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Modelling the hydrologic response of a mesoscale Andean watershed to changes in land use patterns for environmental planning

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Abstract

A multidisciplinary approach is followed for analysis of the effect of changes in land use patterns on the hydrologic response of the Vergara watershed (4340 km^2) located in central Chile. Probable future land use scenarios were generated using heuristic rules and logistic regression models, in order to identify and represent the main pressure on the watershed, namely forestation of extensive areas used for agriculture with rapid growing exotic species. The hydrologic response of the watershed was computed with a physically based distributed precipitation-runoff model, which was calibrated and validated for the current observed scenario. Results show that mean annual discharge increase with agricultural land use and diminish with forest coverage. Thus, implementation of protection laws for native species conservation and regulated land use change are strongly recommended

1 Introduction

Water is essential for human life and welfare, and its demand is increasing. Many people worldwide are already living in conditions of scarcity, and with increasing concentration of populations in urban areas, future supply and availability is a globally sensitive issue (Jenerette and Larsen, 2006). Provision of clean water, as an essential ecosystem service, is a crucial factor in watershed/catchments management (Mark and Dickinson, 2008). Land use and climate changes introduce additional complexity in the management process. A challenging issue for countries with emerging and developing economies, like Chile, where ecosystem services are becoming increasingly vulnerable as demand increase and environment degrade is the generation of scientific information in order to support political decisions on development of environmental relevant projects. Such information can arise from extensively and time consuming centralized monitoring programs, but also complementarily from modelling tools. Typically, mesoscale watersheds in the southern hemisphere represent a challenging management problematic: Development of land use planning instruments considering the conservation of the native forest and the water availability for economic activities, recreation and human consumption.

Tendencies and extent of water yield affected by land use patterns depends on the particular study case. Land use changes modify interception and infiltration affecting surface runoff and groundwater flows (Sahin and Hall, 1996; Costa et al., 2003; Foley et al., 2005). Thus, combined with other biogeophysical properties of the land such as texture, relief, and soil types, land use controls the availability of water for its different uses e.g. irrigation and drinking water (Postel et al., 1996; Vitousek et al., 1997; Bronstert et al., 2002; Naef et al., 2003).

Land use changes might to be modelled using economic, social and ecologic factors (Klocking et al., 2003). Heuristic rules defined by experts (Klocking and Haberlandt, 2002) present a lack between land use change and driving forces (Veldkamp and Lambin, 2001; Verburg et al., 2002). Statistical models (e.g. logistic regression model) improve the understanding of spatial patterns of the land use change (Veldkamp and Lambin, 2001).

The processes dominating watershed hydrological response differ at various spatial scales. In micro-scale catchments (smaller than ca. 1 km^2) response to rainfall is dominated mainly by the runoff generating processes at the hill slopes and the near-stream areas (Anderson and Burt, 1990; Montgomery and Buffington, 1997). In macro-scale watersheds (larger than 10^4 km^2) spatio-temporal distribution of precipitation, drainage pattern and runoff control to a considerable extend the response behaviour (Uhlenbrook et al., 2004). Heterogeneous land use in large watershed introduces additional complexities for modelling the water balance (Wilk et al., 2001). Klöcking and Hamberlandtl (2002) stated that land use changes affect the hydrologic response of large watershed at the subbasin scale, and thus the interaction between the different subbasins plays a key role in the behaviour of the watershed. Even when the hydrologic response of small watersheds (<10 km^2) has been extensively documented in previous studies (Bosch and Hewlett, 1982; Sahin and Hall, 1996; Stednick, 1996; Brown et al., 2005), and the response to land use changes of large scale basins have been documented for the northern hemisphere (Thanapakpawin et al., 2007; Hejazi and Moglen, 2008; Breuer and Huisman, 2009; van Roosmalen et al., 2009) a lack of studies on the response of mesoscale basins located in the southern hemisphere is detected (Costa et al., 2003, Croke et al., 2004).

The relationships between the different components of the hydrological cycle and their sensitivity to changes in land uses can be quantified applying physicaly based hydrologic models (Lahmer et al., 2001; Fohrer et al., 2001; Klocking et al., 2002; Eckhardt et al., 2003; Ott and Uhlenbrook, 2004). In particular, SWAT (Neitsch et al., 2002) allows the computation of hydrologic flows for long term analysis following a semi-distributed approach (Arnold et al., 1998; Fohrer et al., 2001; Fohrer et al., 2005; Arnold and Fohrer, 2005).

In this contribution the hydrologic response of the Vergara watershed to different probable future scenarios of land use was analysed applying the physically based hydrologic model SWAT. The land use scenarios were generated using heuristic rules and the logistic regression model. First, the study area, available hydrometeorological records, and methods for land use analysis and hydrologic flows computation are presented. Next, the model sensitivity analysis, calibration and validation are presented. Finally, simulation results are analysed in order to suggest adequate guidelines for watershed management.

2 Study area

The Vergara watershed (4340 km^2) is located between the parallels 37°29′ and 38°14′ and 71°36′–73°20′. The river is 154 km long and emerges at an elevation of about 1900 m a.s.l. It flows into the Biobío river near the city of Nacimiento at an altitude of 200 m a.s.l. Its Strahler's stream order is 4. The climate in the watershed is temperate mediterranean, with a dry season of 5 months (November–March), and a wet season of approximately 3 months (May–July) during which more than 50% of the precipitation occurs. Ambient mean daily temperature ranges between 18 °C in January and 8 °C in June, with an annual mean of 12.5 °C. The average annual precipitation is 1650 mm. Recorded minimum and maximum mean daily discharges of the river close to the basin outlet, i.e. at Tijeral gaugin station, are 0.81 m^3/s (24 January 2002) and 999 m^3/s (27 May 1984) respectively. Maximum and minimum mean monthly discharges occur during the months of July and February-March, respectively. Fig. 1 shows the location of the basin with the drainage network and digital elevation model, DEM obtained from available images of the shuttle radar topography mission, SRTM DEM (final version).

3 Data sets used

3.1 Soil types

The GIS layer representing the different soils in the watershed was obtained from CIREN (1999a) and CIREN (1999b). The most common soils in the watershed are silt loam soils (33%) originated from volcanic ash deposits, silty clay loam soils (29%) developed from old volcanic ashes and sandy clay loam soils (13%) with granitic origin and richness in quartz. Figure 2 shows the soil type distribution in the watershed.

3.2 Land uses

Land uses were determined from CONAF (1999). Figure 3 shows the land uses of the watershed for the years 1979 and 1994.

In the year 1979 the main land use was agriculture covering a 47% of the watershed area, 31% was covered by native forest and 18% by scrubland. Remarkably, forest plantations covered a negligible area of the watershed, and were minimal compared to the other uses. Agriculture was the dominant land use in the lowest and middle part of the watershed, while at the upper part it was the native forest.

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In the year 1994 the major types of land uses were forestry plantations with 38%, native forest with 21% and agriculture with 32% of the watershed area. In the lowest, middle and highest regions of the basin, the main land uses were agriculture, forestry plantations, and native forest, respectively.

Main economic activities in the watershed are linked with the exploitation of natural resources and development of forest industry, mainly pulp and paper mills. Historically, native forest exploitation was followed by the farming activity which in turn has been gradually replaced by forestation with exotic species, mainly Pinus radiata and Eucaliptus globulus. Table 1 indicates the area covered by each land use and the percentage respect to the watershed area for the years 1979 and 1994.

Main land cover changes in the watershed observed between 1979 and 1994 are the increase in forestry plantations and the decrease of scrubland, native forest and agriculture. In the year 1994, the areas covered by forest plantations increased 10 times with respect to those observed in 1979, mainly occupying previous agriculture land (54% of the total new forest plantation), and areas with shrubs and native forest (56%). The shrub coverage diminished a 50%, of which one half was occupied by forest plantations and one half by agricultural production. The native forest diminished in 40 000 ha, i.e. the 30% of the area covered in 1979. Of this, 75% was replaced by forest plantations. Table 2 shows the land use transition matrix for the years 1979 and 1994.

3.3 Hydrological records

Figure 4 shows the location of the 22 existing hydrometeorologic stations located in or close to the Vergara watershed and the period of recorded series of precipitation, river discharges and ambient temperature.

Figure 5 shows the location of the five gauging stations and corresponding drainage area.

Figure 6 shows the existing hydrographs for the period 1977–2002 recorded at Tijeral, Rehue, Mininco, Renaico, and Malleco gauging stations.

Table 3 indicates maximum, minimum and mean monthly discharges for all gaugin stations.

Observed discharges diminish from Tijeral to Renaico, Malleco and Mininco. Rehue is a nested basin of Tijeral, presenting the smallest discharges.

4 Generation of probable land use scenarios

Probable land use scenarios were generated following two approaches based on heuristic rules and using the logistic regression model. The heuristic rules based assumptions on land use restrictions for limitation of a watershed portion that could be covered by a certain land use. Generated scenarios with this approach simulated the *existence of laws for conservation of native forest*, causing that (1) the actual native forest coverage do not change and the rest of the watershed become covered by introduced forest species, and the *inexistency of adequate land use planning instruments* that allowed a deliberated land use in the watershed causing that (2) the watershed becomes completely covered by introduced forest species, (3) the native forest coverage does not change, but the rest of the watershed becomes completely covered by agriculture land, and (4) the watershed becomes 100% agricultural. The regression model based observed information available in the satellite images of 1979 and 1994 for the prediction of patterns of forest expansion, deforestation advancing, and substitution of native forest generating a scenario where (5) observed patterns of land use changes between 1979 and 1994 continue with the same tendency.

5 Soil and water assessment tool, SWAT

The physically based hydrologic model SWAT computes runoff, infiltration, percolation and groundwater flows at a daily scale for long-term response analysis. In the model, the watershed is divided in subbasins, which for semi-distributed computation of flows are again internally subdivided into hydrologic response units with homogeneous topography, soil type, and land use. For computations, SWAT requires a digital elevation model, soil type and land use maps as well as precipitation and ambient temperature.

Interception, surface runoff and infiltration were computed with the curve number method. The surface runoff is computed following the kinematic wave approach, using Manning's relation for estimation of the runoff speed.

SWAT split groundwater into two aquifer systems: (1) a shallow, unconfined aquifer which contributes return flow to streams within the subbasin, and (2) a deep, confined aquifer which contributes return flow to streams outside the subbasin (Arnold et al., 1993). Water percolation under the root zone is partitioned in two fractions – each fraction becomes recharge contributing to one of both aforementioned aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plants. The model considers transfer from the shallow to the deep aquifer.

The Latin Hypercube Sampling/One-at-a-Time, LH-OAT analysis incorporated in SWAT2005 (Van Griensven et al., 2006) allows the identification and ranking of the model's most sensible parameters. OAT (Morris, 1991) design integrates a local to a global sensitivity method. LH-OAT sensitivity analysis assures that all the parameter range has been sampled and changes in the output of each model run is uniquely attributed to the input change. The automated calibration procedure Parameter Solution Method (PARASOL; Van Griensven et al., 2003) was used for calibration of the most sensible parameters. This procedure used the Shuffle Complex Evolution Algorithm as optimization method, which is a global search algorithm for the minimization of a single function for up to 16 parameters (Duan et al., 1992). It combines the direct search method of the Simplex procedure with the concept of a controlled random search, a systematic evolution of points in the direction of global improvement, competitive evolution and the concept of complex shuffling (Van Griensven et al., 2006). To obtain the optimum solution the sum of the squares of the residuals (SSQ) was used. Upper and lower parameter value bounds used for automated calibration were established based on recommendations made by (Van Liew et al., 2005) and based on own experience from previous work on the Biobío basin (Stehr et al., 2008; Stehr et al., 2009).

6 Results and discussion

For flow computation 51 subbasins with 272 hydrologic response units were defined. For calibration, the time series of years 2000–2002 were used. A novel validation process of the calibrated model was conducted. Performance of the model was evaluated for two periods with different dominant land uses, namely period 1977–1982 with the land use map of 1979, and period 1994–1999 with the land use map of 1994, in order to check if the model is able to adequately reproduce the catchment hydrology under different land use scenarios, i.e. if model performance significantly varies with land use change. Computed and measured discharges were compared at Tijeral, Rehue, Renaico, Mininco and Malleco and model performance was evaluated through RMS error, absolute error, Nash-Sutcliffe's efficiency, determination coefficient, and percent bias.

6.1 Sensitivity analysis

Table 4 shows the ranking of the eight most sensible parameters obtained with LH-OAT analysis for basins P1, Tijeral, P2 Rehue, P3 Renaico, P4 Mininco for years 2000–2002. The subbasin Malleco was not analysed, because there are insufficient discharge records between the years 2000–2002. As Malleco is a subbasin of Tijeral, identical parameter values were considered for both.

6.2 Calibration of the model

The most sensible parameters of the model were calibrated for the years 2000–2002 in order to reproduce the observed discharges at the available gauge stations: Tijeral, Rehue, Renaico, Mininco and Malleco using the parameter solution method PARASOL.

Figure 7 shows the observed and computed discharges for the years 2000–2002 after calibration.

The model satisfactorily reproduced the order of magnitude of the observed discharges, and their changes tendency in time. Nevertheless, the model subestimates peak discharges during high water events. Table 5 shows the RMS error (RRMSE), absolute error (ABSERR), Nash-Sutcliffe's efficiency (EF), determination coefficient (R2), and percent of Bias (PBIAS) for the years 2000–2002.

Overall, calculated and measured discharges are well correlated. The model was able to reproduce the flow regime in the watershed.

6.3 Validation of the model

Figure 8 shows the observed and computed discharges for years 1977–1979 at Tijeral, Mininco and Malleco, using the land use map of 1979. Note that gauge stations Renaico and Rehue did not operate in this period.

With the calibrated parameters, the model was able to correctly reproduce the order of magnitude of the observed discharges in the years 1977–1979, as well as their change tendency in time. Again, peak flows were not precisely reproduced by SWAT. Table 6 shows the RMS error, absolute error, Nash-Sutcliffe's efficiency, determination coefficient, and percentage of bias calculated for the years 1977–1979.

Overall, simulated and observed discharges are well correlated. The model reproduced with sufficient efficiency the flow regime in the subbasins for the calibration period. Figure 9 shows the observed and computed discharges for years 1994–1999 using the land use map of 1994.

The model was able to correctly reproduce the order of magnitude of the observed discharges, as well as their change tendency in time. Peak flows were not precisely reproduced by the model. Table 7 shows the RMS error, absolute error, Nash-Sutcliffe's efficiency, determination coefficient, and percentage of bias calculated for the years 1994–1998 at the different gauge stations.

The double validation process demonstrates that the model was able to compute the hydrologic response of the Vergara watershed under different land use scenarios with at least acceptable performance, i.e. EF>0.75. Thus, it is assumed that the model can be applied for analysis of the hydrologic response of the Vergara watershed to land use changes.

6.4 Modelling the hydrologic response to land use changes

The hydrologic response of the watershed to land use changes was simulated, maintaining the observed precipitation and ambient temperature for the years 1994–1999 as input. Consequently, each simulation differed from the baseline only in the land use conditions.

Figure 10 shows the 1994 land use map, i.e. baseline, and the five generated scenarios according to the described methodology. Note that land uses generated with the logistic regression model (Fig. 10 map e) show a strong growth of forest plantations over most part of the watershed, occupying agricultural areas and substituting native forest at the east hills of the Coastal mountain chain and the foothills of the Andes mountain chain.

Figure 11 shows the changes of mean annual discharges at Tijeral, Rehue, Renaico, Mininco and Malleco under land use scenarios respect to the baseline.

Mean annual discharge under land use scenarios 1 and 5 diminished in all the subbasins, with maximum reductions of ca. 10%. Both scenarios represent land uses with predominant forest plantation. Land use scenario 3, representing a land use with predominant agricultural cover, caused an increase in annual mean discharge in all the subbasins up to ca. 7% in Tijeral and Rehue. In general, forestry plantations tend to reduce mean annual discharge, whereas agriculture increases it. These results are in agreement with those obtained by (Hejazi and Moglen, 2008) for a watershed located in Thailand. Thus, implementation of protection laws for native species conservation and regulated land use change are strongly recommended in order to preserve the water resources of the watershed.

Table 8 shows a comparison of results obtained for the dry (mean values for November to April) and wet (mean values from May to October) season. Major relative changes in mean annual discharge are expected to occur at Rehue, followed by Malleco and Tijeral. Note that Rehue and Malleco are nested sub-basins of Tijeral.

Scenario 2 at Rehue shows a high increment in the flows, which is opposite to the changes shown in all basin for this case, were a reduction of the flows occurs. Scenario 4 caused the major discharge changes in all the analyzed basins.

7 Conclusions

The hydrologic response of a mesoscale watershed to different land use scenarios was analysed, applying heuristic rules and logistic regression models and the semi-distributed model SWAT. The Vergara's watershed response was analysed in terms of the annual mean discharge at the five subbasins gauged in the area which covered ca. 80% of the total watershed.

The current model version successfully passed a double validation process considering monthly outputs, in with two different land use conditions. Calibration and validation of SWAT showed that it is able to reproduce the observed flows at Tijeral, Rehue, Mininco, Renaico and Malleco under different land use conditions satisfactorily.

Simulations of probable scenarios showed that substitution of native forest with plantations of introduced species as well as forestation of regions with predominantly agricultural land uses cause a reduction of the annual mean discharge in ca. 10%. Thus, areas covered with native forest might be regulated in order to protect the water resources of the watershed.

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Table 1. Changes in land cover between 1979 and 1994.

Land cover	Covered area in 1979 (ha)	Portion of the basin (%)	Covered area in 1994 (ha)	Portion of the basin (%)	Land use change (ha)	Change in land cover (%)
Native Forest	133 096	31	92 533	21	−40 563	−30
Scrubland	77 532	18	29 897	7	−47 635	−61
Steppe	3157	1	3157	1	0	0
Forestry Plantation	15 129	3	164 587	38	149 458	988
Agriculture	203 055	47	140 945	32	−62 110	−3
Urban areas	1071	0	1992	0	921	86
Bare soil	108	0	209	0	101	94
Water bodies	814	0	643	0	−171	−21
Total	433 963	100	433 963	100		

Table 2. Land use transition matrix for the years 1979 and 1994.

		Native Forest	Scrubland	Steppe	Forestry Plantation	Agriculture	Water bodies	Bare soil	Urban areas	Total
1994	Native Forest	92 533	0	0	0	0	0	0	0	92 533
	Scrubland	6836	14 228	0	306	8459	15	53	0	29 897
	Steppe	0	0	3157	0	0	0	0	0	3157
	Forestry Plantation	30 428	38 550	0	14 817	80 706	80	6	0	164 587
	Agriculture	3202	24 453	0	6	113 189	72	22	0	140 945
	Water bodies	0	0	0	0	0	643	0	0	643
	Bare soil	31	80	0	0	71	3	24	0	209
	Urban areas	67	222	0	0	631	0	1	1071	1992
	Total	133 096	77 532	3157	15 129	203 055	814	108	1071	433 963

Table 3. Mean monthly discharges (m^3/s) at the different control points in the Vergara basin (1977–2002).

	Tijeral	Rehue	Mininco	Renaico	Malleco
Maximum mean monthly discharge	162.37 (July)	17.17 (July)	40.02 (July)	88.75 (July)	59.17 (July)
Minimum mean monthly discharge	7.39 (February)	0.22 (February)	2.16 (February)	6.89 (March)	3.81 (March)
Mean monthly discharge	57.52	6.07	15.81	42.63	26.58

Table 4. Ranking of the 8 most sensitive parameters per sub-basin P1 Tijeral, P2 Rehue, P3 Renaico, P4 Mininco and P5 Malleco, and their variation range for autocalibration.

Parameter	Description	P I	P2	P3	P4	P5	Range
GWQMN	Threshold water depth in the shallow aquifer for flow	2	3	4	2	2	0–5000 mm
GW_REVAP	Groundwater revap coefficient		4		8		0.02–0.20
ESCO	Soil evaporation compensation factor	7	6	6	7	7	0–1
SLOPE	Average slope steepness	8			5	8	–5%–5 %
CN2	Initial SCS CN II value	1	2	1	1	1	–15%–15%
SOL_AWC	Available water capacity	3	5	2	4	3	–10%–10 %
GW_DELAY	Groundwater delay		8				0–50 days
rchrg_dp	Deep aquifer percolation fraction	4	1	3	3	4	0.5–1
canmx	Maximum canopy storage	6		5		6	0–10 mm
sol_k	Saturated hydraulic conductivity	5		8	6	5	–10%–10 %
sol_z	Soil depth		7	7			–25%–25%

Table 5. RMS error, absolute error, efficiency, determination coefficient and percentage of Bias calculated for the period 2000–2002 after calibration.

	Tijeral	Rehue	Mininco	Renaico	Malleco
RRMSE	0.30	0.51	0.50	0.82	0.37
ABSERR	11.64	1.99	6.31	24.16	7.52
EF	0.93	0.82	0.72	0.54	0.85
R2	0.96	0.88	0.76	0.71	0.93
PBIAS	11.78	21.35	8.32	32.04	14.94

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Table 6. RMS error, absolute error, efficiency and determination coefficient calculated for the period 1977–1979.

	Tijeral	Mininco	Malleco
RRMSE	0.39	0.61	0.44
ABSERR	11.76	5.27	7.96
EF	0.88	0.74	0.77
R2	0.91	0.79	0.80
PBIAS	10.95	19.47	17.15

Table 7. RMS error, absolute error, efficiency, determination coefficient and percentage of Bias calculated for the period 1994–1999.

	Tijeral	Rehue*	Mininco	Renaico	Malleco
RRMSE	0.31	0.63	0.33	0.42	0.38
ABSERR	8.24	2.15	2.98	9.12	5.07
EF	0.93	0.75	0.92	0.82	0.86
R2	0.93	0.89	0.94	0.83	0.88
PBIAS	2.77	32.75	9.13	7.88	10.38

*Measured discharge data since July 1997.

Table 8. Percentage of change respect to the baseline scenario for mean annual, wet season (May–October) and dry season (November–April) flows. (Annual (A), Wet season (W) and Dry season (D)).

	Tijeral			Rehue			Mininco			Renaico			Malleco		
	A	W	D	A	W	D	A	W	D	A	W	D	A	W	D
Scenario 1	−1.86	−2.81	2.93	−10.61	−10.67	−9.94	−8.57	−9.02	−4.42	−2.32	−2.81	0.06	−1.69	−2.48	1.19
Scenario 2	−6.14	−6.63	−3.33	24.04	20.66	59.98	−8.04	−8.46	−4.13	−3.99	−4.95	0.36	−18.21	−18.36	−16.68
Scenario 3	7.30	7.28	6.32	7.23	7.70	1.55	2.38	2.63	−1.06	1.13	1.27	0.81	1.86	1.37	3.86
Scenario 4	7.40	8.42	0.75	38.41	34.96	76.02	4.03	4.38	−0.35	5.85	6.67	2.51	−8.65	−7.27	−13.54

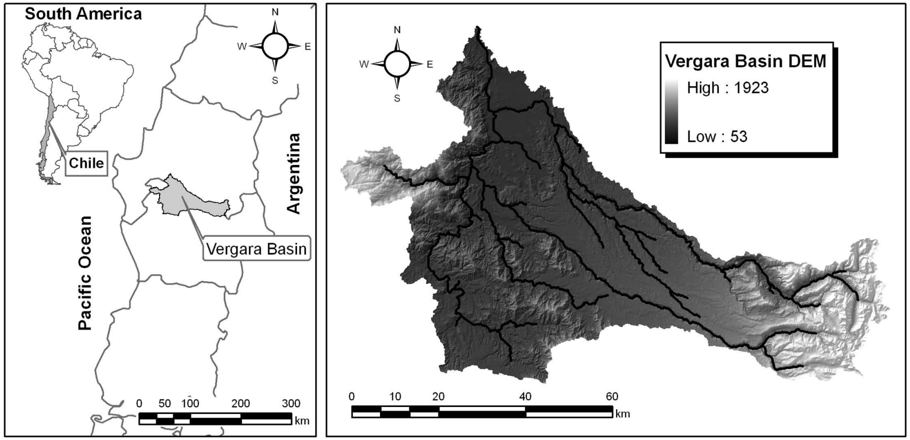

Fig. 1. Location of the Vergara watershed and DEM.

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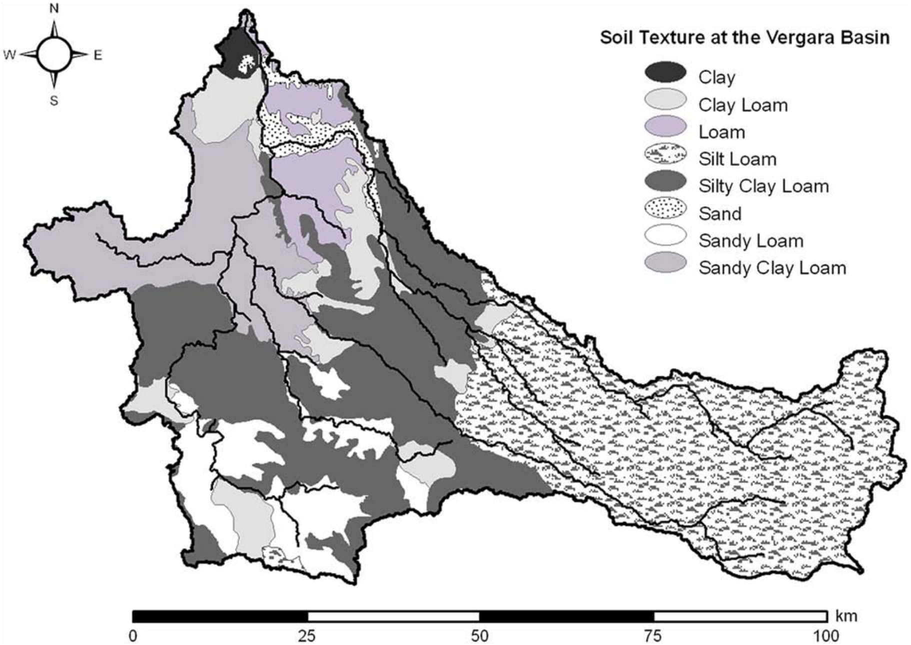

Fig. 2. Soil types in the Vergara watershed.

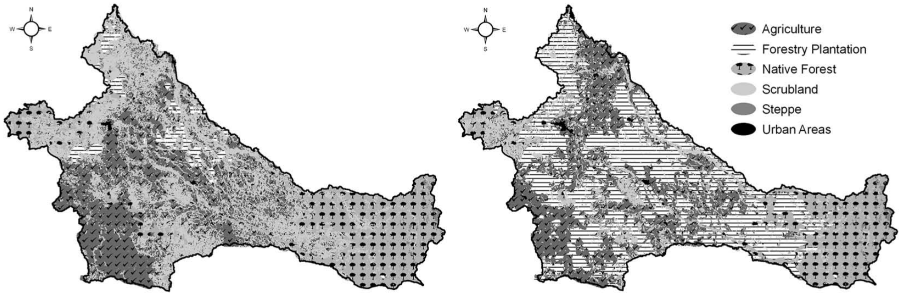

Fig. 3. Land cover in 1979 (left) and 1994 (right).

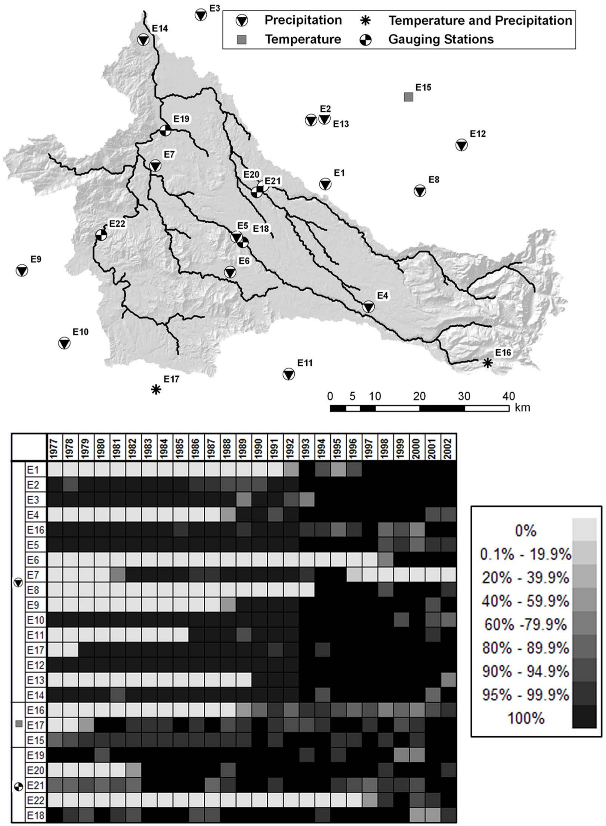

Fig. 4. Location of hydrometeorologic stations and available record periods.

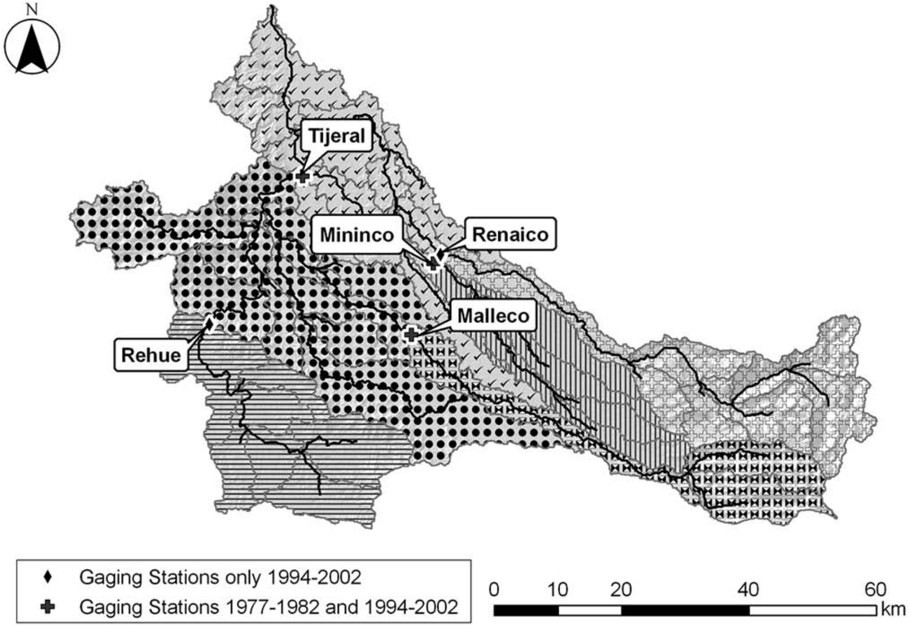

Fig. 5. Gauging stations in the watershed.

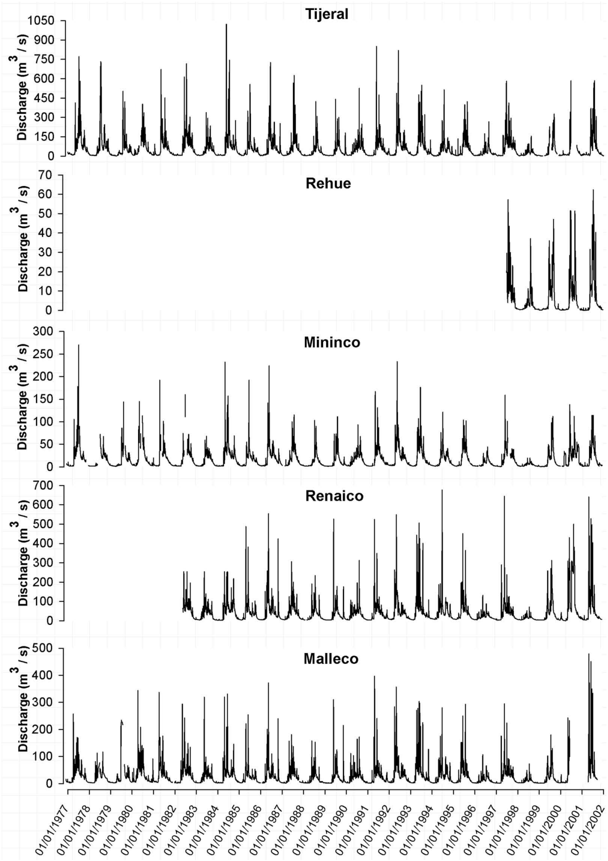

Fig. 6. Hydrographs based on daily mean discharges for the period 1977–2002 recorded at Tijeral, Rehue, Mininco, Renaico, and Malleco gaugin stations.

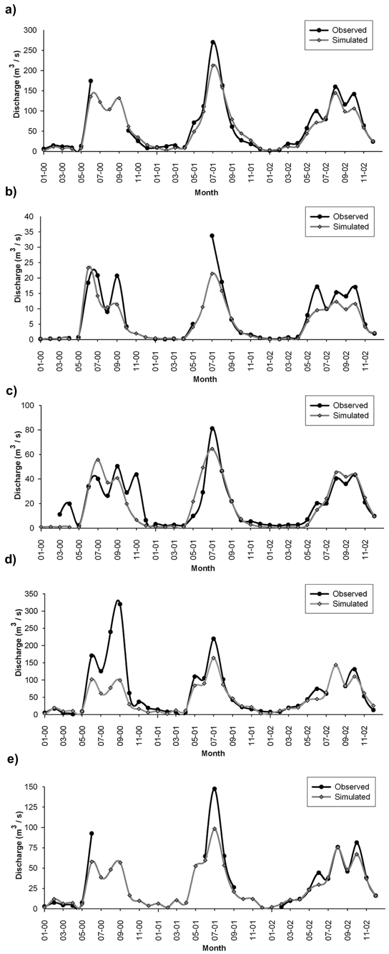

Fig. 7. Observed and simulated mean daily discharges during years 2000–2002 at Tijeral **(a)**, Rehue **(b)**, Mininco **(c)**, Renaico **(d)** and Malleco **(e)**.

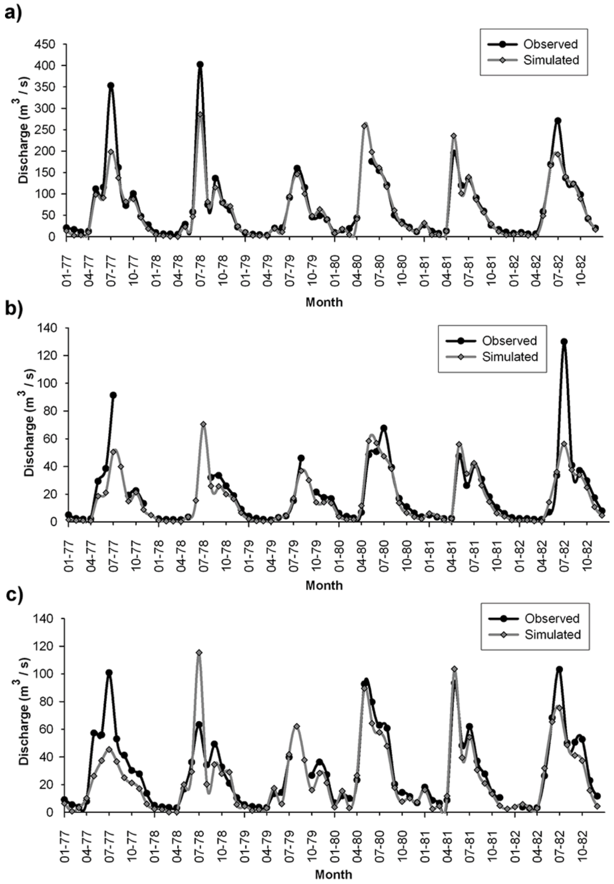

Fig. 8. Observed and simulated mean daily discharges for the years 1977–1979 at the gauge stations Tijeral **(a)**, Mininco **(b)** and Malleco **(c)**.

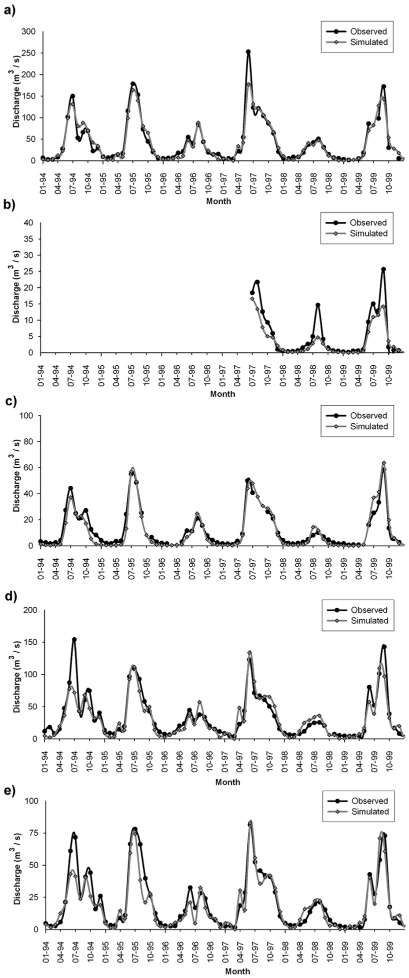

Fig. 9. Observed and simulated daily discharges for the years 1992–1998 at gauge stations Tijeral **(a)**, Rehue **(b)**, Mininco **(c)**, Renaico **(d)** and Malleco **(e)**.

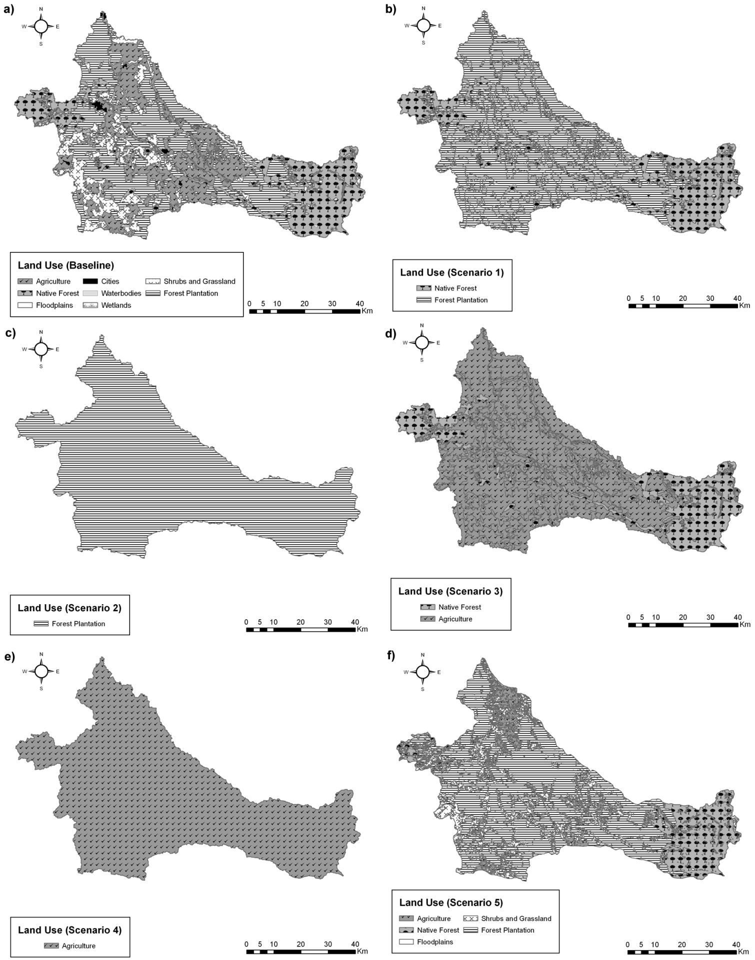

Fig. 10. Land use maps according to observed scenario in year 1994 **(a)** baseline, **(b)** scenario 1, **(c)** scenario 2, **(d)** scenario 3, **(e)** scenario 4 and **(f)** scenario.

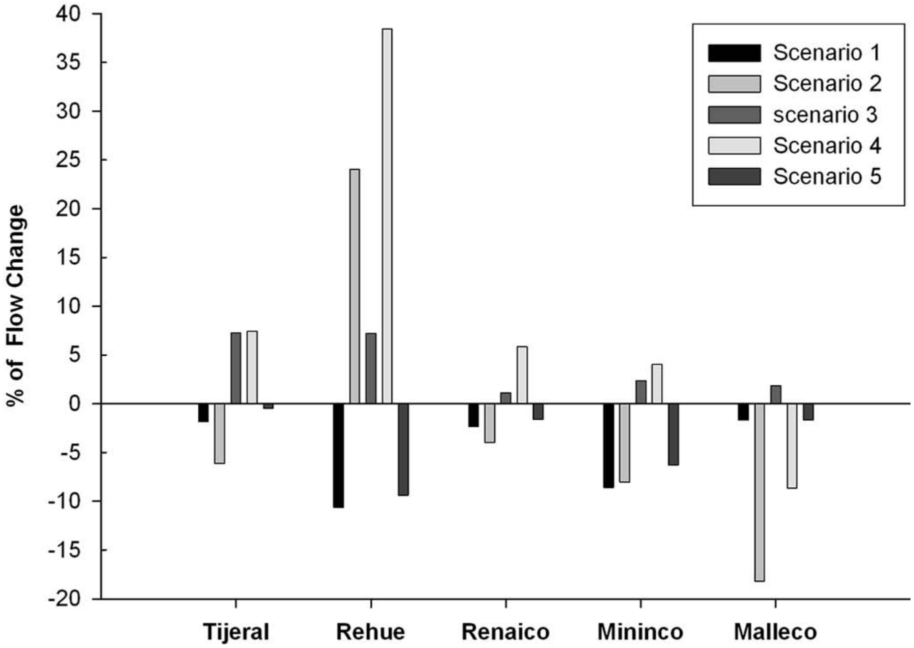

Fig. 11. Changes of mean annual discharges at Tijeral, Rehue, Renaico, Mininco and Malleco under land use scenarios respect to the baseline.