [f] (Salinas, 2010)

C_stomata: stomatal conductance; r_l: stomatal resistance; *f:*shelter factor; LAI: Leaf Area Index ; r_s: surface resistance.

Reference evapotranspiration (ET_0)

The reference evapotranspiration for the grass and shrubs was calculated using the FAO-56 modified Penman-Monteith method (Allen et al., 1998). The FAO-56 formula uses the readily available meteorological data such the wind speed, relative humidity, solar radiation daily minimum and maximum temperature data. These meteorological data were acquired from ADAS (Automatic Data

Acquisition Systems) at Trabadillo station from January 2008 to October 2009. The hourly data was processed into daily basis to calculate the ET_0.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (8)$$

Where: ET_0 is reference evapotranspiration (mm/d), R_n is net radiation at the crop surface (MJ /m^{2}d), G is soil heat flux density (MJ/m^2 d),T is air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m/s), e_s is saturation vapour pressure (KPa), e_a is actual vapour pressure (KPa), $(e_s$-$e_a)$ is saturation vapour pressure deficit (KPa), Δ slope vapour pressure curve(KPa/°C) and γ is psychometric constant (KPa/°C).

The parameters required to calculate ET_0 in Penman equation were obtained from the relevant equations provided in the FAO-56 paper with the use of daily meteorological data. The PET/ET_0 calculated at Trabadillo was used as input of driving force to the recharge model. In the recharge model it was calculated for each grid cell as sum of PET/ET0 of each vegetation cover/tree type in the pyEARTH-2D recharge model.

$$PET_{cell} = A * PET_{ilex} + B * PET_{pyrenaica} + C * ET_{0grass} \qquad (9)$$

Where: A, B, and C are the percentage coverage area of *Quercus ilex*, *Quercus pyrenaica* and grass/short bush, respectively.

The calculated PET was upscaled to the catachment level using the vegetation map prepared from QuickBird image by Salinas (2010) as it is shown in Figure 2.2.

2.1.3. State Variables

2.1.3.1. Soil moisture

Soil moisture measurements were made using the Steven Hydraprobe soil sensor at different depths (25, 50, 75 and 100 cm in the two ADAS (Trabadillo and Mulledes stations). The long term monitoring is continued with one hour interval. The Hydra Probe measures the soil complex dielectric permittivity, which is constituted by its real ε_r and imaginary ε_i components. These two parameters are related to the electrical response of soil and are measured from the response of a reflected standing electro-magnetic wave at a frequency of 50 MHz. ε_r is related to the capacitance (soil moisture) and ε_i to the soil electrical conductivity (Keith, 2007).

The volumetric soil moisture content from the hydra probe is derived using the equations that relate the dielectric permittivity to soil moisture with empirical values defined for different type of soil textures. The equations with the empirical values which suite to the soil texture defined in the study area was selected to calculate the volumetric soil moisture. The volumetric soil moisture values derived from the

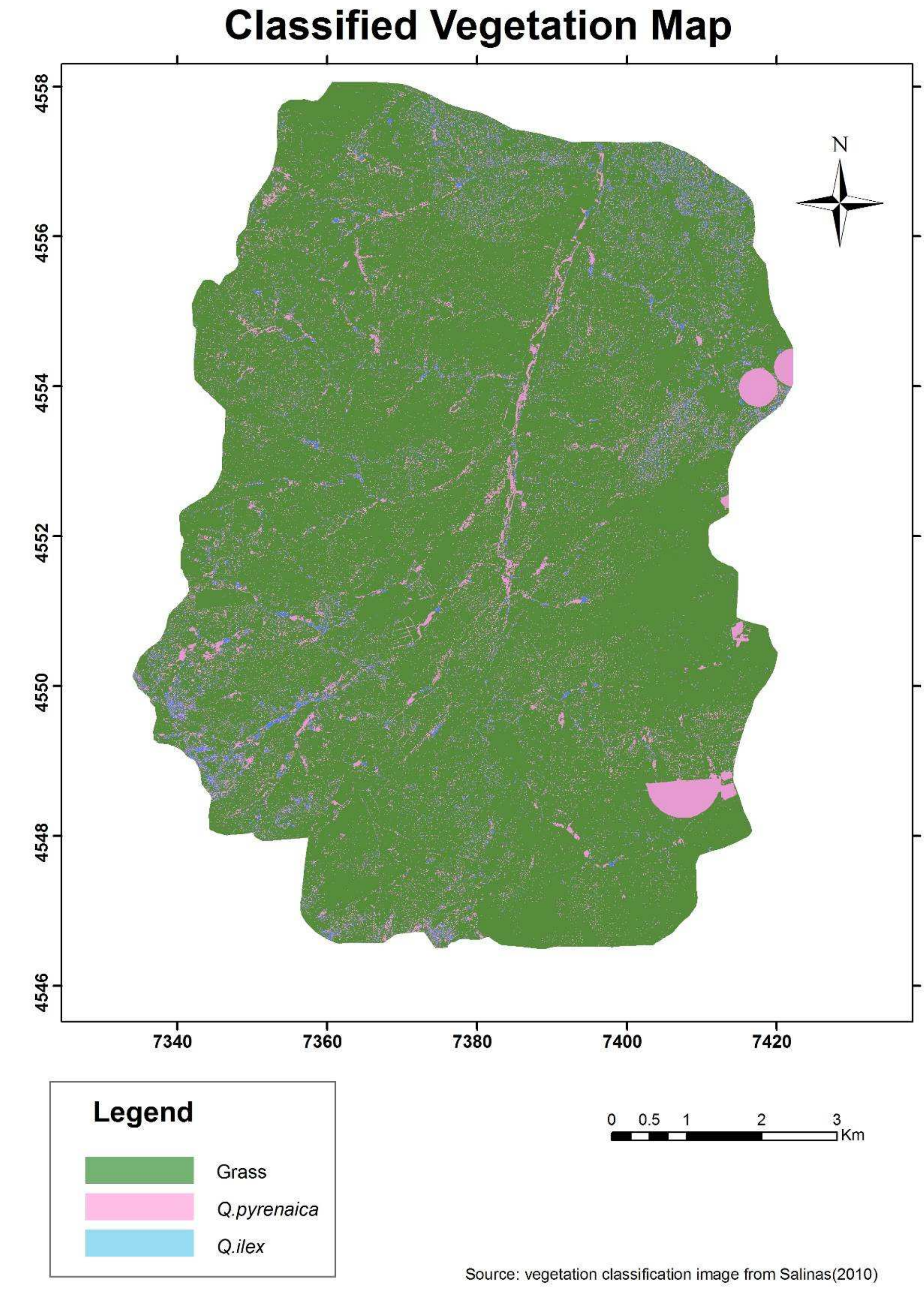


Figure 2-2 Classified vegetation map (Q. *ilex*, *Q. pyrenaica*, Grass) from QuickBird image (Salinas, 2010)

hourly measurements in the two ADAS stations are averaged to daily in order to fit the time step of the recharge model which works on daily basis.

2.1.3.2. Hydraulic head

The groundwater level variations were measured by loggers such as Tirta and Nivolog in the existing piezometers and wells. The general time series hourly records available for the Sardon is from year 2003 to 2009 at six locations with some data gaps and in other six locations have data as of June 2008, where new loggers were installed (Rajapakse 2009). The time series hydraulic head data used in this study was for the period of 2008-2009. The loggers in each piezometer record absolute pressure above the logger sensor and the atmospheric pressure also measured hourly at Trabadillo station with an automated logger. Thus, the difference between the absolute pressure from the logger in the piezometer and the measured atmospheric pressure represents the barometrically corrected water column height above the logger. Finally, the groundwater level in meters was derived from water column height using the altitude measurement. The processed groundwater level data for the 12 piezometers were used to calibrate the transient flow model.

2.1.4. Soil hydraulic parameters

Soil hydraulic properties play important role on the overall water balance and flow partitioning from landscapes to stream and as well as to subsurface. These soil attributes can also be used to classify soil into hydrological zones though soils that exhibit similar hydrological behaviour may be classified as different soils. They are also very useful in parameterization of the unsaturated zone. The soil hydraulic parameters discussed in this text are saturated hydraulic conductivity; field capacity, porosity, and wilting point.

2.1.4.1. Field Data and Laboratory Analysis

Soil samples were collected from 15 locations to derive their soil hydraulic parameters and textural class by laboratory analysis (Fig 2.1 and Appendix 1A).During the field work the main emphasis was dedicated to collecting soil samples using rings for permeameter analysis , soil samples for texture analysis, to infiltration tests and to downloading data from groundwater level loggers and ADAS stations.

The soil texture analysis of the collected soil samples was done in laboratory with the pipette method. The purpose of the analysis was to determine the quantity of sand, silt, and clay fractions in samples of soil. First the soil sample was sieved to separate the gravel (particles coarser than 2-mm) from grains less than 2-mm in diameter and the percent of sand was isolated by sieving through a set of nested sieves. The silts and clays in each sample were determined by using a pipette method that measures the actual percent by weight of each particle size class in the soil sample. The details of the particle size distribution analysis using the pipette method can be found in the laboratory manual or books (Day, 1965).

The laboratory analysis of soil samples using the permeameter, WP4 to derive the soil hydraulic parameters are discussed below separately.

2.1.4.2. Permeameter

The undisturbed soil samples for saturated hydraulic conductivity were taken in metallic rings of 53 cm diameter and 100 cm3 volumes with a closed ring holder (details of field technical operations see www.eijkelkamp.com/Portals/2/Eijkelkamp/Files/P1-31e.pdf). There are two types of permeameters, the constant head permeameter which is used for non-cohesive, high permeability sediments such as sands, and the falling-head permeameter which is more suitable for cohesive, intermediate to low permeability sediments such as clays and silts. In this case the former type was used (for more details on permeameter laboratory operations manuals see www.eijkelkamp.com).

A constant head permeameter is composed of a chamber with a spill over to provide a supply of water at a constant head so that water moves through the samples at a steady state. The permeability coefficient (k-factor), i.e. hydraulic conductivity, is determined using Darcy's law:

$$K = \frac{V * L}{A * t * h} \qquad (10)$$

Where V is the volume of water discharging in time t (m/d); L is the length of the sample; A is the cross-sectional area of the sample (m^2); h is the hydraulic head difference over the sample (m)

As the soil sample rings were taken perpendicular to the ground surface at depth of 25 cm the measurement from the permeameter represents the vertical saturated hydraulic conductivity of the soils.

The porosity, field capacity and bulk density were determined using the drainage method. In this method the saturated samples were first weighed and left to drain for some time. They were weighed at different time steps until the drain of water ceases. Then the samples were oven-dry at 105 ^oC for 24 hours. From the weighed measurements a drainage curve was plotted and the stabilized value of a curve was used to calculate the volumetric water content at field capacity. The porosity was calculated from the weight of the saturated samples while the bulk density from the mass of the sample after oven-drying divided by the original sample volume.

2.1.4.3. WP4 (Water Potential Meter)

The water potential of soils was determined using the Decagon WP4 equipment. The soil samples were saturated with water to have different saturation level (number of water drops) and waited for complete mix-up of soil and water for minimum two hours. Then the sample was put in the WP4 for the measurement of matric potential which varied with saturation level of the samples. The obtained matric potential is plotted with water content to produce a pF curve which was used to calculate the water content at wilting point.

The water retention (also known as soil moisture characteristic) curves relating soil moisture and soil matric potential were established for various samples by measurements of the matric pressure through Decagon's WP4 Dew point Potential Meter device. WP4 measures water potential, giving readings in MPa (Mega Pascal) within five minutes. The soil moisture characteristic curves of 15 samples taken at 5 and 25 centimeter depths from 15 locations were derived. The 15 samples were measured each twice to secure consistency of the measurements that showed good results. To represent the matric pressure - soil moisture relation a power law function was fitted to the measurements and allowed to compute the permanent welting point and the bound water content for a matric pressure of 1.5 MPa and 3.1 MPa respectively (Dingman, 2002) . The range of measurement of WP4 is from 0 to -60 MPa with an accuracy of +/-0.1 MPa from 0 to -10 MPa and +/-1% from -10 to -60 MPa. WP4 uses the chilled-mirror dewpoint technique to measure the water potential of a sample (water potential being the vapour pressure of air in equilibrium with a sample in a sealed measurement chamber).

2.1.4.4. SPAW (Soil–Plant Atmosphere and Water)

The SPAW (Soil-Plant Atmosphere and Water) model is hydrologic software which can give soil water characteristics such as soil hydraulic parameters from the provided percent of sand, silt and clay. The percent of sand, silt and clay of the collected soil samples was used to derive soil hydraulic properties using this soil characteristics model (SPAW).Although the SPAW model can provide many hydraulic parameters, however, the main hydraulic parameters of interest for this study were water contents at field capacity and at wilting point and saturated hydraulic conductivity.

2.1.4.5. Infiltration Test

Infiltration is the process by which water from soil surface enters to subsurface and the rate of infiltration is usually very high at early stages that afterwards gradually decrease to more or less constant value. The maximum infiltration rate of a soil shows its infiltration capacity. The constant value of the infiltration rate is approximately equal to the saturated hydraulic conductivity of the near-surface soil. This rate may have spatial variability so the value given to a certain soil should be averaged of several measurements (Dingman, 2002) .

The infiltration test was done using the double ring infiltrometer to detect if there were any cracks or other related features which could have an effect on the infiltration rate of the soils. The infiltration rate at four different locations with different soil types was measured using three sets of double rings which gave averaged values at each location. The infiltration capacity derived from the infiltration rate was plotted against the cumulative time and fitted with a power function line through the points. The stable line which shows a constant value was used to read the saturated hydraulic conductivity value.

2.1.5. Interception Loss

Rainfall interception may play an important role in the water balance of catchments. Interception is the first hydrologic process that redistributes precipitation near the ground. The amount of precipitation that reaches the ground surface is dependent on the forest type, ground cover and climate. Precipitation is partitioned in to three components: (i) Interception, part which remains on the vegetation and is evaporated after or during rainfall; (ii) Stem flow, part which flows to the ground via stems; and (iii) Throughfall, part which may or may not contact the canopy and which falls to the ground between the various components of the vegetation. The interception loss from forests is usually a significant component (25 to 75%) of the overall evapotranspiration and when expressed in percentage of gross rainfall interception loss may vary from 9% to as high as 60% (David et al., 2006) .

The two types of trees dominant in the Sardon catchment are *Q. ilex* and *Q. pyrenaica*. In Mitra II, experimental site in Portugal, measurements of throughfall and stemflow to estimate the interception loss were done at *Q. ilex* trees. These measurements showed linear relation between the throughfall and gross precipitation assuming the stemflow to be negligible, i.e 0.26% in Equation11. A linear regression established between throughfall and gross precipitation.equation.The Mitra II study reported *Q.ilex* interception loss in order of 29.6% of gross precipitation (Pereira et al., 2009) .

$$T_f = 0.893 * P_g - 1.084 \qquad (11)$$

Interception loss (I) is the difference between gross precipitation and throughfall with negligible stemflow. The substitution of throughfall (T_f) of the above Equation 11 into Equation 12 provides interception loss (I) as function of gross precipitation (Pg) as Equation 13.

$$I = P - T_f \qquad (12)$$

Thus, Interception loss by Q. ilex during all the dry and wet seasons was calculated as follows:

$$I_{ilex} = 0.107 * P_g + 1.084 \qquad (13)$$

The estimation of interception loss from *Q. pyrenaica* done in Rinconada catchment , reported values of 18%, when there were leaves, and 11.9%, when there were no leaves in the trees. The field measurements were conducted for 25 months and included all the wet and dry seasons . The percentage of interception loss of *Q. pyrenaica* was expressed as function of gross precipitation to create relation factor. The relation factor of interception loss from Q. pyrenaica was substituted to Equation 13 and this was used to derived Equation 14 and 15.

.

$$I_{pyrenaica\_leaf} = 0.065 * P_g + 0.661 \qquad (14)$$

$$I_{pyrenaica\_no\_leaf} = 0.043 * P_g + 0.435 \qquad (15)$$

The interception loss by grass was reported about 3-7 % gross precipitation (Corbett and Crouse, 1968). Using the same approach as for the Q.pyrenaica the interception loss for grass was estimated using the following equation.

$$I_{grass} = 0.027 * P_g + 0.279 \qquad (16)$$

The same vegetation type and similarity in climatic conditions between Mitra II experimental site in Portugal and Sardon catchment were the basis for the adaptation of the linear equation to the Sardon catchment (Table 3).

Table 3 Similar conditions for Sardon, Spain and MitraII, Portugal

Site	Portugal**	Spain
Topography	Slightly undulating	Gently undulating
Vegetation	Q. ilex	Q. ilex & Q. pyr
Tree density	35 – 45 ha^{-1}	10~ 60 ha^{-1} [a]
Understory	Mix shrub and grass (dominantly Cistus spp.)	Shrubs & grass (Cistus Spp)
Soil	Shallow (30 cm deep)	50cm (slope) - 200 cm (valley)[b]
Rainy season	Btw Oct & April	Same period[c]
Annual RF	665mm	480 mm[c]
Mean Tree height	6.60+/-0.70 m	6.50+/-0.80[d]
Tree height	7.2 m	6.43m[d]
Crown radius	7.8m	7.17[d]
LAI	2.6	2.42[d]

[a] ;(Cubera and Moreno, 2007); [b] (Tesfai, 2000); [c] (Duah, 1999);[d] (Salinas, 2010) **(David et al., 2006)

The spatial and temporal variation of rainfall interception is usually attributed to the forest /vegetation type, ground cover, and rainfall amount and duration. Hence, in this study to estimate the interception loss spatially in the catchment a vegetation/land cover classification image from Salinas (2010) was used as a basis to identify the vegetation type and their coverage area. The vegetation classification image was reclassified in to three classes namely grass/shrubs , *Q. ilex* and *Q.pyrenaica* in ArcGIS (Fig. 2.2) . Then the reclassified image was converted to feature map and union to a grid map extracted from groundwater model grid. The union of the two maps enabled to calculate coverage area of each vegetation (tree) type with in a grid cell of 100 m x 100 m used in groundwater flow model.

A single grid cell may have a single or combination vegetation type with their respective area coverage percentage. The maps for each vegetation type including their area coverage were prepared in order to calculate the interception loss for each land cover type. These maps as ESRI ASCII files were prepared in ArcGIS as input to the pyEARTH-2D recharge model for the estimate of interception loss at grid cell level. In pyEARTH-2D model the interception value for each grid cell was the sum of interception of each vegetation type within the single grid. The interception loss vary temporally with rainfall and it only uses the rainfall greaterthan 1.5 mm/d

$$I_{cell} = A * I_{ilex} + B * I_{pyrenaica\_leaf} + C * I_{grass} \quad (17)$$

$$I_{cell} = A * I_{ilex} + B * I_{pyrenaica\_no\_leaf} + C * I_{grass} \quad (18)$$

where: A,B, and C are percentage area coverage of *Q. ilex*, *Q. pyrenaica* and Grass

2.2. Subdivision of Sardon Catchment into Soil Zones

The subdivision of the Sardon catchment into zones was a basis for the application of semi-distributed recharge model (pyEARTH-2D) that uses the zones to calculate distributed recharge on cell-by-cell basis. The soil hydraulic parameters are assigned to the zones in which each zone has one value that represent the zone. The division of the catchment in to various zones should take into consideration that those areas with most likely similar conditions, in this case hydrological conditions of unsaturated soil, fall in to one zone.

The sub division of the Sardon catchment was done based on the outcrop digital map prepared by Tesfai (2000). The outcrop map was basically classified in to three zones of fractured granite, massive granite and soil cover. The outcrop map was merged with the hydrography from Geographical Institute of Spain with a buffer of 50 meters to represent the drainage area. Thus, the study area was subdivided in to four zone namely massif outcrop, fractured outcrop, soil cover (regolith) and drainage/ valley.The regolith cover wider area and the fractured outcrop cover less whereas the massif outcrop expose on very limited areas.

The soil hydraulic parameters were assigned to each zone by crossing the outcrop map with the soil points in and the mean values of the soil parameters were assigned to each zone (Table 4).

Table 4. soil parameters for soil zones and pyEARTH-2D

Zones		Massive Outcrop	Fractured Outcrop	Regolith	Drainage
Zone number		1	2	3	4
Max soil moisture	Smax	0.00	0.05	0.35	0.34
Soil moisture at field capacity	Sfc	0.00	0.03	0.25	0.23
Residual soil moisture	Sr	0.00	0.01	0.05	0.10
Initial soil moisture	Si	0.00	0.01	0.17	0.20
Saturated conductivity	Ks	0	2500	10000	6500
Maximum surface storage	SUSTm	0	0	50	250
Number of reservoirs	n	1	1	2	1
Unsaturated recession constant	f	1.0	1.0	3.0	2.0

* Smax, Sfc, Sr, Si (vol%); Ks (mm/d)

* K_s: saturated hydraulic conductivity (mm per day); ϕ : porosity (vol %); θ_{fc}: water content at field capacity (vol %); θ_{pwp} : water content at field capacity (vol %); *n:* number of reservoirs (-); *f:* unsaturated recession constant (-).

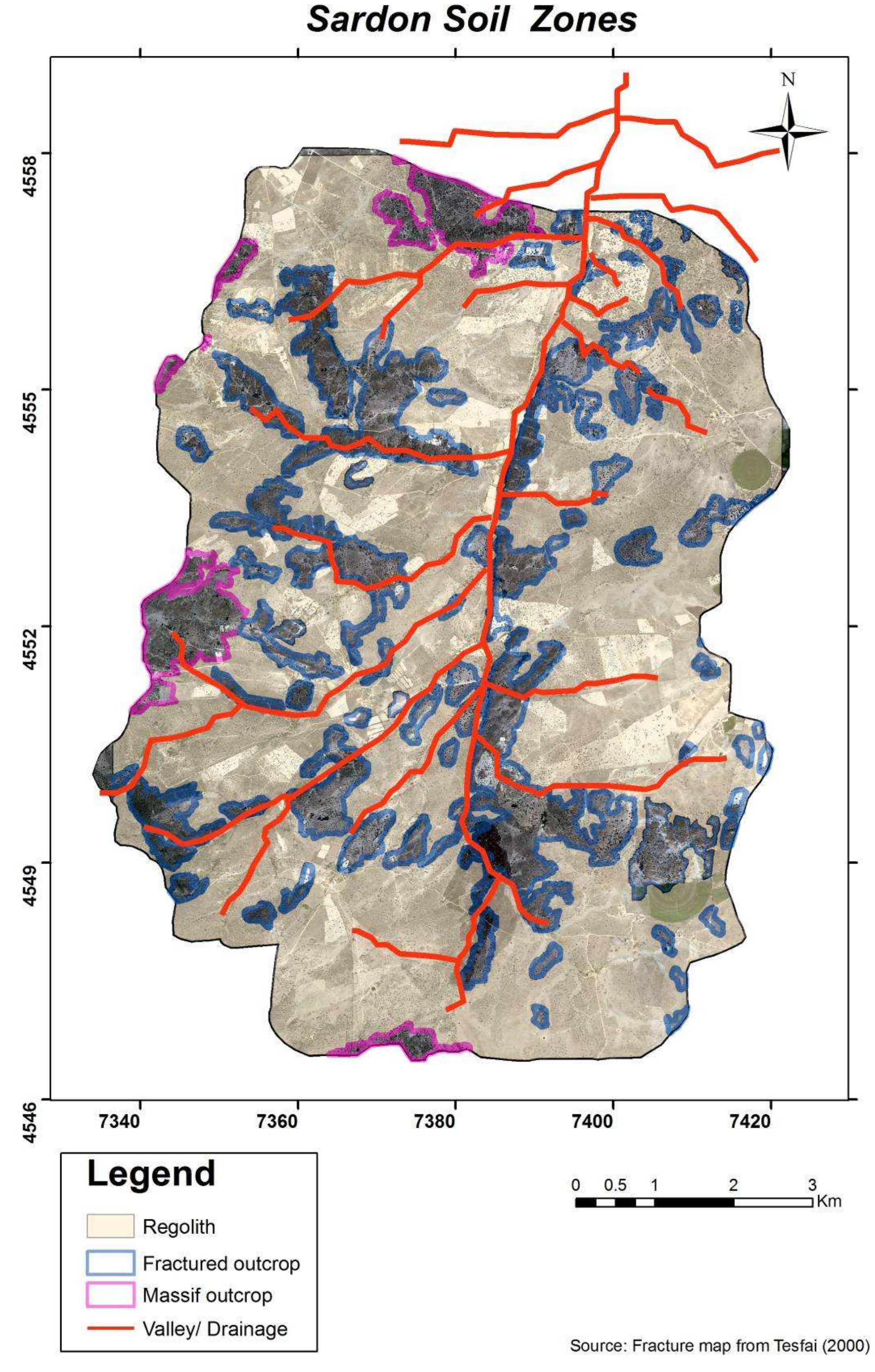


Figure 2-3 Soil zones for recharge model (source Tesfai,2000) overlay on QuickBird image

2.3. pyEARTH-2D distributed recharge model

2.3.1. General concept

The pyEARTH-2D recharge model is a newly developed model which works with the basic underlying principles of the lumped parametric hydrological model EARTH 1D model (Van der Lee and Gehrels, 1990). The pyEARTH-2D model is the conversion of pyEARTH-1D model which is written in Python 2.4 with the basic principles and assumptions of original EARTH model (Frances, 2008). The original EARTH model and pyEARTH-1D model estimate daily recharge at discrete points based on the simulation of soil physical processes (Van der Lee and Gehrels, 1990; Frances, 2008). The pyEARTH-2D is the conversion of pyEARTH-1D model in to a spatially distributed model in which the recharge is calculated on a cell-by-cell basis. The main driving forces of the recharge model are precipitation and potential evapotranspiration while the main input parameters are soil physical parameters such as soil hydraulic conductivity, porosity, field capacity and welting point. The soil moisture is the main state variable for the model which is also used in calibration of the model. The soil physical parameters are assigned to the different zones, i.e. the catchment is subdivided in to zones. The recharge calculated by this model is spatially distributed in which every cell has a single recharge value. The spatially distributed recharge calculated by the model used as in put to the groundwater flow model MODFLOW (Frances, 2008) .

The three modules of the pyEARTH-2D are INTERCEPTION which computes precipitation excess, SOMOS which calculates soil water balance, and LINRES which deals with delay of recharge. The first two modules, INTERCEPTION and SOMOS represent the ‘agro-hydro-meteorological zone’ of the modeled space in which the vegetation and atmospheric influences are considered up to the root zone. The precipitation is redistributed into evapotranspiration, percolation and soil moisture storage. The third module, LINRES, stands for the ‘hydro-geological zone’ of the modeled space and redistributes the percolation in time and represents deep percolation, that is flow from the lower boundary of the root zone to the groundwater table.

2.3.1.1. INTERCEPTION Module: Compute Precipitation Excess

The precipitation excess (Pe) is the portion of the precipitation which reaches the ground surface that infiltrates to subsurface or overland flow. The interception loss (I) was calculated from Throughfall (T_f) as a function of Gross Precipitation (Pg). Interception loss (I) is representative for the surface retention, which is the quantity of water remaining at the surface on leaves and stems while the Tf is the part of precipitation that goes down through the gap between leaves to the ground surface. Interception Loss (I) strongly influences the amount of water that reach the soil. The small storms and the first few raindrops of rain are intercepted and interception loss is used as a threshold for the infiltration. Precipitation Excess (Pe) was approximately equal to the througfall when stemflow is negligible. The equation used in this module was

$$Pe = Tf = A * (a * P_g + b) \qquad (19)$$

Where P_e is precipitation excess (mm), P_g is gross precipitation (mm), A is percentage of vegetation area cover (%); a & b are slope and intercept of linear regression, respectively.

2.3.1.2. SOMOS module

The SOMOS calculates the mass balance in the root zone where the infiltrating water (Pe) is divided into different components: actual evapotranspiration, percolation, ponding and /or runoff and the remaining part is the change in soil moisture storage (Equation 21).

$$\frac{dS}{dt} = P_e - ET_a - R_p - (SUST + Q_s) \qquad (20)$$

Where: S is soil moisture (mm), P_e is the precipitation excess (mm), $ET_{a:}$ is the actual evapotranspiration (mm), R_p is the percolation (mm), *SUST* is the ponding water (mm) and Q_s: the runoff (mm).

The soil moisture S is expressed as the product of volumetric soil moisture content and the thickness of the layer where soil moisture changes occur, i.e. S=W*D, and is expressed in mm.

The actual evapotranspiration (ET_a) is computed as follows:

$$ET_a = PET \cdot \left(\frac{\theta - \theta_{pwp}}{\phi - \theta_{pwp}} \right) \qquad (21)$$

where: *PET* is potential evapotranspiration (mm), θ is actual volumetric soil moisture (vol%), θ_{pwp} is permanent wilting point (vol %) , and Φ:is Porosity (vol %).

The percolation (R_p) is computed with the following equation

$$R_p = K \cdot \left| \frac{dh_p}{dz} + 1 \right| \approx K_{sat} \cdot \left(\frac{\theta - \theta_{fc}}{\phi - \theta_{fc}} \right) \qquad (22)$$

where: K is the unsaturated hydraulic conductivity (mm/d), dh_p/dz: is the gradient of the hydraulic potential, K_{sat}: the saturated hydraulic conductivity (mm./d), θ : the actual volumetric soil moisture, θ_{fc}: the soil moisture at field capacity (vol %), and Φ: porosity (vol%).

The assumption for the simplification of Eq.15 is that percolation equals to the unsaturated hydraulic conductivity, where K.dhp/dz is negligible in relation to the gravitational component.

The actual evapotranspiration and the percolation are computed by linear relations with the soil moisture and soil hydraulic parameters (porosity, field capacity and permanent wilting point).

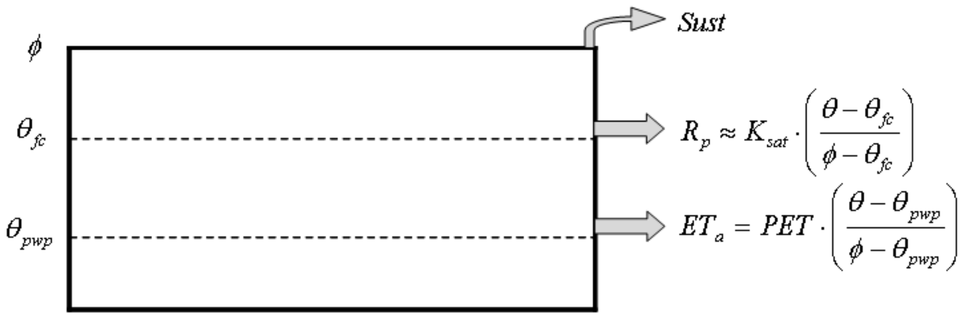


Figure 2-4 Soil reservoir model (Source Frances (2008))

The surface ponding occurs only if the amount of water in SOMOS reaches saturation and the infiltration rate exceeds percolation rate R_p.

$$\frac{d(SUST)}{dt} = P_e - ET_a - R_p - E_o \qquad (23)$$

where: *SUST*: the ponding water (mm); E_0: the open water evaporation (mm).

The overland flow or runoff (Q_s) occurs in conditions where the ponding water exceeds a threshold value ($SUST_{max}$), which is the maximum surface storage capacity.

$$Q_s = SUST - SUST\,\mathrm{max} \qquad (24)$$

2.3.1.3. LINRES module

The equations that are used in the delay R_p in recharge R are:

$$R = Y_n = \frac{f}{1+f}\sum_{i=0}^{n}(1+f)^{-i}Y^*_{n-i} \qquad (25)$$

$$Y_0 = \frac{1+f}{f}R_p \qquad (26)$$

where R is the recharge (mm/d), f is the unsaturated recession constant, n *is* the number of reservoirs, Y^*refers to the result from the previous time step, Y_0 is the upper boundary condition and R_p is the percolation (mm).

The main outputs of the pyEARTH-2D are actual evapotranspiration, percolation, ponding, surface runoff and recharge computed on a daily basis for every cell. The recharge rate has a spatial grid resolution and time discretization into stress-periods of MODFLOW. On the other hand, it follows the format of the MODFLOW RECHARGE package

2.4. Transient- state Groundwater model

The constructed groundwater MODFLOW model consists of two layers. The layers of the model were set up based on available model of Shakya (2001). The grid size of the model is 100 m x 100m, the thickness of layers, value of parameters and initial heads were updated by Rajapakse (2009).

2.4.1. Model input

2.4.1.1. Hydraulic head data

The groundwater level data were processed from the hourly recorded hydraulic heads in 12 piezomenter locations; the hourly data were averaged to daily for the period of June 2008 to October 2009. The fluctuation of hydraulic heads in the piezometers shows the response of the aquifer to recharge and groundwater evapotranspiration.

2.4.1.2. Storage coefficient (S)

The upper unconfined layer (MODFLOW option 1) was assigned the specific yield from 0.03 to 0.35. The second confined/unconfined layer (MODFLOW option 3) was assigned storage coefficient from 0.01 to 0.05 based on Rajapakse (2009).

2.4.1.3. Time discretization

Stress period is a period which represents a uniform groundwater flow regime and is defined within the individual simulation periods of groundwater model in MODFLOW. The stress periods were defined taken in to account the temporal variability of rainfall and hydraulic head fluctuations in piezometers. The stress periods defined for the period of June 2008 to October 2009 are 8 irregular periods varied from 4 to 16 weeks (Table 5). The stress periods were divided into time steps of one week each to facilitate model running. The selected stress periods can be divided into two with respect the seasons as dry summer season, where groundwater was lowered continuously, and wet season, where the groundwater was replenished by recharge.

Table 5. Stress periods defined for simulation in transient model (June 2008 – October2009)

Stress period	Start	End	Days	Weeks
1	6/1/2008	6/28/2008	28	4
2	6/29/2008	10/19/2008	112	16
3	10/20/2008	10/26/2008	98	14
4	1/27/2009	3/10/2009	42	6
5	3/11/2009	4/8/2009	28	4
6	4/9/2009	6/18/2009	70	10
7	6/19/2009	8/28/2009	77	11
8	8/29/2009	10/31/2009	63	9
Total			511	73

2.4.2. Standard (Non-Coupled) Transient Model

A standard transient model was first prepared for period of June 2008-October 2009. The model of Rajapakse (2009) was updated with new elevation of the aquifer layer computed using a accurate DEM obtained from the Geographical Spanish Institute (IGN) and new initial hydraulic heads of June 2008 – October 2009. New 8 stress periods were defined and using the Recharge and ET zones of previous model average recharge and evapotranspiration were assigned to each stress period. Similar rising, declining and stabilized hydraulic heads were identified in each stress period of both the standard model and Rajapakse's model. The recharge and evapotranspiration of the stress periods of similar rising heads from Rajapakse model were identified and their value was averaged as input to the stress period of new standard model with rising heads. The same approach was used for the declining and stablized heads of standard model. The recharge and ETg in volume were converted to mm/d by dividing averaged recharge to grid area multiplied with total number of time steps. However, the vertical and horizontal hydraulic conductivity, storage coefficient and drain conductance of Rapajapkse’s model were maintained.

2.5. Coupling of pyEARTH-2D and MODFLOW using PEST

The linking of the two models was done using PEST by calibrating on soil moisture simulated by pyEARTH-2D and on heads simulated by MODFLOW. The optimized parameter in this study was only field capacity for pyEARTH-2D while for MODFLOW parameters no optimization was done due to the instability the model. The optimization on field capacity was done by setting the lower and upper boundary was set to wilting point and porosity, respectively. During optimization initial soil moisture set equal to fc, as tied parameter in PEST.

Since soil moisture is in volumetric percentage while heads are in meters a weight was given to soil moisture following the approach recommended on manual of PEST (Doherty, 2002) , to obtain residual same order as heads.

The measured soil moisture used in the calibration using PEST was from Trabadillo (Tb1) for period of June 2008 – Novemver 2009 and Mulledes (Pmu3) for period of June 2009 – November 2009. Since the soil thickness of regolith zone was taken as 50 cm the soil moisture from Trabadillo ADAS (Tb1) was average of 2 hydraprobe measurements at depth of 25 and 50 cm. The thickness at the valley was taken 100 cm and the soil moisture from Mulludes ADAS (Pmu3) was average of 4 hydraprobes at depth of 25, 50, 75, and 100 cm.

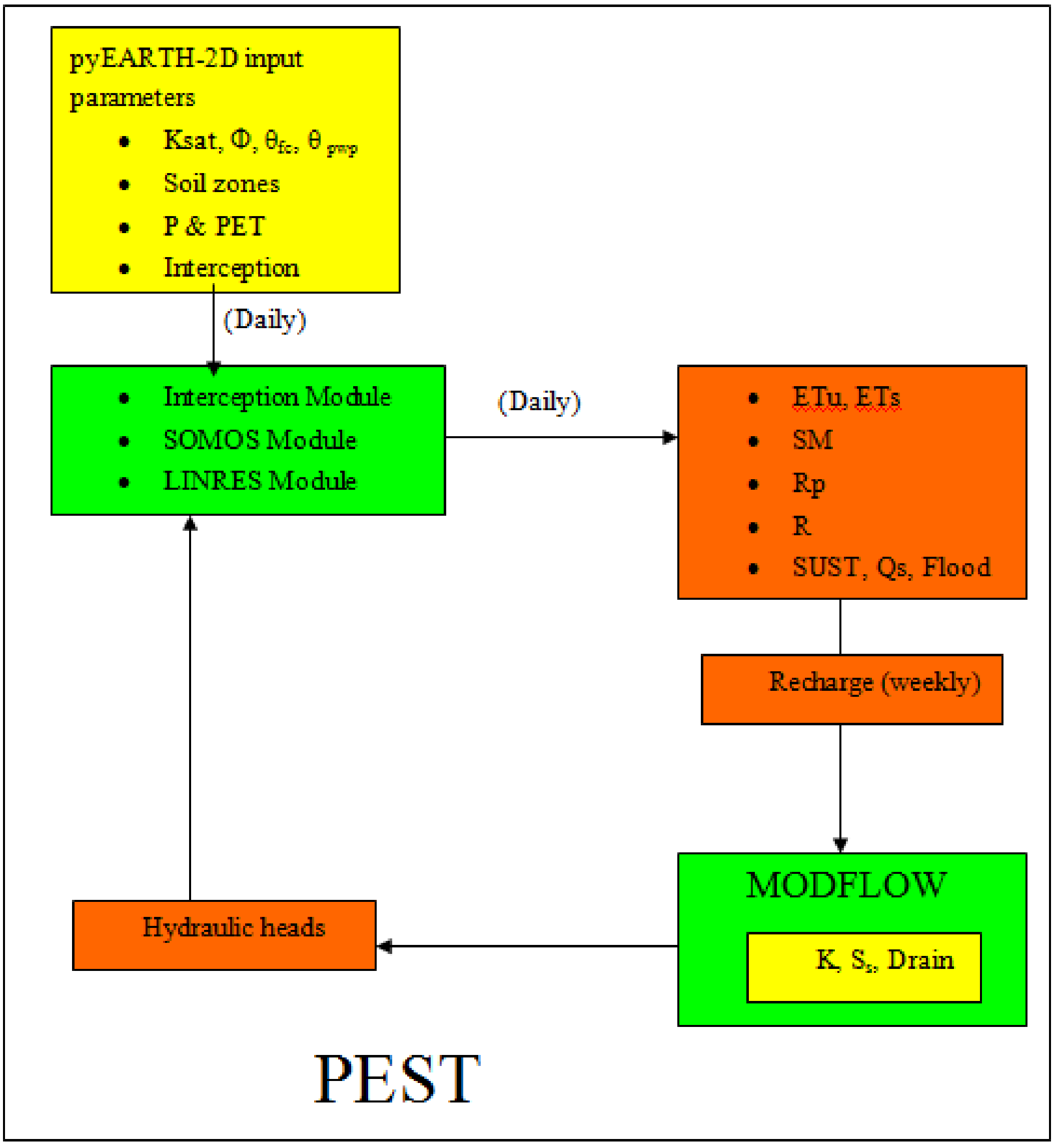


Figure 2-5. Sketch diagram of the coupling of pyEARTH-2D and MODFLOW using PEST
Note: Yellow Box : input parameters ; Red Box: Model outputs; Green Box: Model/ processes
See text for abbreviations

3. Results and Discussions

This chapter consists of all the results obtained during the whole process of this research project including the field and laboratory results. The discussions are also included in each section following the results.

3.1. General Input data

3.1.1. Driving forces

The rainfall and potential evapotranspiration are the two driving forces for the Py Earth recharge model applied in this study. The rainfall from June 2008 to October 2009 shows a daily vriability from 0.2 mm to 32 mm. During the months of February to June of 2009 there was no rainfall, however, some small rains were in July and August. The significant rains started only in October 2009. The potential evapotranspiration calculated using the Penman- Monteith equation for the period of June 2008 to October 2009 show a range from 0.05 mm to about 3 mm per day for the trees, while for the grass FAO-56 reference evapotranspiration show a range 0.4 mm up to 7 mm per day. The grass reference evapotranspiration computed by modified FAO-56 (Allen et al., 1998) was much higher than the tree-specific, potential evapotranspiration computed by Penman-Monteith equation. The lower values for PET for the trees because of the aerodynamic and surface resistance effects of which the Peman-Monteith equation is very sensitive. Theoretically , potential evapotranspiration occurs when trees are well watered and resistance is approximately zero, however , assigning certain value to the surface resistance make the results vary dramatically and this shows sensitivity of Penman-Monteith equation to surface resistance.

The temporal variability of precipitation and potential evapotranspiration are presented in Figure 3.1.

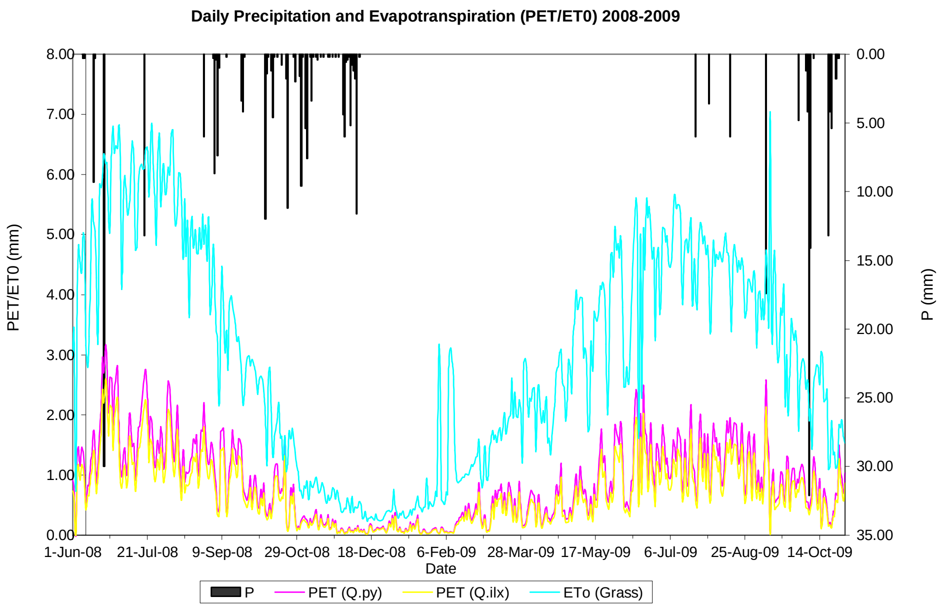


Figure 3-1. Daily precipitation and PET at Trabadillo (June 2008 - October 2009)

3.1.2. State variables

The state variables which were used in this study were soil moisture and hydraulic head. The time series data for these two state variables were recorded hourly in the monitoring points, ADAS stations and loggers in the piezometers.
The soil moisture measurement recorded by Hydra probe at different depths (25, 50, 75, 100 cm) was processed for the period of June 2008 to October 2009 at Trabadillo station and from June2009 to October 2009 at Mulludes. The hourly measured data was processed and averaged to daily (see section 2.1.3.1)

Due to the decreased rainfall in the catchment during the period June 2008 to October 2009 the soil moisture was observed to have a generally decreasing trend (Fig 3.2).

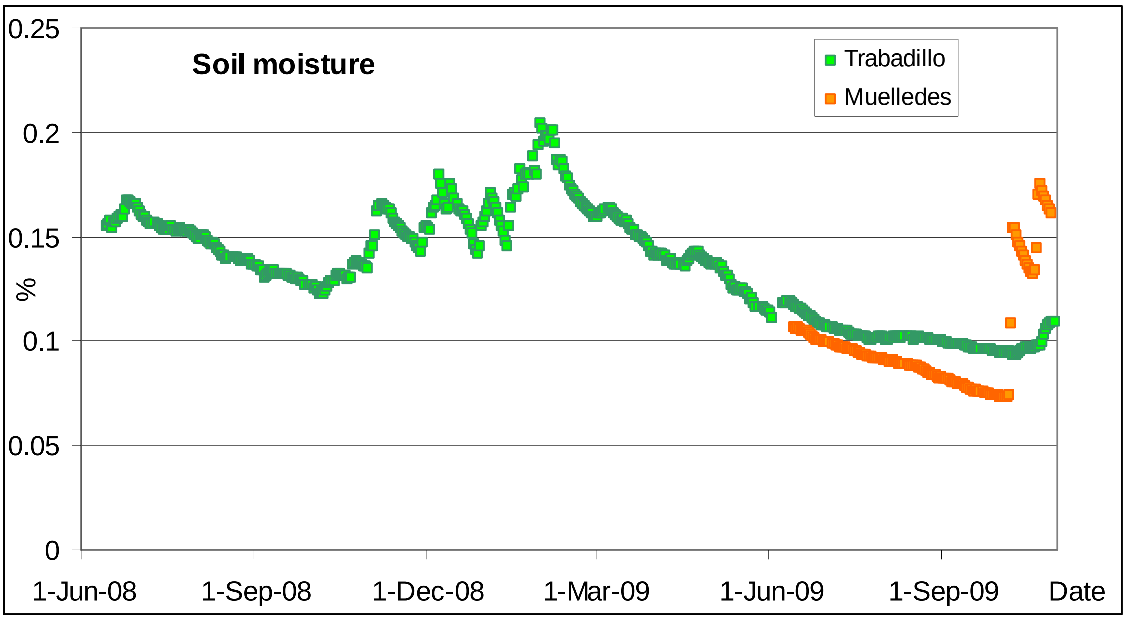


Figure 3-2. Soil moisture measurements at Trabadillo and at Muelledes used for the calibration of the recharge model (June 2009 – October 2009)

The hourly groundwater level data recorded by the loggers in the piezometers was processed and averaged to daily for the period of June 2008 to October 2009 (see section 2.1.3.2). The hydraulic head data from the 12 piezometers that exist in the catchment was used during calibration of the transient model. The hydraulic head in the piezometers is usually an indication of response of the aquifer to the recharge. The decreasing trend of the hydraulic heads shows removal of groundwater either by pumping (human interference) or evapotranspiration (mainly tree transpiration) under semi-natural conditions. The rising of hydraulic heads may indicate the replenishment of the aquifer from recharge from various sources such as precipitation.

The fluctuation of the hydraulic heads could be used to define the stress period in the groundwater regimes which show uniform conditions, for instance a decreasing trend may indicate the dry period and rising of the water level could show the replenishment that is wet period or season. Therefore, using the mentioned approach 8 irregular stress periods were defined for the transient model for the period of June 2008 to October 2009.

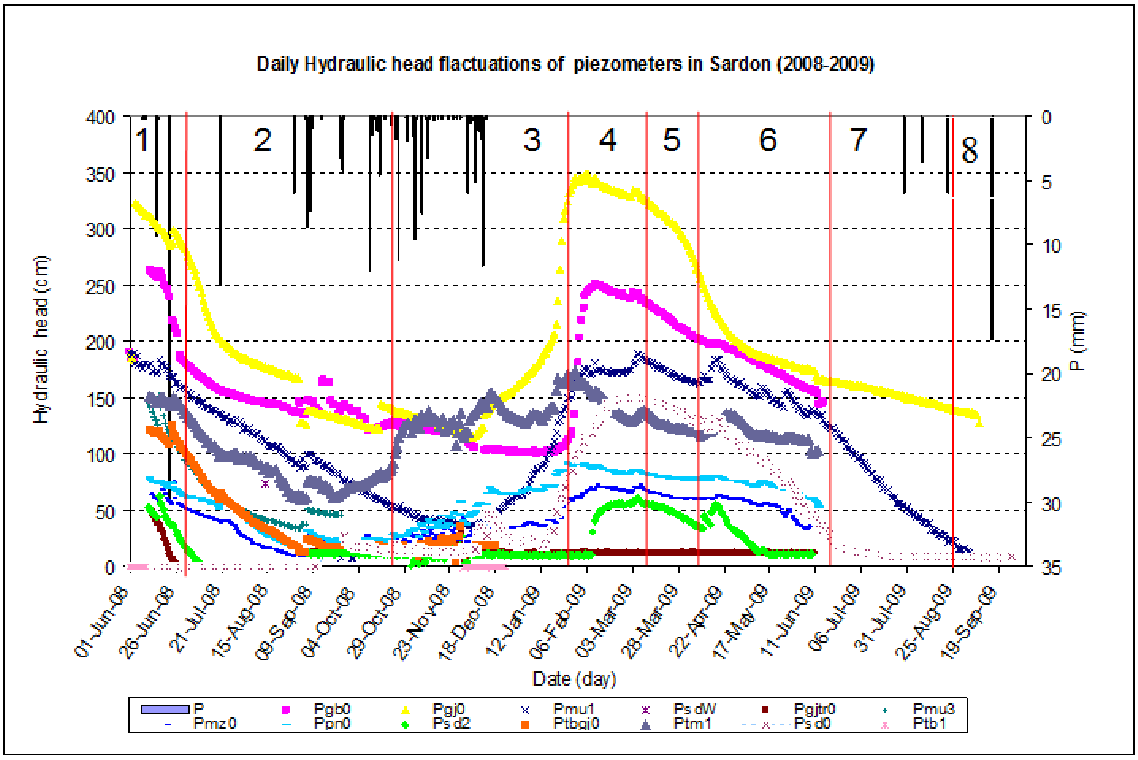


Figure 3-3. Hydraulic head distribution of piezometers (June 2008 – October 2009)

3.1.3. Soil hydraulic parameters

Soil hydraulic properties of soils can be applied as main factors that characterize the hydrological behaviour of unsaturated zone. These soil properties are very important in the classification or division of soils which show different hydrological response into different zones. The soil hydraulic parameters which could play a major role in the soil water balance that were analyzed in this study include saturated hydraulic conductivity; field capacity, porosity, and wilting point (Table 6).

From the particle-size distribution laboratory analysis the collected soil samples were categorized into different soil texture classes based on the fraction of sand, silt and clay content. The soils show high content of sand between 60 and 90%, and lower content of silt 7 to 26 % and clay 4 to 22% (Appendix). These fractions of sand, silt and clay were used to derive soil hydraulic parameters using the SPAW (Soil -Plant and Atmospheric Water) hydrological software. The saturated hydraulic conductivity ranges from 226 mm/d (sandy clay loam) to 2922 mm/d (sand); porosity /saturation from 39% (Sandy loam) to 41% (Loam sand) in volume; water content at field capacity and welting point ranges from 6% (Sand) to 24 % (Sandy clay loam) and 2% (Sand) to 13 % (Sandy clay loam) in volume, respectively.

The soil hydraulic parameters determined using the constant head method of laboratory permeameter found to have a big range of saturated hydraulic conductivity from about 600 mm/d (Loam sand) to more than 40000 mm/d (Sandy loam). The range of values for porosity and water content at field capacity using drainage method were 32% (Loam sand) to 47 % (Sandy loam) and 27% (Loam sand) to 41 % (Sandy loam) in volume, respectively.

The water content at the welting point determined using the Decagon Water potential (WP4) ranges from 1% (Sandy loam) to 9 % (Sandy clay loam).

The soil hydraulic parameter values determined using the permeamter (and drainage method) laboratory show higher value for Sandy loam and lower value for Loam sand. Therefore, these values were used in the parameterization of the unsaturated zone. Since the correlation between the values obtained from SPAW and permeameter was very low correlation, r^2 =0.3. The values from SPAW were not used in the parameterization of the unsaturated zone (Table 6).

Table 6. Soil hydraulic properties of soils derived using different laboratory and field methods

				Ksat (mm/d)			WC(fc) (%)			WC(wp) (%)		Porosity (%)	
				Method			Method			Method		Method	
CODE	ID	Description	Soil type	SPAW	Perm*	Infil*	SPAW	Perm*	WP4	SPAW	WP4	SPAW	Perm*
P4	Mu-Hill	Mulledes-Hill	Sandy Loam	1539	3217	1183	11	29		4	x	40	39
	Trb-twr	Trabadilo tower	Sand	2922		3667	6		17	2	2	41	
P1	Gejo	Gejo	Sandy Loam	1801	534	2433	10	41	8	3	1	40	33
P2	GjDB	Gejelo Del Barro	Loamy Sand	2147	1763	4150	8	27		3	x	40	32
P7	Sar-vlg	Sardon Village	Sandy Loam	1450	41425		11	31	18	5	5	39	37
P6	PNB-WW	Penalbo WW	Sandy Loam	896	748		15	39	19	7	4	39	47
P5	PNB-S	Penalbo S	Loamy Sand	2192	x		8	34	10	3	3	40	37
P10	Trm	Trmedal (piezometer)	Loamy Sand	2687	657		7	27	23	2	6	41	41
P9	Trb-pyr	Trabadilo - Pyrenica	Sandy Loam	749	11331		16	33	21	8	5	39	38
P8	Trb-ilx	Trabadilo- Ilex	Loamy Sand	1578	641		10	27	21	4	5	40	46
P3	Mu-AD	Mulledes-ADAS	Sandy Clay Loam	226	3892		24	34	25	13	9	39	36
P4	PNB-W-P	Penalbo-W-Pond	Loamy Sand	2372			8		54	3	7	41	
	Trm-W	Tremedal-West	Sandy Loam	1139			13		66	5	3	39	
	GjDB-Trm	Gejelo Del Barro-Tremedal	Loamy Sand	2238			8		68	3	3	41	
	Sard-S-Hill	Sardon-South - Hill	Loamy Sand	2421			8		44	2	4	41	

Ksat: Sat. Hydraulic conductivity ; WC(fc); field capacity (vol%), WC(wp): welting point; Porosity (vol%) ; Perm : Permeameter , Infil*: Infiltration test

3.1.3.1. Infiltration test

The infiltration rate measurement at the four locations in the catchment namely was taken average of the three set of measurements done in each location. The average infiltration rate for Gejo, Mulledes, Gejelo Del Barro and Trabadillo was 0.30, 0.15, 0.19 and 0.28 cm per minute, respectively. The saturated hydraulic conductivity derived from infiltration test is presented in Table 6.

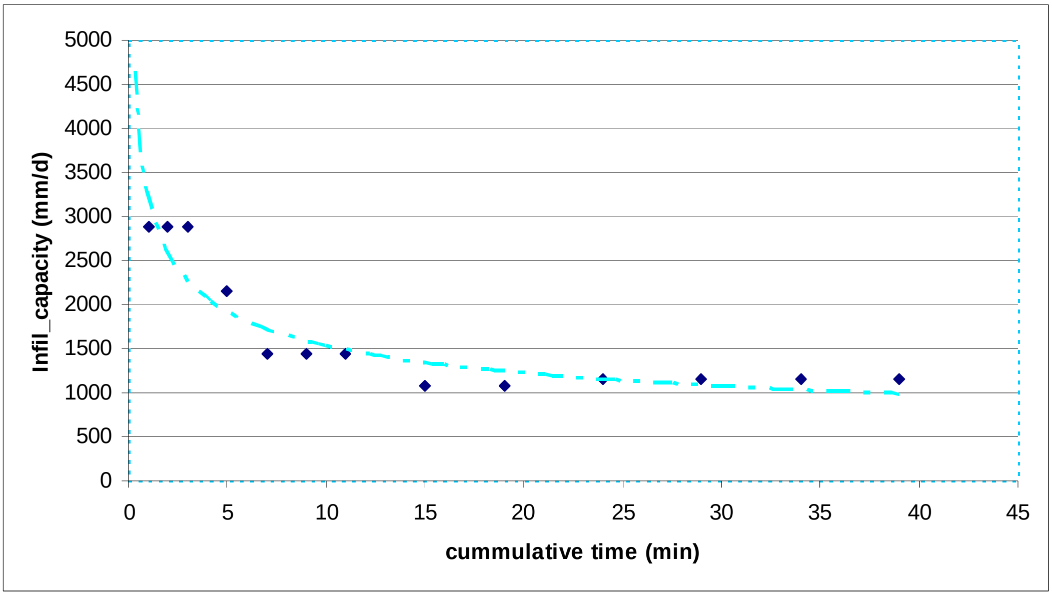


Figure 3-4. Infiltration rate of soil at Mulledes area.

3.1.4. Interception loss

The two types of trees dominant in the Sardon catchment are Q. ilex and Q. pyrenaica. The linear regression equation used to calculate interception loss as function of gross precipitation. The interception loss for Q. ilex in Sardon was 26.17% of gross precipitation which is similar to the range of values reported in various studies of same species (David et al., 2006; Pereira et al., 2009). The interception loss estimated for Q. pyrenaica with leaves and with no leaves was 15.95 % and 10.8% of gross precipitation, respectively. These values are similar to the range what was reported by Moran et al (2008).The interception loss estimated for grass was 3 % of gross precipitation and is with in the range reported by Corbett (1968).

The linear equations used to estimate interception loss for Q. ilex, Q. pyrenaica and grass are explained in section 2.1.5. The equations were derived from the re-arrangement of the linear equation that relates throughfall as function of gross precipitation adopted from Pereira et al (2009). These linear equations were used in the INTERCEPTION module of recharge model pyEARTH-2D. The use of single interception threshold value which is constant for various land covers in both dry and wet seasons could under- or over-estimate the effective precipitation (precipitation excess). The amount of precipitation excess affects the amount of water that would infiltrate to the subsurface soil which indirectly also influences the amount of water to that could eventually be added to the groundwater table as recharge.

Therefore, in this study it has been tried to estimate interception loss in its spatial and temporal variation in the catchment at grid cell level. The interception loss for the different types of trees or vegetation cover is estimated from the gross precipitation by a linear relation between interception and precipitation.

3.2. Subdivision of Sardon Catchment in to Zones

The soil texture depends on the proportion of sand, silt, and clay sizes, based on the inorganic soil fraction. There are correlations between suites of soils and the outcrops of specific formations or units. Soil texture characteristics are controlled by geological structures and their mineralogical character is conditioned by the mineralogy of the original rock.

The Sardon catchment was subdivided into four zones (i) massif outcrop, (ii) fractured outcrop, (iii) soil cover (or regolith) and (iv) drainage area (or valley).The large part of the Sardon catchment is covered with regolith (Tesfai, 2000). The fractured outcrops cover less whereas the massive outcrop expose on very limited areas. The soil hydraulic parameters were assigned to each zone by crossing the outcrop map with the soil points in R-software and then mean value of the soil parameter was assigned to each zone (**Error! Reference source not found.**)

3.3. Standard (non-coupled) transient todel

The Standard transient model prepared for this study period used the averaged recharge (R) and groundwater evapotranspiration (ET_g) of Rajapakse model as input for each stress period . The averaged R and ETg were distributed spatially based on the zones existed in the Rajapakse model which were defined and prepared using GIS index overlay method (Rajapakse , 2009 #57). The non-coupled transient model was run several times and calibrated with observed heads. The simulated head were not following the trend of the observed heads and it show an increasing trend in all the the graphs presented in Figure 3.8 and 3.9.

3.4. pyEARTH-2D distributed recharge model

The distributed recharge model pyEARTH-2D was able to provide spatially distributed recharge at cell level. The average recharge estimated for Sardon catchment during the period of June 2008 – October 2009 was minimum 0 mm/d (no recharge) and maximum 0.89 mm/d to as it showed in Figure 3.8. Generally during the simulated period there was hardly any recharge with exception of small areas which show relatively higher recharge along the centre of the catchment close to the Sardon River. The simulated average soil evaporation (ETu) rate showed a range minimum 0 mm to maximum 0.71mm/d. The soil evaporation (ETu) rate was higher in large area with the maximum average rate 0.417 to 0.710 mm/d as it is shown in Figure 3.9. Therefore, these ETu values show that the very little rainfall that falls on the catchment was evaporated from the unsaturated zone before it reaches to the groundwater as recharge.

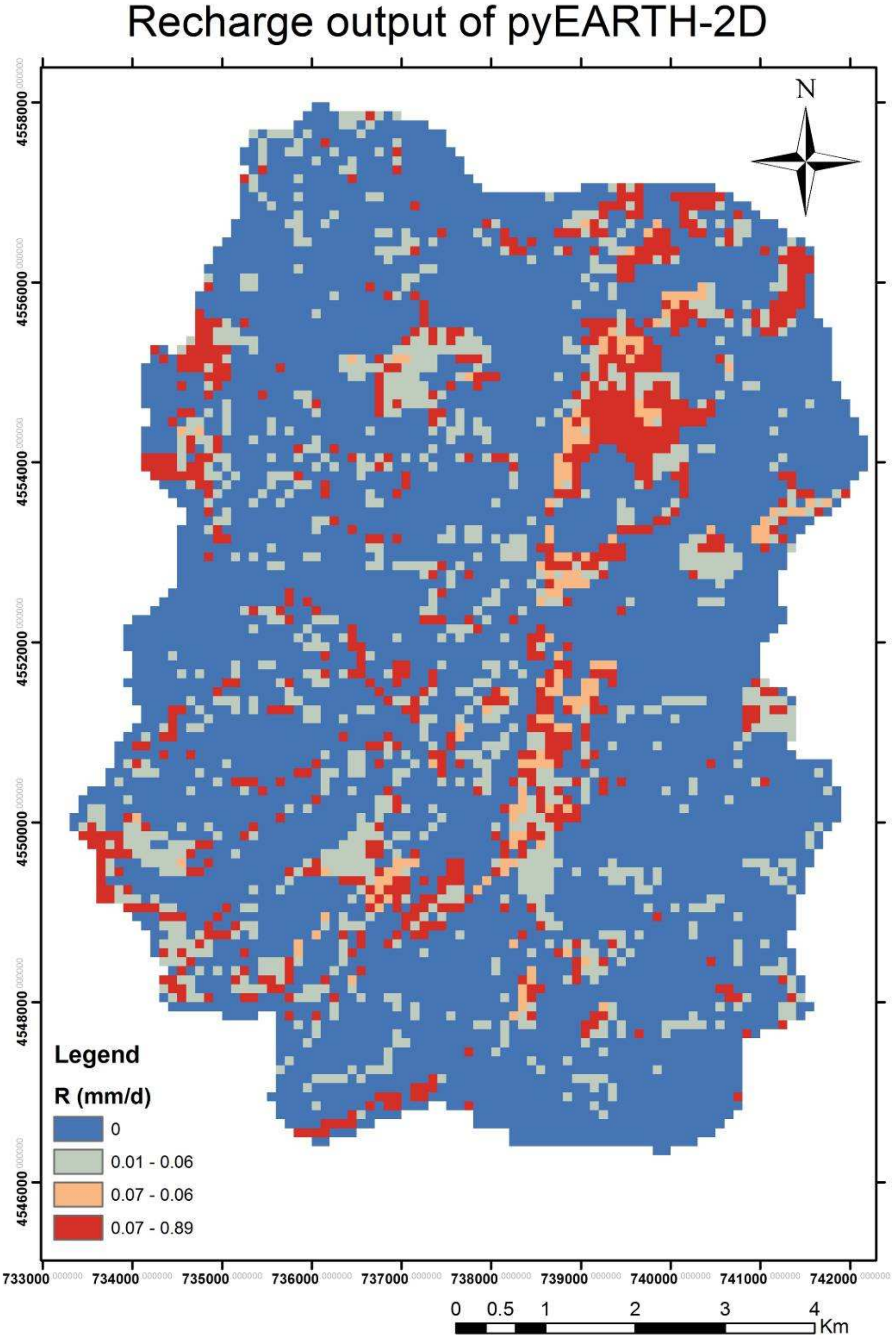


Figure 3-5 Average Recharge rate map for period of June 2008 – October 2009

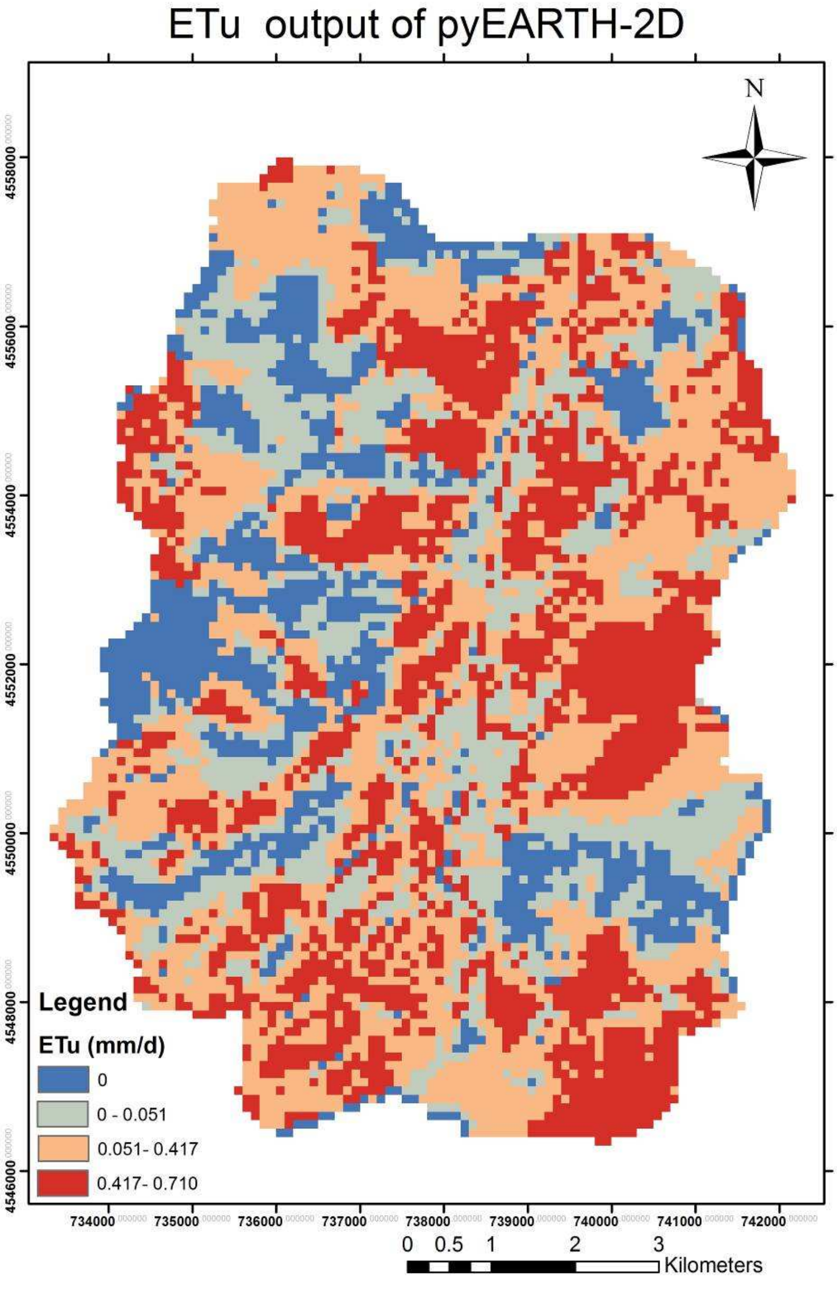
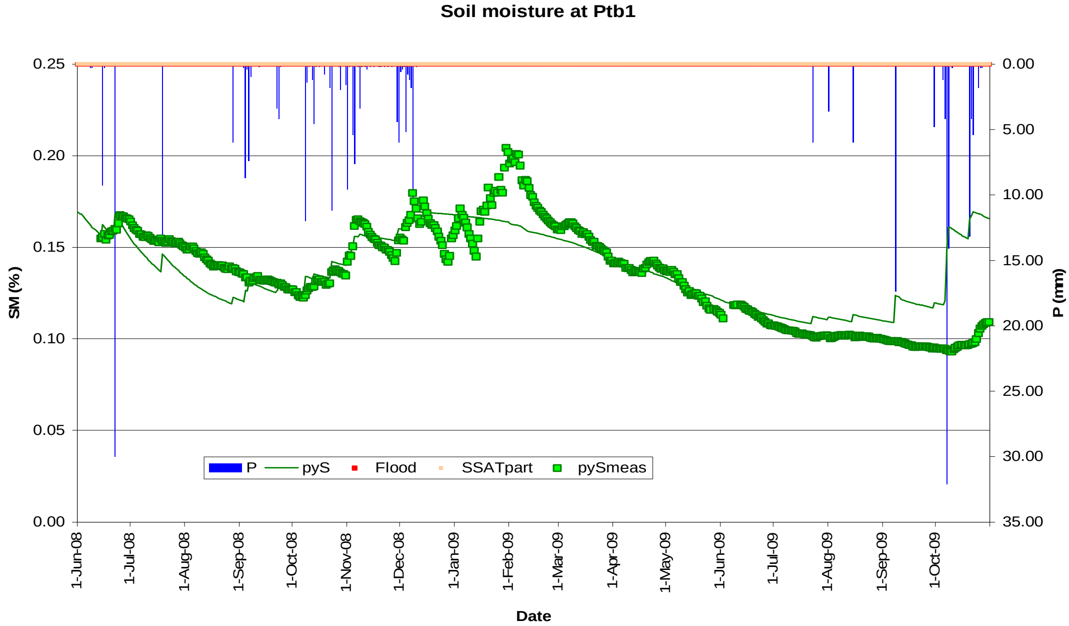


Figure 3-6 Average Soil evaporation (ETu) rate map for period June 2008 –October 2009

3.5. Coupling of pyEARTH-2D and MODFLOW using PEST

The calibration was done against soil moisture (2 locations) and heads (11 piezometers). The optimization was on the following parameters of the unsaturated zone model pyEARTH-2D for each soil zones (fractured outcrop, regolith and drainage): field capacity (SOMOS module) and the unsaturated recession constant and number of reservoirs (LINRES module). The initial soil moisture was declared equal to the field capacity (the month before the starting of the modelling was wet). The optimization of the MODFLOW parameters was not done due to some model cells went dry during PEST process. The coupled pyEARTH-2D calibrated using PEST simulates the soil moisture that closely follow the trend of the measured soil moisture at Ptb1 (Trabadillo station) and Pmu3 (Mulledes station) and are presented in Figure 3-8.



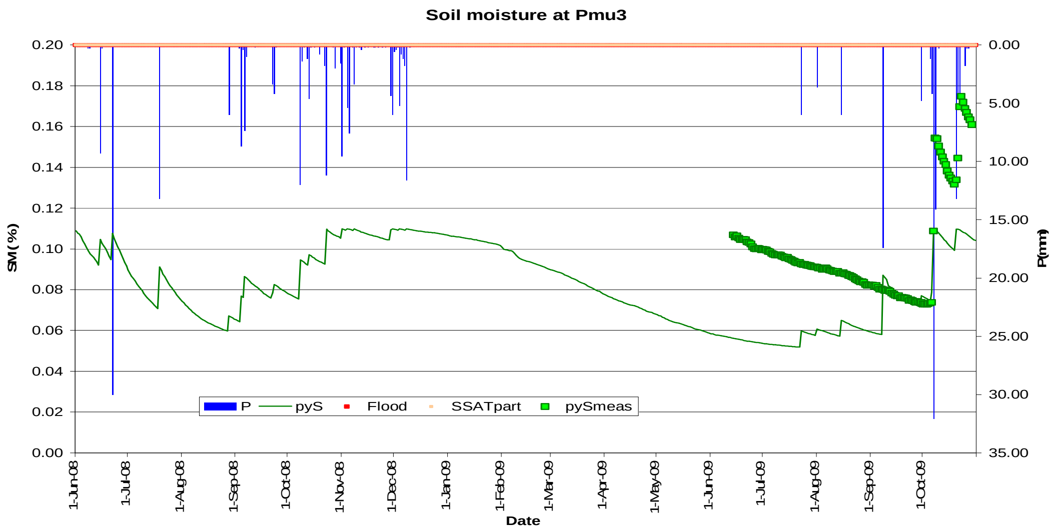
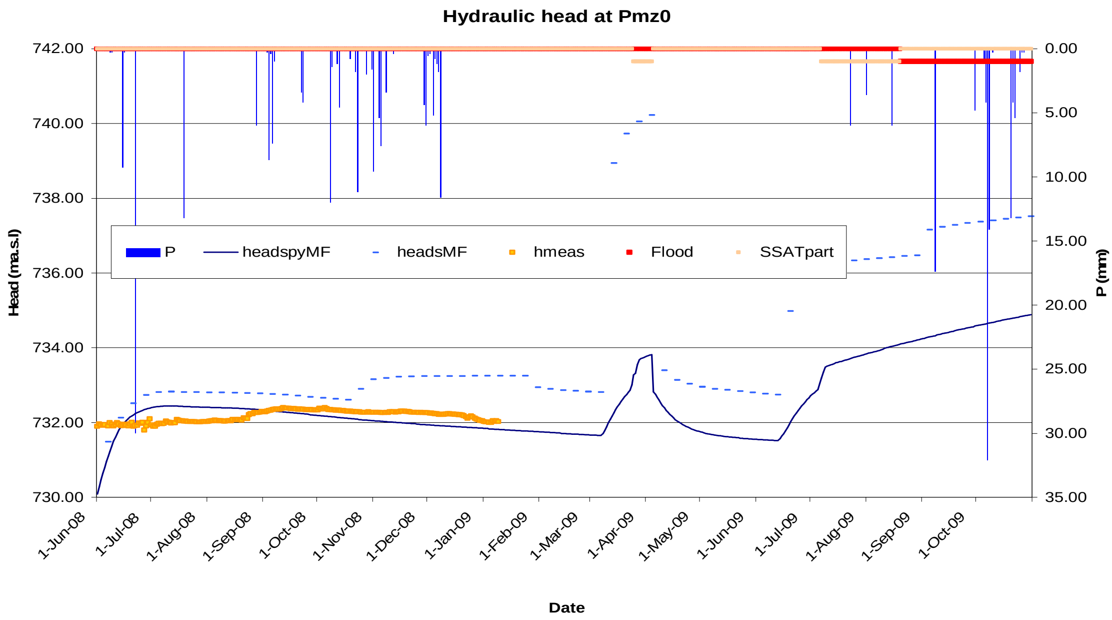


Figure 3-7 Soil moisture simulated by coupled pyEARTH-2D at Ptb1 and Pmu3 stations

The simulated heads (smooth line) by the coupled pyEARTH-MODFLOW at piezometer Pmz0 show a close fit to the observed heads (orange color) than the simulated heads (dashed line) by the standard (non-coupled) MODFLOW as it is shown in Figure 3-10 (upper graph). The RMSE (root mean square error) for the coupled pyEARTH-MODFLOW and standard (non-coupled) MODFLOW was 0.3661 and 0.7580, repectively. The lower RMSE of coupled pyEARTH-MODFLOW indicate the recharge input from pyEARTH-2D was critical in the response of MODFLOW to simulate heads which are close to the observed conditions.



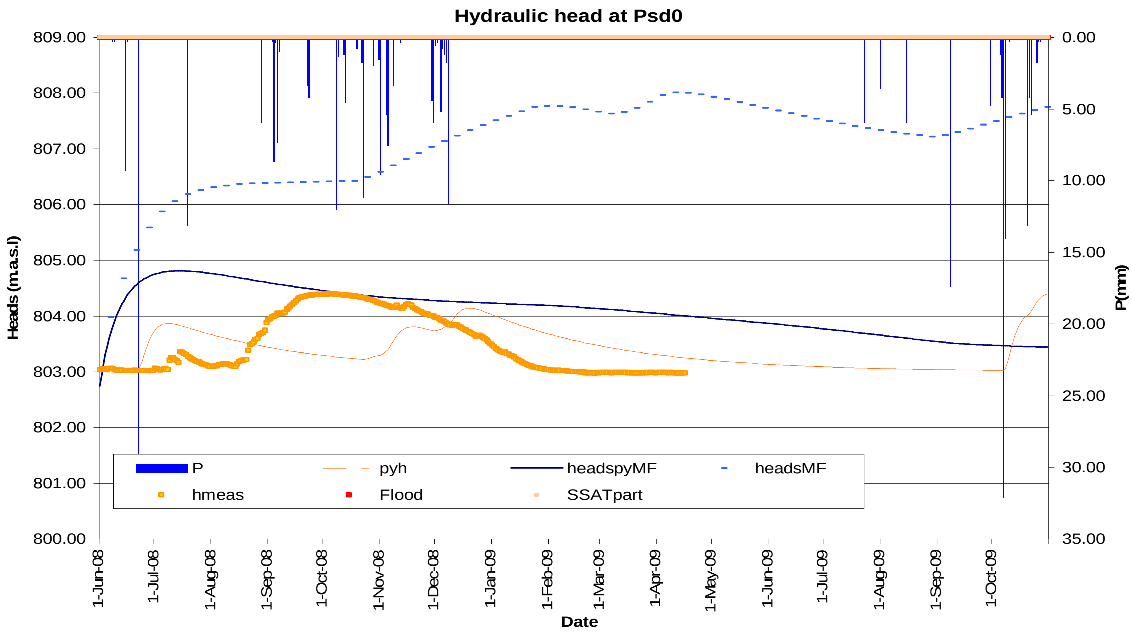


Figure 3-8.Hydraulic head simulated by coupled pyEARTH-MODFLOW and Standard MODFLOW at Pmz0 and Psd0.

The simulated head (smooth line) by coupled-pyEARTH-MODFLOW show a similar decreasing trend to the observed heads (orange thick line) at piezometer Psd0 while the simulated head (dashed line) by the standard (non-coupled) MODFLOW show an increasing trend, which is opposite. At this location the RMSE of coupled pyEARTH-MODFLOW and standard (non-coupled) MODFLOW was 1.0133 and 3.4796, respectively. As it is shown in Figer 3-8 (lower graph) the coupled pyEARTH-MODFLOW was able to reflect the existing situation of the hydraulic head much better than the standard MODFLOW.

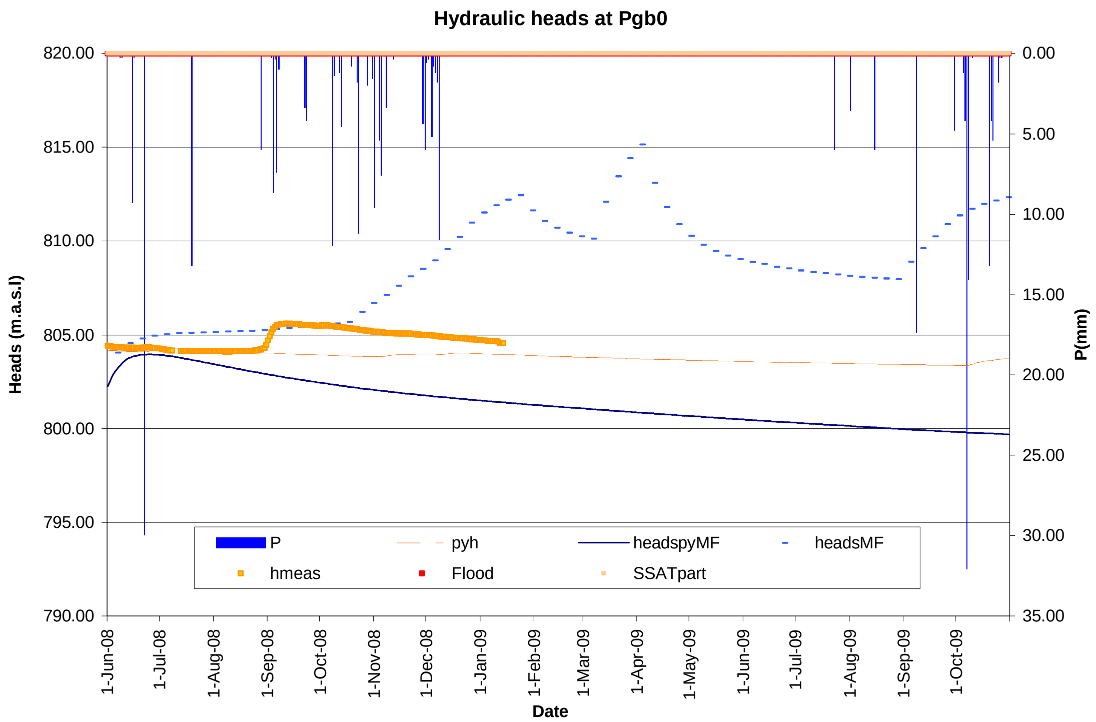


Figure 3-9 Hydraulic head simulated by coupled pyEARTH-MODFLOW and Standard MODFLOW at Pgb0.

At Pgb0 the simulated heads (smooth line) from coupled pyEARTH-MODFLOW showed a similar trend but lower than observed heads (orange thick line). Where as the standard MODFLOW simulated heads (dashed line) show a rising trend (Fig 3-10).The RMSE of coupled pyEARTH-MODFLOW and the standard MODFLOW was 2.4650 had 2.8389, respectively.

3.6. Water Balance

The water balance evaluated from standard (non-coupled) MODFLOW and coupled pyEARTH-MODFLOW model describes all the inflows and outflows to the groundwater system (Figure 3-10). The inflow was only groundwater recharge while the outflows were groundwater evaporation and drains. The water balance for all the stress periods by standard MODFLOW showed that inflow (groundwater recharge) greater than outflows (ETg and Drain), however, the storage of the aquifer was negative (Table 7 & Figure 3-10). This means standard MODFLOW assign high recharge and this could be the reason for the rising simulated heads.

The water balance evaluated by coupled pyEARTH-MODFLOW show all the fluxes are small and the storage as well. Taking into account the low rainfall the recharge was expected to be low and the coupled pyEARTH-MODFLOW shows the conditions close to reality, that is low recharge during the simulated period.

Table 7 Water balance of all stress periods from standard MODFLOW (1 June 2008- 31October 2009)

mm/day	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	TOTAL
STORAGE	-0.00237	-0.00218	-0.00748	-0.00134	-0.00321	-0.00117	-0.00067	-0.00421	-0.0226
DRAINS	-0.00013	-0.0006	-0.00067	-0.00031	-0.00012	-0.00058	-0.00033	-0.00034	-0.0031
RECHARGE	0.0027	0.00428	0.00849	0.00199	0.00369	0.00241	0.00214	0.00476	0.03045
ET	-0.00021	-0.00148	-0.00033	-0.00035	-0.00036	-0.00066	-0.00114	-0.00021	-0.0047

Table 8. . Water balance of all stress periods from coupled PyEARTH-MODFLOW (1 June 2008- 31October 2009)

mm/day	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	TOTAL
STORAGE	-0.00030	0.00142	-0.00083	0.00056	0.00041	0.00101	0.00139	-0.00120	0.00246
DRAINS	-0.00011	-0.00051	-0.00052	-0.00024	-0.00008	-0.00042	-0.00026	-0.00022	-0.00235
RECHARGE	0.00062	0.00057	0.00168	0.00001	0.00001	0.00003	0.00003	0.00161	0.00455
ET	-0.00021	-0.00148	-0.00032	-0.00034	-0.00034	-0.00061	-0.00116	-0.00019	-0.00465

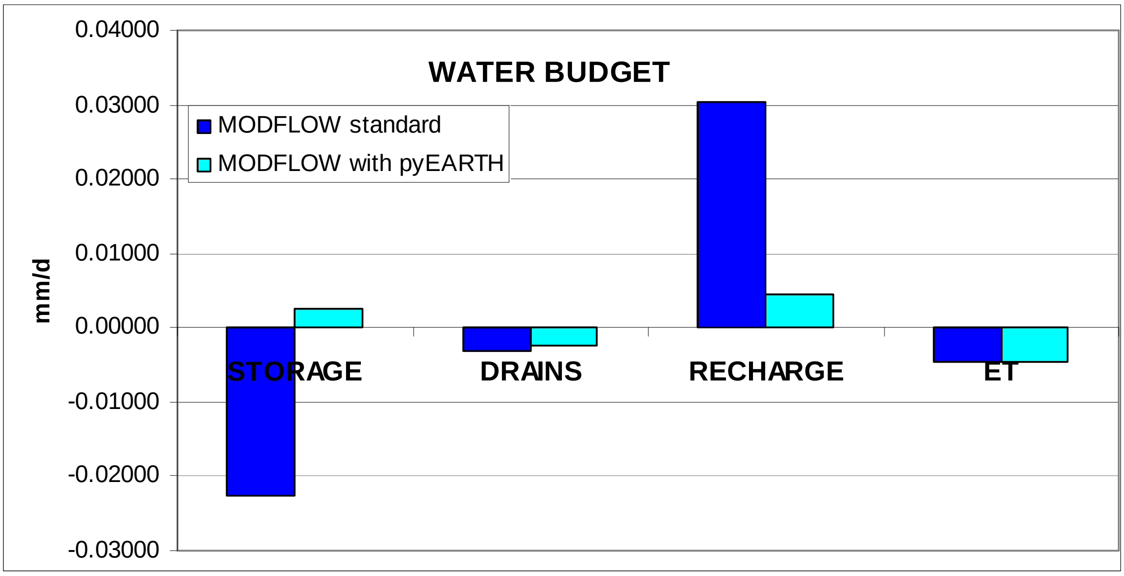


Figure 3-10 . Water Budget from MODFLOW standard and MODFLOW with pyEARTH.

4. Conclusion and Recommendation

The main objective of this study was to improve groundwater model reliability by coupling pyEARTH-2D recharge model with MODFLOW using PEST.

The semi-distributed recharge model pyEARTH-2D was applied to estimate spatially distributed recharge. The recharge model with input of interception loss function, soil parameters and soil zones, driving forces of P and PET was able to give R, ETu, ETs, SM, Rp, Qs and SUST for the period of June 2008 – October 2009. The effect of interception loss by trees in the study area was very low because of their low density coverage area as compared to the grass/ bush. The low recharge estimated by the pyEARTH-2D was due to low rainfall occurrence during the simulated period.

The simulated heads by coupled pyEARTH-MODFLOW show more similar trend to the observed heads than the standard (non-coupled) MODFLOW heads. The water balance shows that the latter model considers too high recharge while the former model simulates lower recharge which more closely resembles the real conditions during the period as confirmed by observed time varying hydraulic head and soil moisture.

The RMSE and the similar trend of simulated heads by coupled pyEARTH-MODFLOW show the improvement of MODFLOW simulation due to the accurate recharge input from pyEARTH-2D.

The coupling and calibration of pyEARTH-2D by using PEST, result in good simulated soil moisture which show similar trend to the measured. The optimization of field capacity parameter of recharge model pyEARTH-2D coupled with MODFLOW using PEST show good improvement in the out put of the recharge model namely, Recharge, ETu and ETs,

From this study the following recommendations can be madeL

The calibration of the two models should be done simultaneously with their parameters (soil moisture and heads) using PEST. The optimization of the pyEARTH-2D parameters such as field capacity, porosity, wilting point and of the MODFLOW such as hydraulic conductivity, storage coefficient and drain conductance should be done. To get a better calibration of the pyEARTH-2D model to simulate the soil moisture a longer period of simulation which starts at the very dry season should be used.
To avoid dry model cell in the calibration of MODFLOW, a model improvement in thickness of layers and better defined zones of hydraulic conductivity and other parameters is recommended.

The performance of pyEARTH-2D model is best checked when it starts at the end of dry period when the soil moisture is zero and when it is calibrated for long period including several seasons with different rainfall and recharge.

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