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Facultad de Ingeniería

Maestría en Hidrología con mención en Ecohidrología

Applying hydrological modeling to unravel the effects of land use change on the runoff of a paramo ecosystem.

Trabajo de titulación previo a la obtención del título de Magíster en Hidrología con mención en Ecohidrología

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Resumen:

El páramo es muy susceptible al cambio en el uso de la tierra y al cambio climático, y la forestación de ecosistemas de páramo con pino es una práctica común. Los efectos de las plantaciones de pinos son múltiples, incluso sobre la hidrología de la cuenca. Para conocer mejor el impacto de la forestación en la hidrología de una cuenca hidrográfica se realizó un estudio comparativo con el objetivo de obtener respuestas a las siguientes preguntas: 1) ¿Cómo calibrar los parámetros de los modelos hidrológicos sujetos a cambios de uso de la tierra? 2) ¿Cuál es el impacto sobre los picos, el caudal total y el caudal base cuando el uso de la tierra cambia gradualmente de pasto a plantaciones de pinos? y 3) ¿El impacto es diferente cuando el uso de la tierra cambia gradualmente de aguas arriba a aguas abajo (U-D) o de aguas abajo a aguas arriba (D-U)? La investigación se llevó a cabo en dos cuencas pares, respectivamente, la cuenca del Zhurucay con vegetación de pasto y la cuenca de Mpinos con plantaciones de pino. La hidrología se simuló con el software HBV-light. Además de la calibración tradicional, se utilizó la relación caudal base / caudal total como función objetivo. Este procedimiento muestra una mejora considerable en la sensibilidad del parámetro PERC, mejorando la calibración del modelo para imitar el cambio de uso de la tierra. Después de la calibración y validación, se simularon escenarios de cambio de uso de la tierra transfiriendo los valores de los parámetros calibrados. Los resultados muestran que el flujo total y el flujo base se reducen respectivamente en un 21% y un 66% y los picos se reducen en un promedio del 21%, pero individualmente pueden caer hasta el 61%. Además, encontramos que el impacto es más fuerte en los períodos secos que en los húmedos. La diferencia en el impacto entre los enfoques D-U y U-D no es contundente y debería estudiarse más. Este estudio presenta un procedimiento de calibración para cuantificar los efectos del cambio de uso de la tierra antes de que se lleve a cabo. Estas herramientas son de bajo costo y podrían usarse en muchas aplicaciones en temas como la planificación del uso de la tierra, la gestión de los recursos hídricos y la conservación del agua.

Palabras clave: Cambio de uso de la tierra. Calibración. Modelos. HBV-light. Ecosistema de páramo.

Abstract:

Paramo is very susceptible to land use and climate change, and afforestation of paramo ecosystems with pine is a common practice. The effects of pine plantations are multiple, including on the basin's hydrology. To gather insight into the impact of afforestation on the hydrology of a river basin a comparative study was conducted with the objective to derive answers to the following questions: 1) How to calibrate the parameters of hydrological models subject to land use change? 2) What is the impact on peaks, total flow, and baseflow when land use gradually changes from tussock-grass to pine plantation? and 3) Is the impact different when land use changes gradually from upstream to downstream (U-D) or from downstream to upstream (D-U)? The research was conducted on two paired catchments, respectively the Zhurucay basin with tussock grass vegetation and the Mpinos basin with pine plantation. The hydrology was simulated with the HBV-light software. In addition to the traditional calibration, the baseflow/total flow ratio was used as an objective function. This procedure shows a considerable improvement in the sensitivity of the PERC parameter, improving the calibration of the model to mimic land use change. After calibration and validation, scenarios of land use change were simulated by transferring the calibrated parameter values. The results show that total flow and baseflow are respectively reduced by 21% and 66% and peaks reduce on average 21% but individually they can drop up to 61%. Also, we found that the impact is stronger in dry periods than in humid periods. The difference in the impact between D-U and U-D approaches is not conclusive and should be further studied. This study presents a calibration approach to quantify the effects of land use change before it is done. These tools are low-cost and could be used in many applications on issues such as land use planning, water resources management, and water conservation.

Keywords: Land use change. Calibration. Modeling. HBV-light. Paramo ecosystem.

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Glossary of Symbols

recharge = Input from soil routine [mm/Δt]

SUZ = Storage in soil upper zone [mm]

SLZ = Storage in soil lower zone [mm]

PERC = Maximum percolation to the soil lower zone [mm/Δt]

Ki = Recession coefficient [1/Δt]

Qi = Runoff component [mm/Δt]

runoff = Total amount of generated runoff [mm/Δt]

FC = maximum soil moisture storage (mm)

LP = soil moisture value above which AET reaches PET (mm)

BETA= parameter that determines the relative contribution to runoff from rain or snowmelt (-)

Alpha = non-linearity coefficient (-)

MAXBAS = Length of triangular weighting function (Δt)

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1. Introduction

Paramo is an intertropical ecosystem with dominant scrub vegetation providing important ecosystem services (Célleri & Feyen, 2009b). This ecosystem is the most important source of water in the Andean highland (Minaya Maldonado, 2017), contributing or affecting the water storage, flow regulation, and biodiversity (Buytaert et al., 2006a; Célleri & Feyen, 2009a; Roa-García et al., 2011; Vuille, 2013). The ecosystem is very susceptible to a change in land use and climate (Buytaert et al., 2011; Farley et al., 2013), and when they take place are the functional capacity and biodiversity of those ecosystems affected (Erwin, 2009). Afforestation with pine plantations is a common practice in Ecuador's paramo ecosystems (Buytaert et al., 2007).

There are several impacts when land use is changed for example from natural grasslands to pine vegetation. Flow regime changes drastically, peaks and baseflow are reduced severally and water yield decreases as a consequence of higher evapotranspiration (Buytaert et al., 2007). Interception tends to be higher in forests; therefore, evaporation from the canopy increases too (Farley et al., 2005). Afforestation with pine lowers total flow (Scott et al., 2004) and lessens water retention in soils due to organic carbon matter losses (Farley et al., 2004; Molina et al., 2007). Balthazar et al. (2015) showed that changing grassland to pine forests leads to negative impacts such as a decrease in soil water content, soil organic matter, water retention capacity, and probably to the irreversible provision of ecosystem services. Hence, it is crucial to maintain paramo grasslands as pristine as possible. There is not enough in-deep local knowledge about the impact of pine plantations in paramo's hydrology (Buytaert et al., 2007). Because of its specific geography and climate, its hydrologic characteristics could the impact of afforestation in paramo be significantly different than in other ecosystems.

To quantify the effect of land-cover change on hydrology requires continuous monitoring over a long period (Farley et al., 2004, 2005) before and after the alteration. This approach is not always possible. To solve this issue hydrological models can be used to evaluate land use change scenarios and predict those impacts based on knowledge from other sites (Hrachowitz et al., 2013; Post & Jakeman, 1999; Razavi & Coulibaly, 2013; Said et al., 2007). It is possible to model a catchment with a specific land cover to estimate its parameters (Hrachowitz et al., 2013). The problem with this approach is how to transfer parameters between catchments to mimic land use change. This has not been fully studied or validated on paramo ecosystems.

The objectives of this study are: 1) How to calibrate model parameters in catchments to simulate land use change? 2) What is the impact on peaks, total flow, and baseflow when land use changes gradually from tussock-grass to pine plantation? and 3) What are the differences in the impact when land use changes gradually from U-D or D-U? The results of the study will allow local governments and water-related key stakeholders to improve decision-making on issues such as land use planning, water resources management, and water conservation.

2. Materials

2.1 Study Sites

Two paired catchments were selected located in the southern part of Ecuador. The principal catchment is called "Zhurucay" which is divided into 6 sub-catchments (Figure 1) and Mpinos. Both catchments are typical paramo ecosystems.

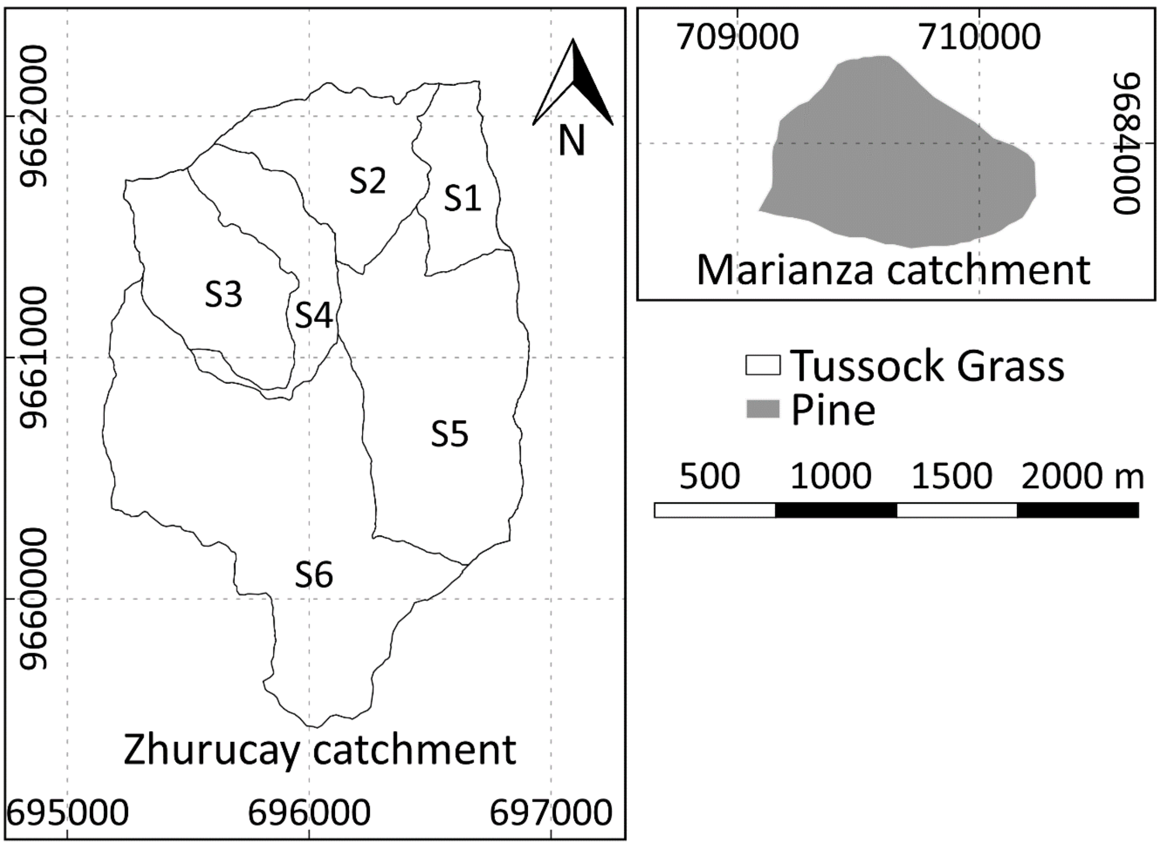

Figure 1. Zhurucay and Mpinos catchments.

The main characteristics of the catchments are listed in Table 1. The catchment areas are small, varying between 0.2 and 3.28 km^2. Zhurucay is covered by tussock grass and Mpinos is a pine plantation. The elevation for all the catchments varies between 3245 and 3900 m a.s.l. Soils are the same for all catchments, namely Andosols. The mean temperature is 6.1°C for the Zhurucay catchment and 8.5°C for the Mpinos catchment. The average annual precipitation is 1160 mm for Zhurucay and 945 mm for Mpinos. The mean annual runoff is approximately 725 mm for

Zhurucay and 180 mm for Mpinos while the average annual baseflow is approximately 280 mm for Zhurucay and 100 mm for Mpinos. For the six Zhurucay sub-catchments (S1 to S6) varies the runoff coefficient from 0.56 to 0.74, whereas for Mpinos the runoff coefficient is 0.19.

Table 7. Main characteristics of the S1 to S6 sub-catchments of the Zhurucay basin.

Code	Altitude m a.s.l	Area km2	Soils	Wetland %	Tussock Grass %	Pine %	Runoff Coefficient	Baseflow/total Flow ratio
S1	3777-3900	0.2	Andosol, Histosol	15	85	0	0.56	0.31
S2	3770-3900	0.38	Andosol, Histosol	13	87	0	0.61	0.38
S3	3723-3850	0.38	Andosol, Histosol	18	82	0	0.64	0.44
S4	3715-3850	0.65	Andosol, Histosol	18	82	0	0.74	0.41
S5	3680-3900	1.4	Andosol, Histosol	17	83	0	0.64	0.34
S6	3676-3900	3.28	Andosol, Histosol	24	76	0	0.57	0.41
Mpinos	3245-3680	0.59	Andosol, Histosol	0	10	90	0.19	0.56

2.2 Data

Despite the size of the catchment areas was precipitation measured by only two tipping-bucket rain gauges at a height of 1.5 m above the soil surface to account for small-scale spatial variability. The resolution of the precipitation was depending on the type of rain gauge respectively 0.254 (Onset HOBO Data-Logging Rain Gauge), 0.2 (Davis Instruments Rain Collector II), or 0.1 mm (Texas Electronics Collector Rain Gauge).

Streamflow was measured at the outlet of each catchment using a compound sharp-crested weir (for high flows a triangular-rectangular section was used and for low flows a V-shaped section) equipped with pressure transducers. Recordings of water level were taken each 5 min. Zhurucay and Mpinos are equipped with a meteorological station that measures wind speed, relative humidity, solar radiation, and temperature with a 5 min interval. There are no gaps in the data for Zhurucay catchment for the period 01/10/2013 – 30/09/2016 (precipitation, flow, and meteorological variables) while in Mpinos a 16% of flow data is missing. Available data periods for calibration and validation are shown in Table 2.

Reference evapotranspiration (ET_o) was calculated using the Penman-Monteith equation (1) (Allen et al., 1998),

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

where,

ET_o reference evapotranspiration [mm day^{-1}],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],

T mean daily air temperature at 2 m height [°C],

u_2 wind speed at 2 m height [m s^{-1}],

e_s saturation vapor pressure [kPa],

e_a actual vapor pressure [kPa],

$e_s - e_a$ saturation vapor pressure deficit [kPa],

Δ slope vapour pressure curve [kPa °C^{-1}],

γ psychrometric constant [kPa °C^{-1}].

This method has already been used in Zhurucay and tested on its accuracy by Córdova et al. (2015).

2.3 Model conceptualization and description

HBV-light is a semi-distributed and reservoir-based model. It can simulate different vegetation zones and sub-catchments, and hydrological processes based on its routines to compute runoff. The routines used in this study are: 1) the soil routine calculates for each vegetation zone the recharge to the groundwater and the actual evapotranspiration as a function of water storage, 2) the response process transforms the water stored in the reservoirs into runoff, and 3) the routing procedure computes the routing of the runoff at the catchment outlet. For more details see (Seibert & Vis, 2012).

HBV-light has 11 different structures that vary from one to three reservoirs and different spatial distributions according to the vegetation zones. In this study, we used the basic version, consisting of two reservoirs. The first one is the storage in the upper soil reservoir (SUZ) that receives water from the soil routing and simulates fast flow and interflow (near-surface and subsurface flow). The second one is the storage in the lower soil reservoir (SLZ) that takes water from the first one based on a percolation rate; this reservoir simulates the slow flow (baseflow) as shown in Figure 2.

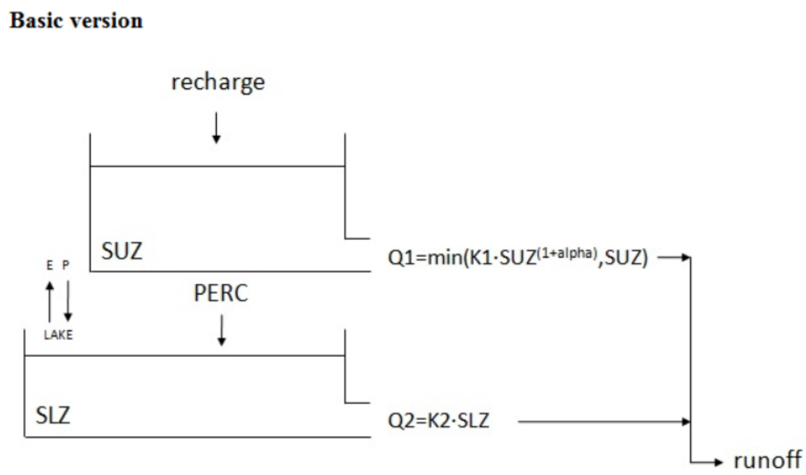

Figure 2. Structure of the HBV-light Basic version of the conceptual model.

We selected the simplest structure because the target was to have few parameters and be able to relate them to the hydrological processes mimicking the effect of land use change, and since it has been proven that this structure works well for the Zhurucay catchment (Sucozhañay & Célleri, 2018).

The Zhurucay catchment was divided into six sub-catchments and two vegetation zones, respectively tussock grasses and cushion plants, whereas Mpinos was simulated as a single catchment with pine as the only vegetation.

3. Methodology

Initially the flow components were separated using the WETSPRO tool (Willems, 2003), then the two catchments were calibrated and validated applying the split sample technique. Subsequently, The Monte Carlo (MC) simulation approach was used for calibration and the Kling-Gupta efficiency (KGE) index and baseflow/total flow ratio were the main objective functions. Then, the calibrated Mpinos parameters were transferred to each of Zhurucay's sub-catchments simulating different land use change scenarios. Finally, the impact of these scenarios was evaluated using several statistical indices.

3.1 Sensitivity Analysis

A total of 50,000 simulations were performed for the 6 sub-catchments of the Zhurucay basin using the MC technique, while a million simulations for the Mpinos catchment, since 50.000 simulations did not yield enough behavioral sets for the sensitivity analysis. Simulations over 0.4 for KGE and NSE were selected as behavioral and then each parameter vs KGE was plotted.

In our study, to improve the calibration procedure (with the objective to simulate land use change), we used the baseflow/total flow ratio as an extra objective function. Doing so allows not only to calibrate the total flow but also baseflow. The latter improves the sensitivity of the PERC parameter which controls how much water flows from the upper reservoir to the second reservoir. The flow was separated using the WETSPRO tool into two components, runoff and baseflow, then the observed baseflow/total flow ratio was calculated for each sub-catchment. Using the same MC simulation results (simulations over 0.4 for KGE and NSE), we additionally applied the baseflow/total flow ratio (with a maximum error of 5%) of the observed and simulated data as an extra objective function and then plotted the graphs again. This permitted looking for differences in the parameters and their sensitivity between a traditional calibration and the baseflow/total flow ratio as an extra objective function approach.

3.2 Model calibration and validation

The time-series data were separated into two independent periods using the split sample technique. The calibration and validation periods are depicted in Table 2. The first month of the period was copied backward during all the simulations as a warming-up period.

Table 8. Calibration and validation periods.

	Calibration		Validation	
	Starts	End	Starts	End
Zhurucay Sub 1 al 6	01/10/2013	30/09/2015	01/10/2015	30/09/2016
Mpinos	13/03/2006	13/03/2007	30/10/2004	29/08/2005

KGE (Eq. 2) was used as the main index to evaluate the model calibration performance. We also used the Nash–Sutcliffe model efficiency coefficient (NSE) (Eq. 3). However, NSE improves its performance by underestimating flow simulations, while KGE does not have this issue, and therefore represents better both, high and low flows (Gupta et al., 2009). Volume errors were calculated using Eq. 4.

Additionally, to select the best set of parameters, the right baseflow/total flow ratio was considered (the maximum accepted error was 5%) of the observed and simulated data. This was done because the model should be working properly not only on total flow but also on the sub-components of runoff and baseflow.

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (2)$$

$$r = \frac{Cov_{sim-obs}}{\sigma_{sim} * \sigma_{obs}}$$

$$\alpha = \frac{\sigma_{sim}}{\sigma_{obs}}$$

$$\beta = \frac{\mu_{sim}}{\mu_{obs}}$$

$$NSE = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q_{obs}})^2} \quad (3)$$

$$Volumen\ error = 1 - \frac{|\sum(Q_{obs} - Q_{sim})|}{\sum(Q_{obs})} \quad (4)$$

Calibration of the Zhurucay sub-catchments was done using the MC technique with 50.000 simulations, starting by calibrating the headwater sub-catchments and then going downstream. First, the S1, S2 and S3 sub-catchments were calibrated to obtain the best fitting parameters for each one. Next, another 50.000 MC simulations were performed to calibrate the model parameters of the S4 and S5 sub-catchments. Finally, the same procedure was conducted for the calibration of the S6 sub-catchment. The calibration of the Mpinos catchment was accomplished using the first 50.000 MC simulations to keep the same conditions for the calibration of all sub-catchments.

To select the best fitting parameters the following steps were taken:

1. 50.000 model runs using the MC technique.
2. The simulations with values over 0.4 for KGE and NSE, and a maximum error of 5% on the baseflow/total flow ratio were selected as behavioral, the rest of the simulations were not considered for analysis. For example, for sub-catchment S1 the observed baseflow/total flow ratio is 0.31. Therefore, only the simulations with baseflow/total flow ratios between 0.295 to 0.326 were selected. On average 4.000 of the 50.000 simulations were selected for the next step.
3. Simulations from step 2 were ordered from higher to lower based on KGE values, the top simulation was selected, but when similar KGE values were found, NSE and volume error was considered to select the best-calibrated model.

Validation was pursued using the same calibrated parameters for an independent period. KGE, NSE, and volume error were calculated for these periods, and KGE and NSE values were considered satisfactory for values above 0.5 (Moriasi et al., 2007; Thiemig et al., 2013).

The followed procedure yielded the best fitting parameters to represent the land use of pine in Mpinos catchment and tussock grass in Zhurucay sub-catchments.

3.3 Land use change scenarios

The pine land use parameters, derived from the Mpinos calibration were transferred to each tussock grass sub-catchment of the Zhurucay basin to mimic land use change. FC, LP, and BETA (vegetation zone parameters) and PERC are the main parameters to be transferred because they control the model land use.

In Eq. 5 is FC the maximum soil moisture storage, rainfall (P) is divided into the water filling the soil box and groundwater recharge, depending on the relation between the water content of the soil box (SM [mm]) and FC [mm]). BETA (Eq. 5) is the parameter that determines the relative contribution from rain to runoff (Seibert, 2005).

$$\frac{recharge}{P(t)} = \left(\frac{SM(t)}{FC}\right)^{BETA} \qquad (5)$$

LP in Eq. 6 is the soil moisture value above which the actual evapotranspiration (ET_{act}) reaches potential evapotranspiration (ET_{pot}) (mm). Actual evaporation from the soil box equals the potential evaporation if SM/FC is above LP, while a linear reduction is used when SM/FC is below LP.

$$E_{act} = E_{pot} * \min\left(\frac{SM(t)}{FC * LP}, 1\right) \qquad (6)$$

The designed scenarios are a function of the percentage of land use change area (i.e., sub-catchment) and location in the Zhurucay catchment. In total 11 scenarios were evaluated considering land use change from D-U and U-D. The selected scenarios are representative for the region. Scenarios D-U are more likely to occur because the agricultural frontier gets higher more frequently. It is easier to start using the land D-U.

The scenarios to be evaluated, the percentage of change, and which sub-catchments are going to be altered from tussock grass to pine are shown in Table 3 in the same order as shown in Figure 3. The baseline condition corresponds to ESC0 (80.76% of land use with tussock grass).

Table 9. Percent change of tussock grasses to pine for the 11 scenarios of land use change.

	% area changed	Sub to Pine
ESC0	0	-
ESC1	5.18	S1
ESC2	15.26	S1-S2
ESC3	24.76	S1-S2-S3
ESC4	31.51	S1-S2-S3-S4
ESC5	52.26	S1-S2-S3-S4-S5
ESC6	80.76	S1-S2-S3-S4-S5-S6
ESC7	28.5	S6
ESC8	49.25	S6-S5
ESC9	56	S6-S5-S4
ESC10	65.5	S6-S5-S4-S3
ESC11	75.58	S6-S5-S4-S3-S2

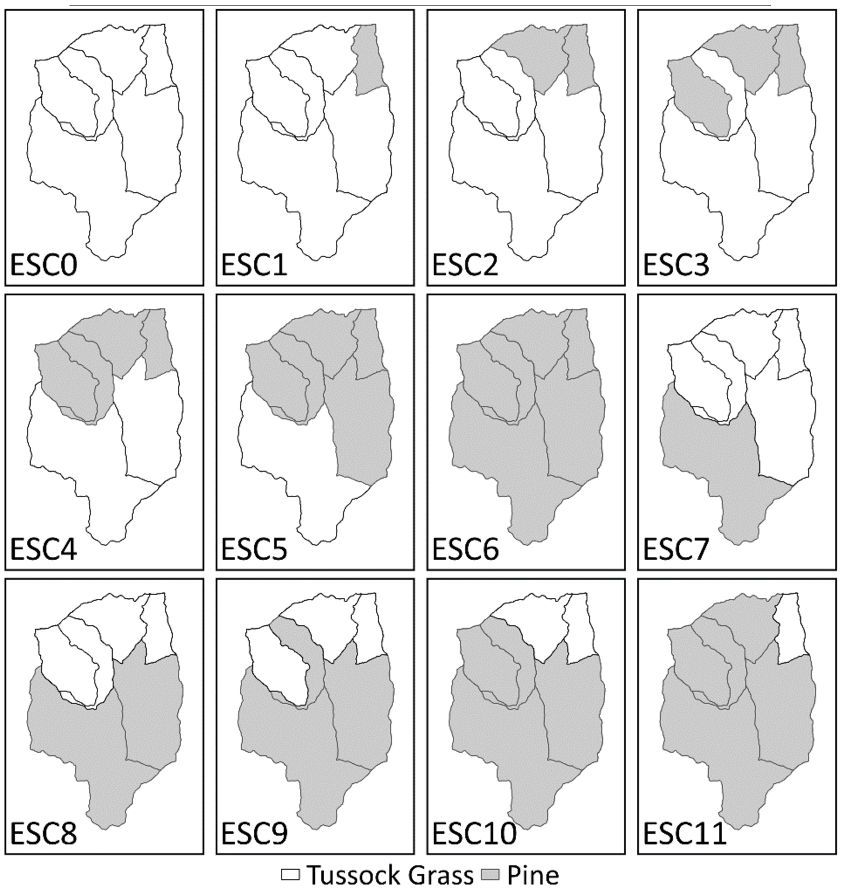

Figure 3. Tested land-use change scenarios for simulating the effect of changing tussock grasses to pine in the Zhurucay sub-catchments. The white color represents tussock grass while the gray color pine land use.

3.4 Evaluation indices to quantify the effect of land use change and relative error between two approaches (U-D and D-U)

To quantify the effect due to land use change some indices were applied: the runoff coefficient, total flow volume, baseflow volume, the average difference in peaks, and FDC (Percentiles 10, 50, and 90). The runoff coefficient and the total flow volume permit checking what proportion of water production is being affected by land use change. The baseflow volume will allow estimating how the slow flow is affected by land use change, not only during precipitation events but also when no precipitation events occur (i.e., in dry periods). The average difference in peaks, computed as the average of the absolute values of the differences between the peaks of the scenarios and the baseline (ESC0) in percentage, enables visualizing the impact on high flows (Eq. 7). The relative error between the two approaches (U-D and D-U) permits comparing quantitatively those options. Finally, FDC (Percentiles 10, 50, and 90) can be used as a measure of the magnitude and the frequency of streamflow. Also, these curves allow comparing the complete range of flows and how they might alter under land use change. Many studies use and recommend using FDC and its percentiles to evaluate the impact of land use/cover change on the different magnitudes of streamflow: (high (P10), medium (P50), and low (P90) flows (Best et al., 2003; Cisneros et al., 2007; Croker et al., 2003; Lane et al., 2003; Shao et al., 2009).

$$ADP_{ESCi} = \frac{\sum_{1}^{j} \frac{\left|P_{j_{ESC0}} - P_{j_{ESCi}}\right|}{P_{j_{ESC0}}} * 100}{18} \quad (7)$$

where,

ADP_{ESCi} is the average difference in peaks for $ESCi$

i is the scenario number, goes from 1 to 11

$P_{j_{ESC0}}$ is the value peak for position j of the $ESC0$

$P_{j_{ESCi}}$ is the value peak for position j of the $ESCi$

j is the peak number, goes from 1 to 18

4. Results

4.1 Sensitivity Analysis

The PERC parameter changes its sensitivity when baseflow/total flow ratio is used as an objective function, as shown in Figures 4, 5, 6, and 7. Only the four parameters (PERC, FC_1, LP_1 and BETA_1) that control land use are shown in this section, the remaining parameters are not sensitive and not shown here. We depict in the text only the representative figures of the sensitivity analysis (i.e., S1 sub-catchment), the rest of the parameters and sub-catchments are shown in Annex.

The S1 sub-catchment sensitivity analysis for the four transferred parameters for traditional calibration is presented in Figure 4. PERC and BETA_1 reveal no sensitivity, while FC_1 tends to lower values near to 100 and LP_1 to high values close to 1.

Figure 5 is the same graph as Figure 4, but the baseflow/total flow ratio is included as an objective function. It is clear that FC_1, LP_1, and BETA_1 are similar to Figure 4 but now PERC is more sensitive, showing better performance for values between 0.6 to 1.15. BETA_1 shows no sensitivity. Figure 5 illustrates that when the baseflow/total flow ratio is used as an objective function, the total number of behavioral simulations is reduced to 3%. Thus, only this small percentage of simulations can model properly both, total flow and baseflow in contrast to the results shown in Figure 4.

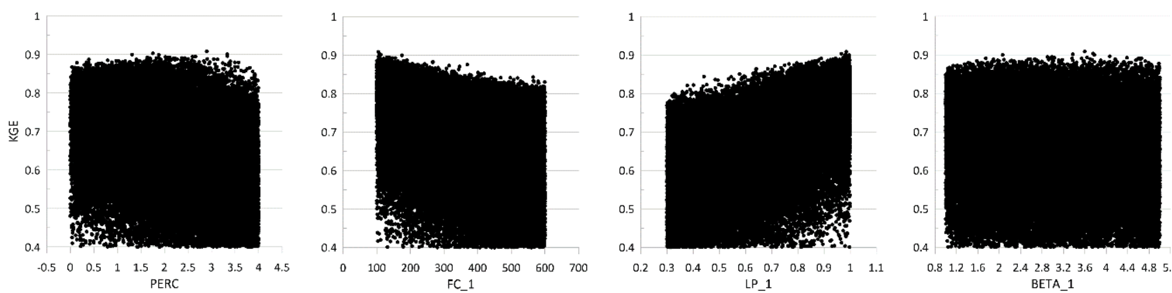

Figure 4. S1 sub-catchment sensitivity analysis for the four transferred parameters (traditional calibration).

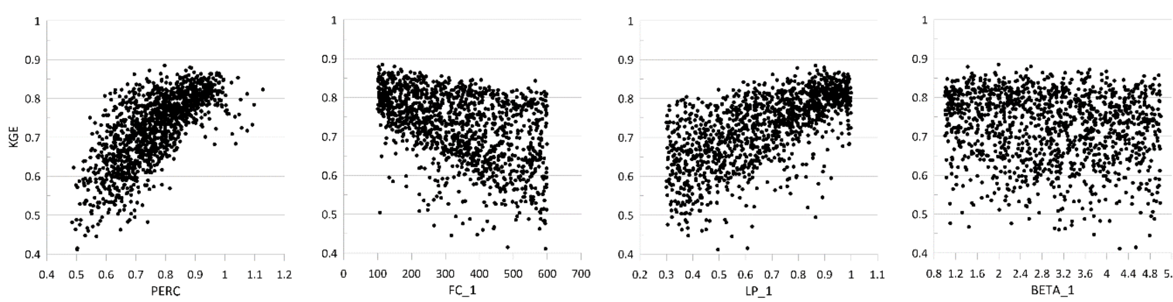

Figure 5. S1 sub-catchment sensitivity analysis for the four transferred parameters (baseflow/total flow ratio included).

Figure 6 presents the sensitivity analysis of the Mpinos catchment for the four transferred parameters. PERC and BETA_1 show no sensitivity while FC_1 tend to values above 200 and LP_1 between 0.3 to 0.75.

In Figure 7 we applied baseflow/total flow ratio to Mpinos catchment. PERC turns sensitive showing an optimal range between 0.33 to 0.42, while FC_1 is between 400 to 600, and LP_1 is between 0.3 to 0.62. The optimal values for BETA_1 are between 1.6 to 3.6. When baseflow/total flow ratio is applied (Figure 7) behavioral simulations are only 0.5% of the number of behavioral simulations shown in Figure 6.

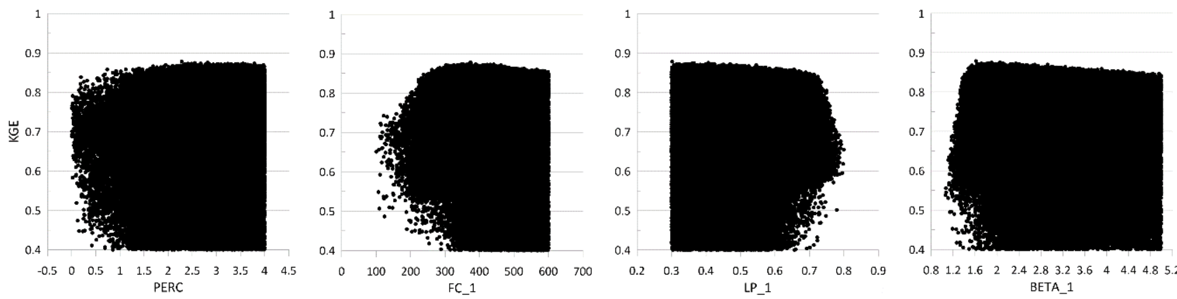

Figure 6. Mpinos catchment sensitivity analysis for the four transferred parameters (traditional calibration).

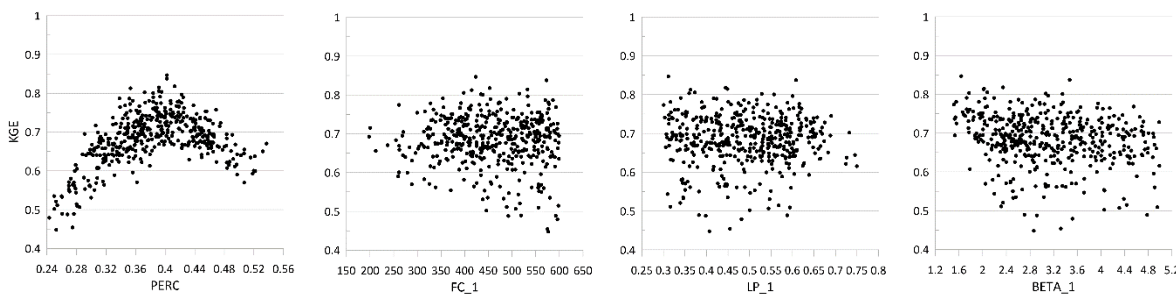

Figure 7. Mpinos sub-catchment sensitivity analysis for the four transferred parameters (baseflow/total flow ratio included).

4.2 Calibration and validation

The calculated indices for all sub-catchments are depicted in Tables 4 and 5. KGE, NSE, and volume error values obtained are satisfactory for both calibration and validation. KGE is always higher than 0.69 for calibration and 0.57 for validation. On the other hand, NSE is always higher than 0.57 for calibration and 0.64 for validation. The model is adequately representing the rainfall-runoff interactions and the proportion of baseflow/total flow. The volume error is on average 11% for calibration and 12% for validation.

Table 10. Statistical indices for the calibration period, respectively for the land uses tussock-grass (Zhurucay) and pine plantation (Mpinos).

	Zhurucay						Mpinos
	S1	S2	S3	S4	S5	S6	
KGE	0.88	0.78	0.82	0.70	0.70	0.91	0.69
NSE	0.78	0.60	0.76	0.67	0.68	0.83	0.57
Volume Error	0.97	0.99	0.89	0.77	0.86	1.00	0.76

Table 11. Statistical indices for the validation period, respectively for the land uses tussock-grass (Zhurucay) and pine plantation (Mpinos).

	Zhurucay						Mpinos
	S1	S2	S3	S4	S5	S6	
KGE	0.83	0.72	0.81	0.62	0.72	0.57	0.79
NSE	0.81	0.67	0.73	0.67	0.73	0.67	0.64
Volume Error	0.95	0.82	0.89	0.78	0.99	0.80	0.90

The best model parameters based on 50.000 MC simulations are listed in Table 6. The FC1 parameter for the Zhurucay sub-catchments are on average 145 while for Mpinos 442. The LP1, BETA1 and PERC parameters for the Zhurucay sub-catchments is on average 0.9, 2.47 and 1.3, while 0.6, 4.74 and 0.3 for Mpinos. These are the main parameters to be transferred because they control land use in the model. As seen, there is a clear difference in the calibrated parameter values between the two catchments due to the distinct land use cover.

Table 12. Best sets of model parameters based on 50.000 Monte Carlo simulations for each sub-catchment.

Sub-micro-catchment	FC1	LP1	Beta1	FC2	LP2	Beta2	PERC	Alpha	k1	k2	MAXBAS
S1	114.05	0.87	2.00	132.73	0.70	3.29	0.80	0.12	0.66	0.16	1.24
S2	235.45	1.00	4.21	370.09	0.98	1.48	0.85	0.18	0.40	0.17	1.48
S3	151.71	0.97	1.46	203.40	0.67	1.79	1.15	0.95	0.40	0.07	1.47
S4	102.12	0.94	1.09	123.74	0.42	2.44	1.23	0.91	0.51	0.20	1.17
S5	114.26	0.93	1.40	257.97	0.92	2.98	1.32	0.85	0.77	0.17	1.13
S6	151.05	0.69	4.66	331.73	0.43	4.39	2.45	0.56	0.22	0.19	1.49
Mpinos	442.35	0.61	4.74	-	-	-	0.33	0.13	0.25	0.06	1.45

4.3 Land use change scenarios

The runoff coefficient decreases from 0.52 to 0.41 (or the total flow falls from 607 mm/year to 479 mm/year) when 81% of the area's land-cover is changed (ESC 6) from tussock grass to pine as shown in Figure 8a, corresponding to a 20.9% reduction. When land use is changed D-U, the runoff coefficient (or total flow) is always higher than the other option (i.e., from U-D). For example, when 30% of land use is changed the runoff coefficient is 0.51 for the D-U approach while the runoff coefficient is 0.47 for the U-D approach; the difference is approximately 8%.

Zhurucay catchment´s baseflow volume is 278 mm/year under current conditions (tussock grass-covered), but when the land use change to pine is about 81% of the area (ESC 6), it can be as low as 95 mm/year (Figure 8b), representing a 66% drop. In contrast to the runoff coefficient, the trend for baseflow is different, baseflow is always lower when land use change is implemented from D-U. For example, when 30% of land use is changed baseflow is 227 mm/year for the U-D approach while baseflow is 190 mm/year for the D-U approach, a difference of 13%.

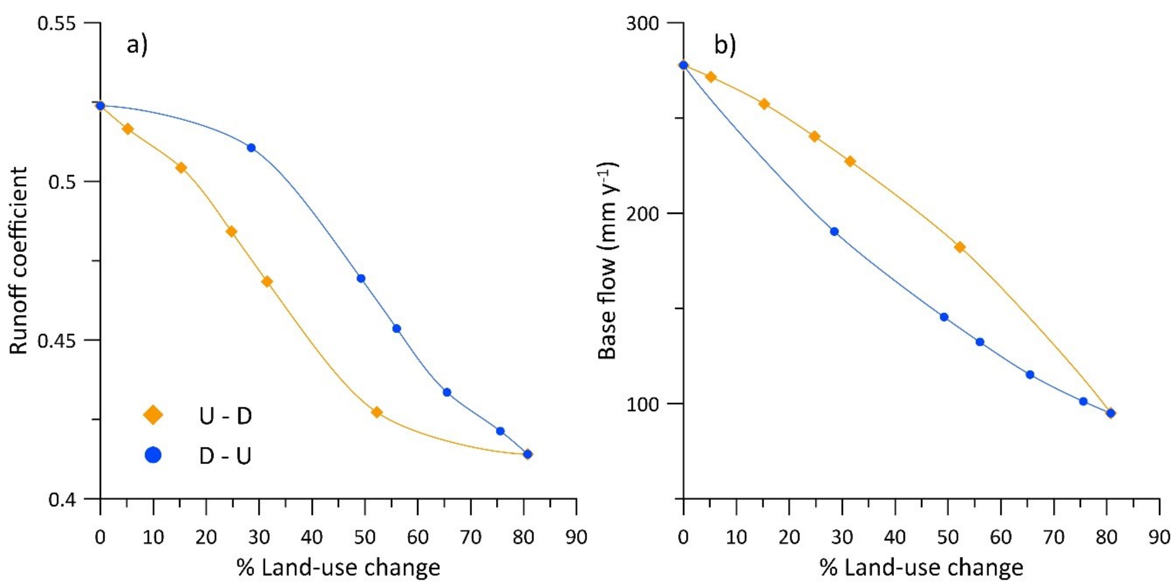

Figure 8. Change of the runoff coefficient (a) and baseflow (b) in response to a cumulative land use change from tussock-grass to pine plantation. U-D represents the upstream to downstream, and D-U the downstream to upstream land use change.

The results also show that when land use is changed from tussock grass to pine, most of the time there is a fall in the discharge peaks (Figure 9a) compared with the baseline condition (ESC0). Average differences (drop) in peaks can reach 21.4% when 81% of the area is changed to pine (Figure 9b), but also we can see that this average raises gradually as the land use change area increases. Single differences (fall in peak discharge) can be as high as 61%. From 0% to 25% of land use change there is no significant difference between the D-U or U-D approaches. Higher percentages of land use change areas show that the average differences in peaks are always larger for the U-D option. For example, when near 50% of land use is changed average differences in peaks are about 18% for the U-D approach, while 12% for the D-U option, a difference of 6% between both approaches. However, this difference can be as high as 18% (51% for the U-D and 33% for the D-U option) when we consider the difference in peaks individually.

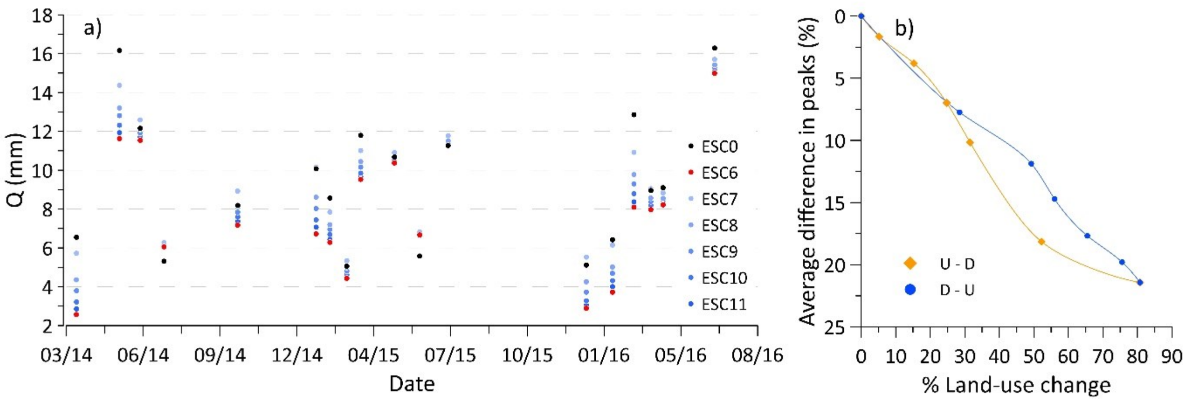

Figure 9. Peaks for the different scenarios of the D-U approach (a) and average differences in peaks (average of the absolute values of the differences between the peaks of the scenarios and the baseline (ESC0) in percent) (b) in response to a cumulative land use change from tussock-grass to pine plantation. U-D represents upstream to downstream, and D-U downstream to upstream land use change.

The analysis of FDC is a common practice to evaluate the impact of land use change on streamflow. Figure 10 shows that discharge always decreases when land use change increases from tussock grass to pine plantation in both approaches (U-D and D-U). However, the impact is not the same for high, medium, and low flows. For example, between ESC0 and ESC6 we can see a reduction of 13%, 40%, and 38% for high flows (P10), medium flows (P50), and low flows (P90) respectively. The results of the FDC show that there is no evident difference between the U-D (Figure 10a) and D-U (Figure 10b) options.

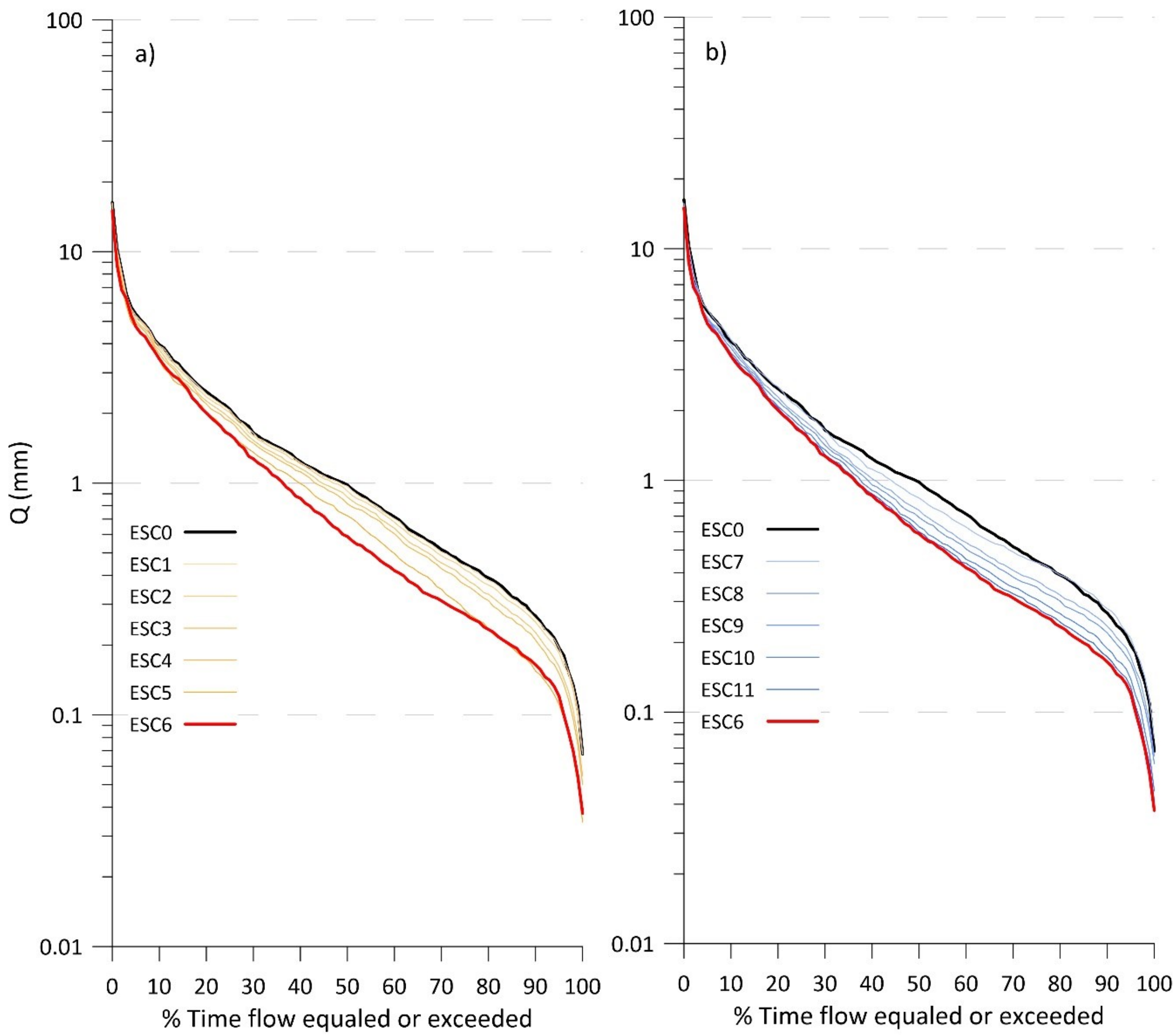

Figure 10. Flow duration curves for a gradual cumulative land use change from tussock-grass to pine plantation: The orange color represents the upstream to downstream (U-D) land use change (a), while the blue color the downstream to upstream (D-U) land use change (b).

5. Discussion

The results reveal that it is possible to properly calibrate the model parameters to simulate land use change. This was achieved by combining the traditional calibration method with the baseflow/total flow ratio. This is proven by 1) the sensitivity analysis showed different ranges of values between land uses for three of the four transferred parameters (PERC, FC_1, and LP_1) and the BETA_1 parameter is intimately related to the FC_1 parameter (Eq. 5), 2) the results on the impact of land use change are consistent with other studies, such as a reduction in total flow, baseflow, and peaks; and an increment of evapotranspiration (ET) (Buytaert et al., 2007; Buytaert et al., 2006b; Fahey & Watson, 1991; Farley et al., 2004, 2005).

The current study found that almost 21% in total flow and 66% in baseflow is reduced after land use change from tussock grass to pine plantation (ESC6 - 81% of land use change) (Figure 8 a&b). These results corroborate the findings of the literature, for example, Farley et al., (2005) analyzed 26 afforestation cases, 13 of them were originally grassland. The drop in total flow and baseflow is likely due to the fact of an increase of ET, being higher in a forest than grassland (Zhang et al., 2001), but also a decline in soil moisture is expected (Célleri & Feyen, 2009b; Farley et al., 2004, 2005; Molina et al., 2007).

The reduction in total flow (21%) in this investigation was lower compared to Buytaert et al. (2007) who found a 50% decrease. These differences could be explained by the difference in altitude, the Zhurucay catchment (3676-3900m a.s.l) is situated at a higher altitude than the other study site (2980-3810m a.s.l). Córdova et al. (2016) found that for every 1000 m rise in altitude, the temperature falls approximately 7°C and a lower temperature would result in lower ET, thus, resulting in higher flows. Comparing our result with Farley et al. (2005), who analyzed 26 afforestation cases, the average reduction from Mean Annual Precipitation is 14% whereas in our study 11% for similar percentages of land use change area (84% on average and 81% respectively).

One surprising finding was that the U-D approach on total flow and peaks (Figure 8 & Figure 9 a&b) had a higher impact than the D-U approach. These results are contrary to Vertessy et al., (2003), who found that the D-U approach has a higher impact than the U-D approach based on model predictions. As an explanation, these authors state that in higher situated areas ET is less than in lower areas. In our study site, there is a small variation in altitude (224 m), this variation is not large enough for evaluating the altitudinal effect on ET. These contrary findings suggest more investigation is needed using experimental data because both studies are based on modeling. In Figure 8b, the D-U approach shows a higher impact than the U-D approach on baseflow. One possible explanation could be that pine trees will consume more water in lower than in higher lands, because of altitude differences and the conditions for transpiration.

It is evident that the impact is stronger on low flows (P90) than medium (P50) and high flows (P10) looking at FDC (Figure 10), which agrees with Scott & Smith, (1997) and Farley et al., (2005). This means that the impact of land use change is larger in dry than humid periods. Scott et al., (2004) state that a strong reduction of baseflows after afforestation is expected. This effect is probably related that tree roots can access water deeper in the soil even under dryer conditions (Hodnett et al., 1995). In accordance with Buytaert et al. (2007) are for similar conditions to this study (tussock grass and pine plantation) peaks and baseflow reduced (Figure 8b and Figure 9). Maximum events are absorbed by the pine plantation, due to higher consumption and higher evapotranspiration, but at no-rainfall events, flow can be reduced to values close to zero for the same reason (Cisneros et al., 2007). We found similar FDCs for the scenarios ESC0 and ESC6 (Figure 10), with the difference that there is less regulated volume when land use change is applied.

As stated by Buytaert et al. (2006), in the Andean region land use change could be more severe than climate change and it is easier to control. These problems can become critical, and effective land use planning might become more stringent than the management of the effects of climate change.

6. Conclusions

Returning to the question posed at the beginning of this study, based on the results of the research it is possible to state that using the HBV-light model, land use change simulation can be implemented by calibrating the model parameters using the baseflow/total flow ratio in addition to the traditional calibration procedure. The most relevant parameters related to land use and their sensitivity were identified (i.e., PERC, FC_1, LP_1, and BETA_1). This new understanding should help to improve predictions of the impact of land use change from tussock grass to pine plantation on a paramo ecosystem. This calibration procedure could be replicated using different types of land uses on the same or different ecosystems. Total flow and baseflow are reduced by 21% and 66% respectively and peaks on average can be reduced by 21%, but individually as high as 61% when land use change is applied from tussock-grass to pine plantation. Also, we found that the impact is stronger in dry than in humid periods. The results also suggest that more investigation is needed to correctly define the influence of the plantation location (i.e., U-D and D-U) on the catchment water balance. This could be addressed using experimental data, taking many years to collect, or physically distributed models requiring more detailed information for model implementation and calibration. The results show that low flows decrease considerably when planting pines. The strong reduction of low flows can cause shortages in the supply of water for human consumption and for irrigation, which is a critical issue for water managers. This study on modeling land use change yields a calibration approach enabling quantifying the effects of land use change before its implementation. These tools are low-cost and could be used in many applications on issues such as land use planning, water resources management, and water conservation.

7. Annex

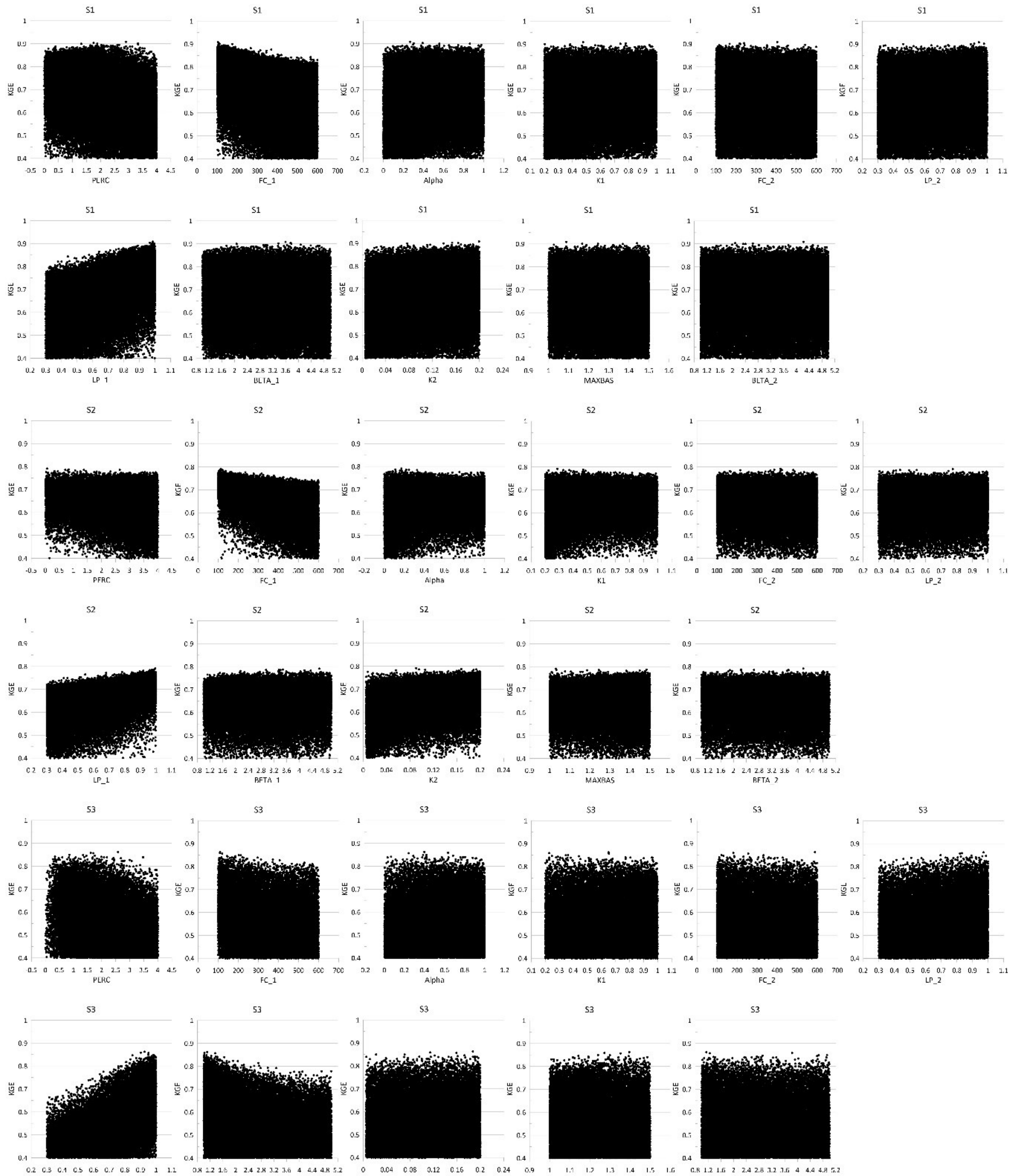

Figure 11. Zhurucay sub-catchments (S1 to S3) sensitivity analysis for all parameters (traditional calibration).

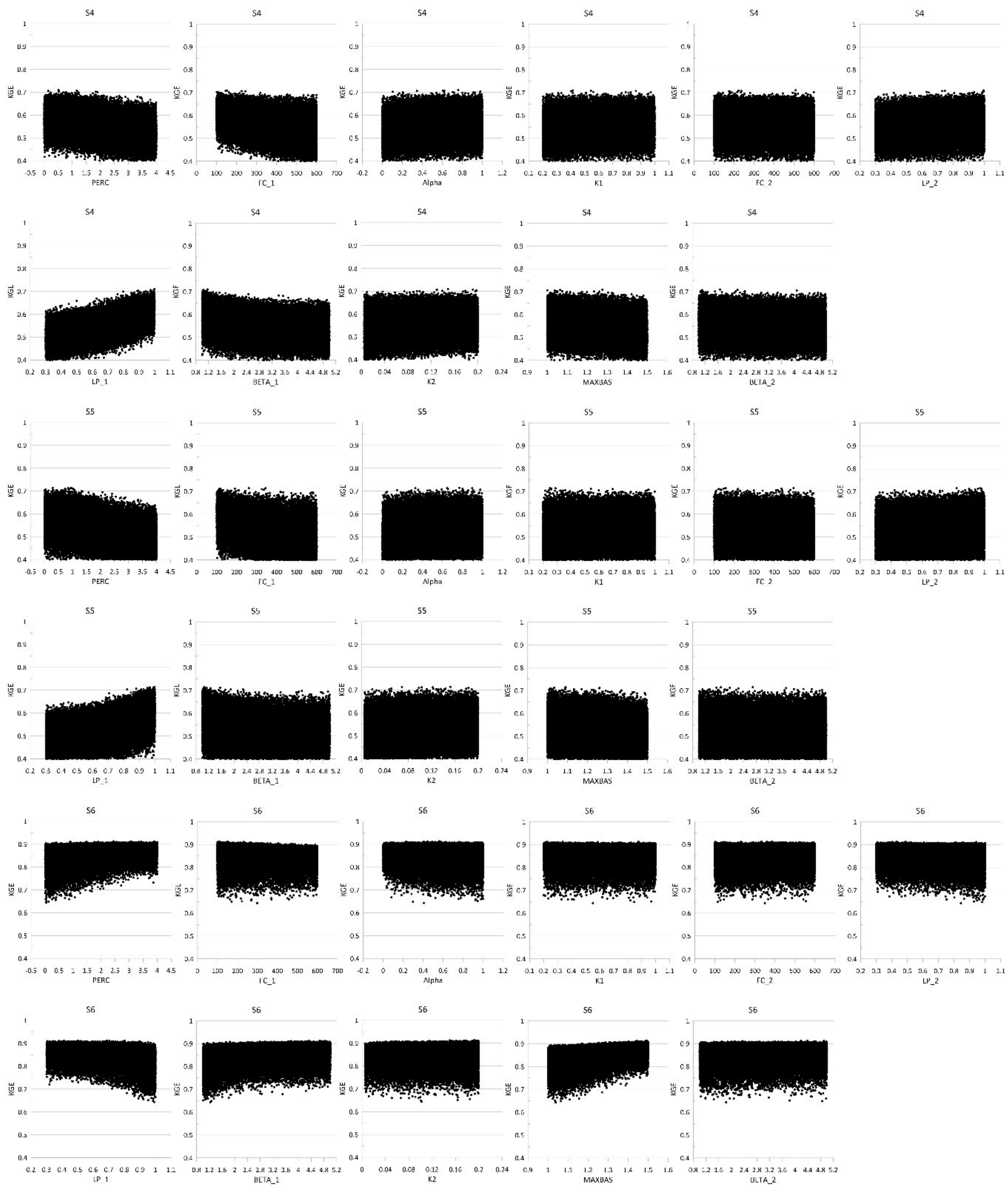

Figure 12. Zhurucay sub-catchments (S4 to S6) sensitivity analysis for all parameters (traditional calibration).

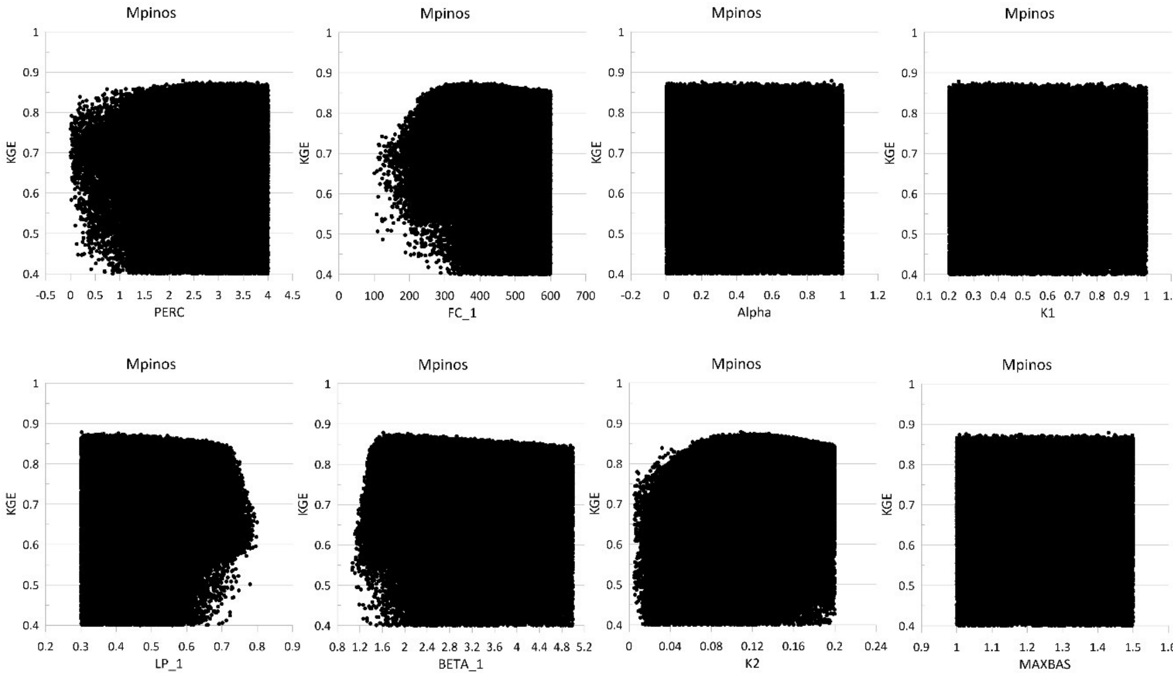

Figure 13. Mpinos catchment sensitivity analysis for all parameters (traditional calibration).

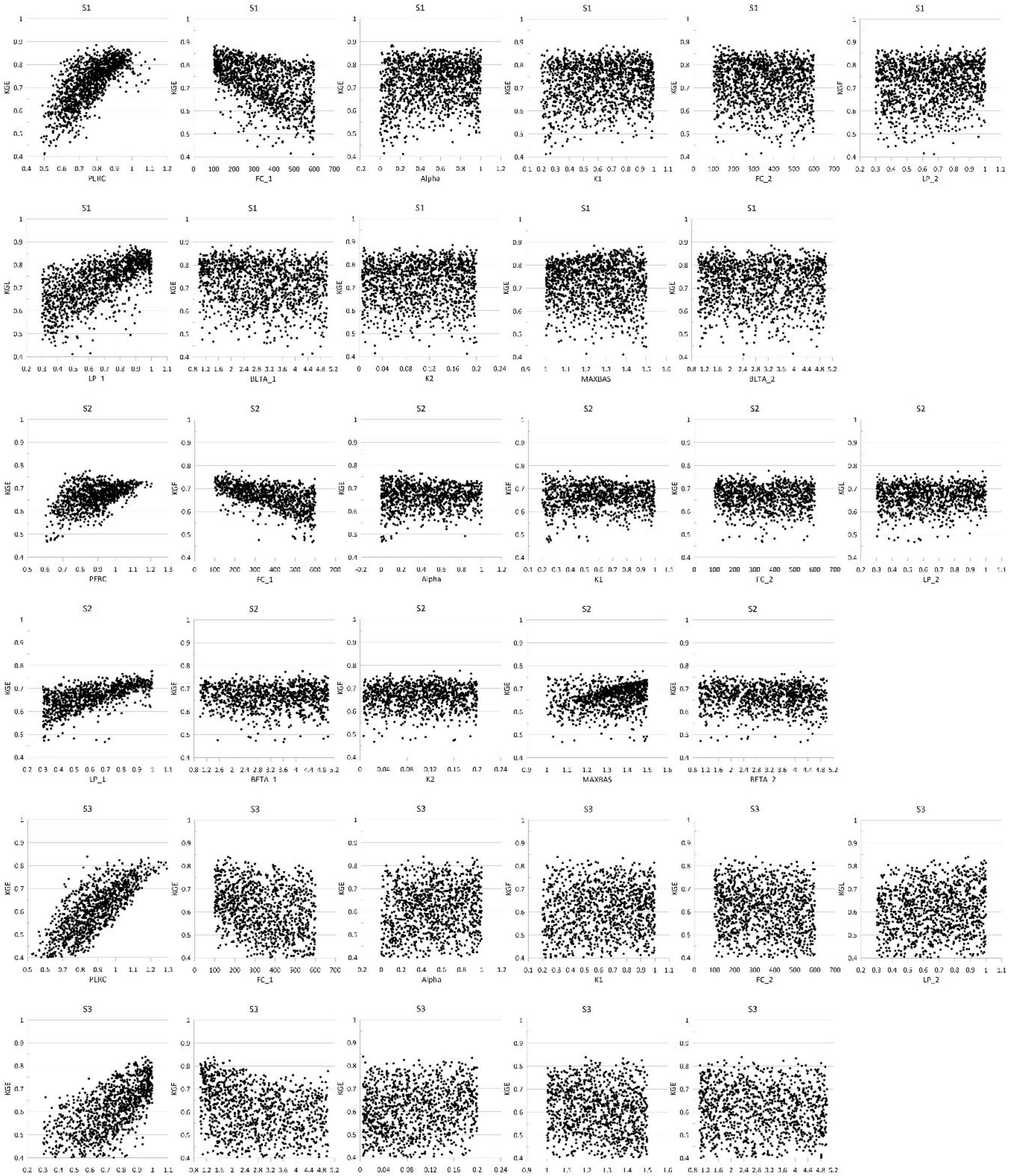

Figure 14. Zhurucay sub-catchments (S1 to S3) sensitivity analysis for all parameters (baseflow/total flow ratio included).

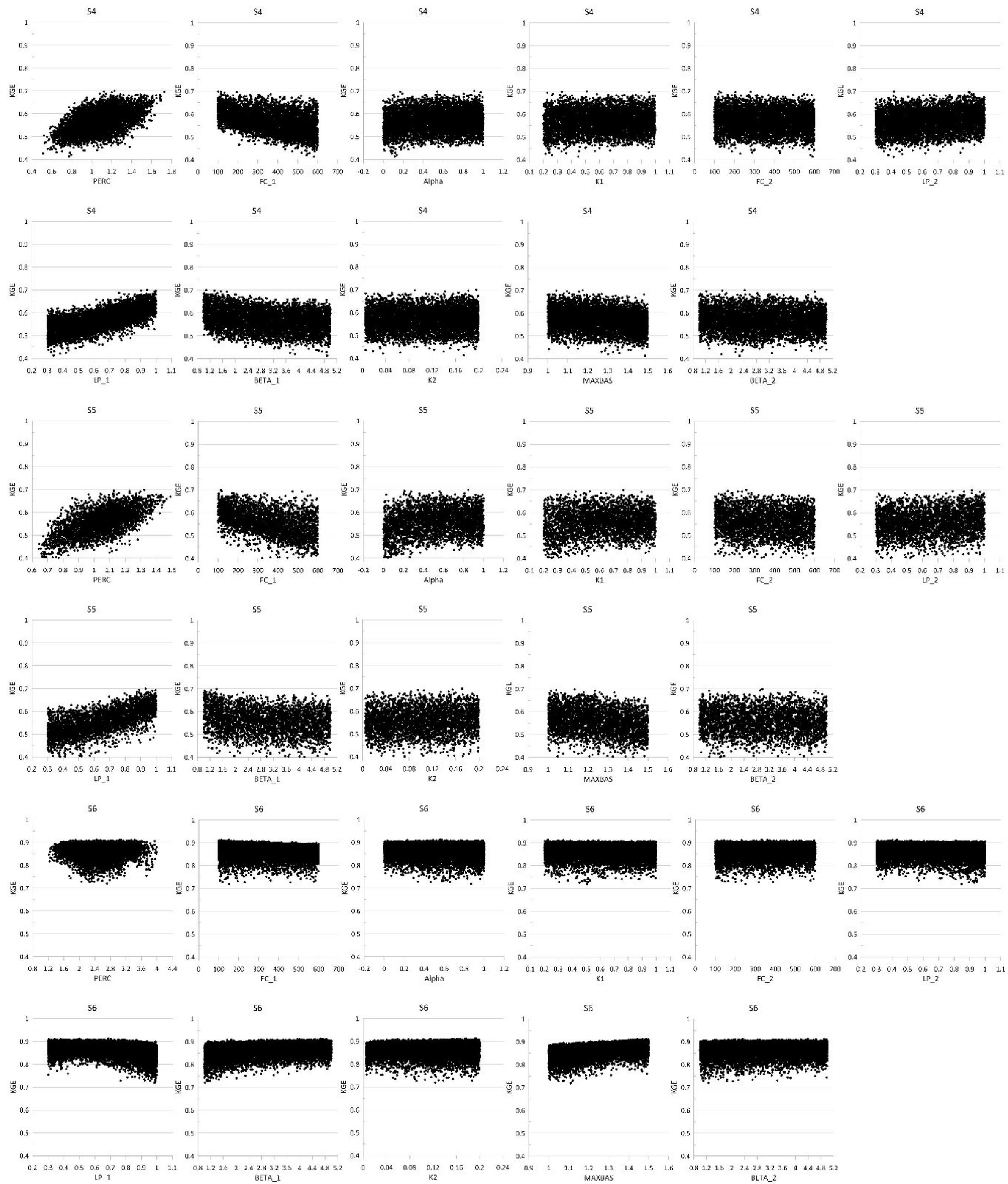

Figure 15. Zhurucay sub-catchments (S4 to S6) sensitivity analysis for all parameters (baseflow/total flow ratio included).

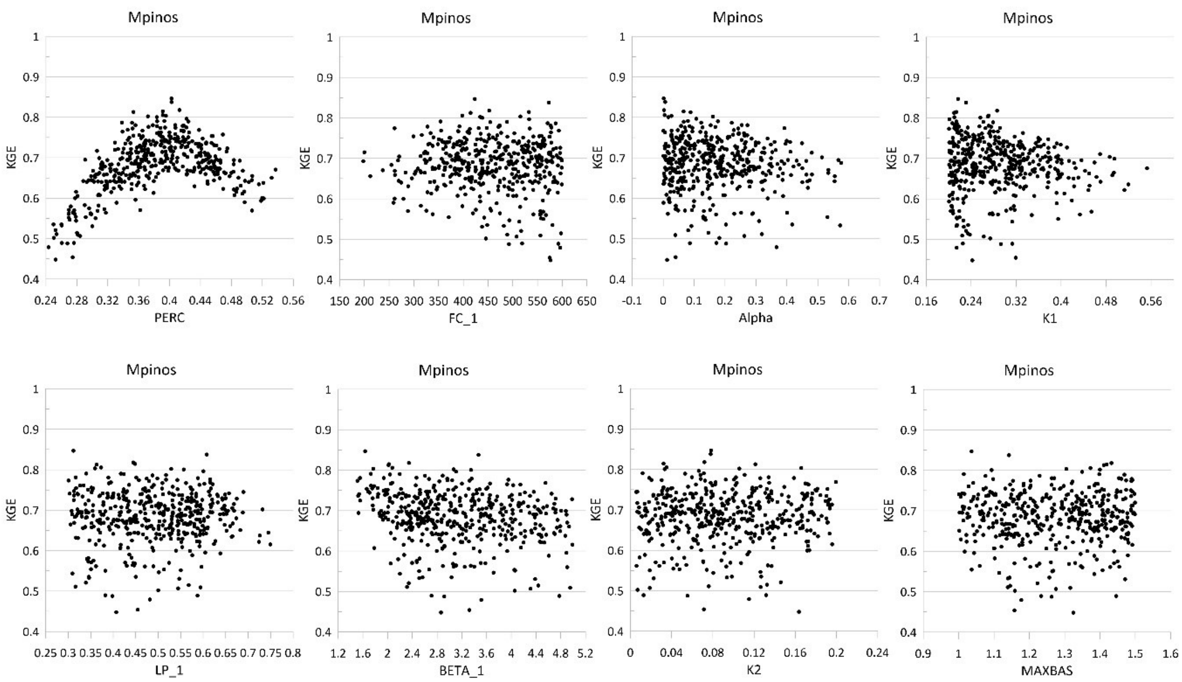

Figure 16. Mpinos sub-catchment sensitivity analysis for the four transferred parameters (baseflow/total flow ratio included).

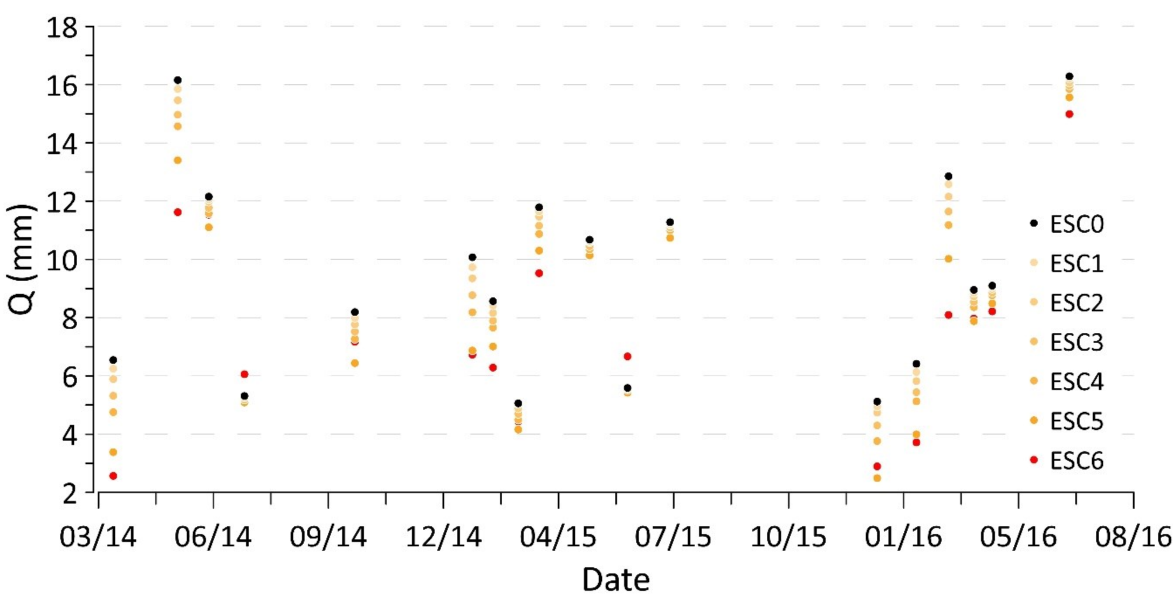

Figure 17. Peaks for the different scenarios of the U-D approach.

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