Final Report

Post-Doc Fellowships to Non-EU Researchers (BELSPO)

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My research project entitled "Impact of forest cover change on water supplies in the headwater of the Ecuadorian Andes" was performed within the framework of the FOMO project on "Remote sensing of forest transition and its ecosystem impacts in mountain environments", which is funded by the Belgian Science Policy (BELSPO). This report covers the duration of my stay from December 24th, 2010 to September 30th, 2011 at the Department of Earth and Environmental Sciences, Division of Geography, KULeuven (host institution).

The following research activities were performed based on the objectives and methodologies proposed in the application, and finally the results are discussed.

1. Research objectives

This study aimed to quantify the hydrological response of steep headwater catchments to changes in forest cover and land use, and to evaluate the change in water provision after the conversion of natural vegetation.

We quantified forest cover and land use change from 1963 to 2010 to examine the effect of land use change on streamflow in the Pangor catchment in the central part of the Ecuadorian Andes.

We hypothesized three possible scenaries:

1. Deforestation has caused a decrease in streamflow

2. Increased streamflow as a result of natural regeneration or restored soil

3. Afforestation has led to a reduction in streamflow

2. Methodology

2.1. Selection of the headwater catchment with distinct disturbances

We selected the Pangor catchment (about 282 km^2) located in the province of Chimborazo in the central part of Ecuador based on the following criteria:

1. Contrasting land use/cover change through time
2. Existing information on hydro-meteorological data covering a span time of several decades
3. Accessability to the catchment, so that the field work for validation of the maps, soil sampling and the identification of the vegetation can be easily done.

Over the past 50 years this catchment has undergone a massive deforestation of the montane cloud forest and large areas of páramo grassland have been converted to agricultural land and exotic forest plantations (pines). Furthermore, hydrological and meteorological equipment has been installed since 1970, so that information of daily streamflow and rainfall are available.

2.2. Data on forest cover and land use

The principal data sources to identify the land use patterns and changes in land use through time were black and white aerial photographs and satellite images. The generation of land use/land cover maps were carried in collaboration with the University of Louvain (UCL). We divided the tasks to obtain the land use/land cover maps according to the experience of the research groups. The Department of Geography of the UCL was in charge of the generation of land use/land cover maps using satellite images given its expertise in remote sensing. While my task was only focused on the generation of land use/land cover maps based on aerial photographs. Five time series were identified according to the information available. Maps of 1963 and 1977 were derived from aerial photographs, whereas maps for the years 1991, 2001 and 2009 were obtained from satellite images.

In order to generate land use/land cover maps, the following procedure was carried out:

- Photo-interpretation

Two sets of aerial photographs were used to produce land use maps of 1963 and 1977. Both sets of aerial photographs were taken by the Instituto Geográfico Militar (Instituto Geográfico Militar 1963, 1977). These photographs have a spatial scale of approximately 1: 60.000. The image quality of the photographs is poor to moderate, the photographs have a poor image contrast within the photograph and a low spatial resolution. The interpretation of the aerial photographs was carried out with a mirror stereoscope (Wild ST4 stereoscope – 4 times magnification). Through the observation of the ground features in three dimensions, the visual interpretation of the aerial photographs is facilitated. In total, 24 aerial photographs were used both in 1963 and in 1977. Four major land use classes were identified, which were delineated with markers on transparent overlays.

- Georeferencing and orthorectification

Aerial photographs do not provide orthogonal representation of ground features as they have several geometric errors (such as tilt and relief displacement, Lillesand and Kiefer 2000). Most notably in the representation of the ground features are the effects of relief displacement, which makes that the objects are not represented in their correct relative position and scale (Campbell, 1996). As a result of these geometric errors, the raw and uncorrected images cannot be used as the basis for accurate measurements. In order to analyse ground features on the aerial photographs, the relief and tilt distortion must be removed by using specialised software. When the aerial photographs are geometrically corrected for radial and tilt displacement and when each point on the photograph is characterised by a unique geometrical co-ordinate, the photographs are called orthophotos. In this study, the ILWIS software (ILWIS 3.3, Integrated Land and Water Information System, 2005) was used to georeference and to orthorectify the aerial photographs. This software needs the following requirements to carry out the orthorectification of a photogrammetric aerial photograph:

1. high-resolution scan of the aerial photograph. In this study, the entire aerial photograph (23 * 23 cm) could be scanned and all fiducial marks were clearly visible on the scan (resolution of 1000 dpi).
2. Knowledge of the focal length of the photogrammetric camera. In this study, the focal length of the images of 1963 is 151.418 mm and of the images of 1995 is 152.68 mm.
3. The digital terrain model (DTM) of the study area was created at a spatial resolution of 30m.
4. Ground control points (GCPs): The most important procedures to collect ground control points are: GPS measurements (Geographic Position System), digital topographic information and analogue maps. Here, two analogue topographic maps of Pallatanga and Villaunión on the spatial scale of 1:50.000 made by the IGM (Instituto

Geográfico Militar, 1968) were scanned and were used as source material to extract ground control information.

- Satellite image classification

In this report is only referred to the methodology used to classify the satellite images as this task was performed by the research group of the UCL. Land use/land cover maps based on satellite images were generated for the time periods of 1991, 2001 and 2009. Satellite images were corrected in three different ways for topographic effects, illumination and shadowing applying the techniques developed within the framework of the FOMO project. Land use/land cover maps for 1991 and 2001 were derived from a LANDSAT TM image and a LANDSAT ETM image respectively, both images with 30m resolution. While the land use/land cover map for 2009 was obtained from a Worldview 2 image with 1m resolution. This image was bought by BELSPO and put it at the disposal of the FOMO project.

- Field campaign to validate the land use/cover maps

In summer 2011, the field campaign was carried out in Ecuador during three weeks from July 17th to August 7th. The working team was composed by four persons, both the KULeuven and the UCL.

The following activities were done during the field work in Ecuador:

1. Taking of ground control points (GCPs)

In order to validate the land use/land cover maps obtained from the classification of the satellite images, we took ground control points using a Trimble GPS (GeoExplorer 3000 Series GeoXM Handheld), which has an accuracy of 1 to 3 meter. The GPS measurements were taken for each type of land use/land cover and they were spatially distributed within the catchment. In general, 20 ground control points were taken for each site selected (approximately 150), so that the control points data were sufficient to assess the land use/land cover maps. In addition to this, control ground points were also taken to enhance the accuracy of the georeference of the satellite images.

2. Soil sampling

Soil samples were taken to determine the physical properties of soil under different land use/land cover types, it will allow us to assess the level of disturbance of soil and at what extent the vegetation cover may affect the soil conditions. Hand auger equipment (Eijkelkamp) was used to take soil samples at the upper layer (< 30cm). For each type of land use/land cover, 10 soil samples were taken, which were taken to the soil laboratory of the faculty of Agriculture at the University of Cuenca. The following physical properties of soil were determined: soil texture, bulk density, permeability and porosity.

3. Identification of the main species of plants

Giving the richness of the tropical montane cloud forest (TMCF) in this part of the Andes of Ecuador, we identify de main species of plants to characterize the TMCF. The identification of the main species of plants highlights the importance of these ecosystems to preserve natural forest with a high biodiversity in the composition of plants. A local botanist was hired to carry out a plant survey in the field. This task took three days, which were scheduled at same dates of our field work. Below is indicated the most important species identified with their scientific names:

Elaeis guineensis, Myrtus communis, Bromelia balansae, Juglans Regia, Aloysia polystachya, Cedrella odorata, Grama ss.pp, Euphorbia lactiflua, Arundo donax, Bactris gasipaes, Passiflora mollisima L, Gonolobus condurango, Rubus glaucus, Bacharis ss.pp, Phalaris canariensis, Osmunda cinnamonea, Polylepis incana.

2.3. Collection of rainfall and streamflow data

Daily rainfall and streamflow data were obtained from the National Institute of Meteorology and Hydrology of Ecuador (INAMHI) from 01/01/1970 to 31/12/2008. Five meteorological stations and two hydrological stations were selected for this study based on the criteria of the quality of data and location. Table 1 summarizes the quality of data in terms of missing data, while Table 2 shows the locations, coordinates and altitude.

Table 1

Codigo	Nombre	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
M130	chillanes	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
M391	pallatanga	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	0
M402	CHIMBO DJ PANGOR	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	0	12
M404	Cañi-Limbe	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
M409	pangor-j.de velasco	12	12	12	0	12	12	12	12	12	0	12	12	12	12	12	12	12	12	12	12
H338	CHIMBO DJ PANGOR	12	12	12	12	12	12	12	12	12	12	11	12	12	12	12	12	9	12	12	12
H337	PANGOR AJ CHIMBO	0	0	0	0	12	12	12	12	12	12	12	11	12	12	12	12	9	12	12	12

Codigo	Nombre	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
M130	chillanes	12	12	12	12	12	12	12	12	12	12	11	12	12	2	11	11	12	12	12
M391	pallatanga	12	12	12	12	12	12	12	12	12	12	12	11	12	3	9	7	12	12	12
M402	CHIMBO DJ PANGOR	12	12	12	12	12	12	12	12	12	12	12	12	11	2	8	6	11	12	12
M404	Cañi-Limbe	12	12	12	12	12	12	12	12	12	12	11	11	11	1	12	9	11	12	12
M409	pangor-j.de velasco	12	12	12	12	12	12	12	12	12	12	12	12	12	0	12	12	9	12	12
H338	CHIMBO DJ PANGOR	12	12	12	12	12	12	12	12	12	12	**6**	**1**	**6**	12	11	12	12	12	4
H337	PANGOR AJ CHIMBO	12	9	9	11	12	12	11	0	11	12	12	12	12	12	12	12	12	12	4

M = Meteorological station. H = Hydrological station. 12 =some months filled in.

Table 2

Name	Coordinates		Code	Altitude (m)
	Latitude	Longitude		
Pangor J.de Velasco	1°49’42” S	78°52’54” W	M 409	3109
Cañi-Limbe	1°46’18” S	78°59’25” W	M 404	2800
Chimbo DJ Pangor	1°56’24” S	79°0’16” W	M 402	1542
Pallatanga	1°59’57” S	78°57’54” W	M 391	1500
Chillanes	1°58’32” S	79°3’48” W	M 130	2330
Chimbo DJ Pangor	1°55’56” S	79°0’26” W	H 338	1452
Pangor AJ Chimbo	1°55’53” S	79°0’13” W	H 337	1480

Overall, data are of good quality, however missing data were found in some years covering time periods from days to months. For streamflow during periods of recession (flow is not dependent on rainfall, but rather on surface and sub-surface storage), the method of exponential decay was performed through the interpolation between the logarithmically transformed points before and after the gap. During periods of variable flow when the flow is dependent on rainfall, relation/regression equations were applied to fill in missing data between Pangor AJ Chimbo and Chimbo DJ Pangor as they are neighbouring stations and presented a good correlation ($r = 0.95$). On the other hand, missing data of rainfall were filled in using the method of quantile regression, which was suitable due to the high correlation ($r > 0.85$) among rain gauge stations.

Daily streamflow data between 1974 and 2008 were separated into baseflow and stormflow using a Water Engineering Time Series PROcessing tool (WETSPRO) which uses a continuous time series of any hydrological variable as input (Willems, 2009). Estimated baseflow and stormflow data were used for further analysis.

2.4. Empirical Mode Decomposition

In the tropical Andes, precipitation and streamflow are strongly influenced by El Niño-Southern Oscillation (ENSO) at seasonal, annual and decadal timescales (Poveda and Mesa, 1997; Restrepo and Kjerfve, 2000). Although it is usually accepted that temporal variability of precipitation is the major factor of large-scale variability of streamflow. However, these ecosystems have been modified by anthropogenic disturbances, particularly changes in land use/land cover, which may have an effect on streamflow as important as changes in climate. In order to separate the strong effect of precipitation variability and to assess the effect of land use/land cover change on streamflow, we used the Empirical Mode Decomposition (EMD) method. The EMD can be applied to non-linear and non-stationary time series, this method is appropriate to decompose non-linear oscillatory patterns of higher frequencies from those of lower frequencies and a trend (Huang et al., 1998; Peel and McMahon, 2006). For our purpose we applied the EMD to precipitation and streamflow time series and quantified the proportion of variation in streamflow, which is represented by the residual or trend.

3. Results

3.1. Land use/cover change

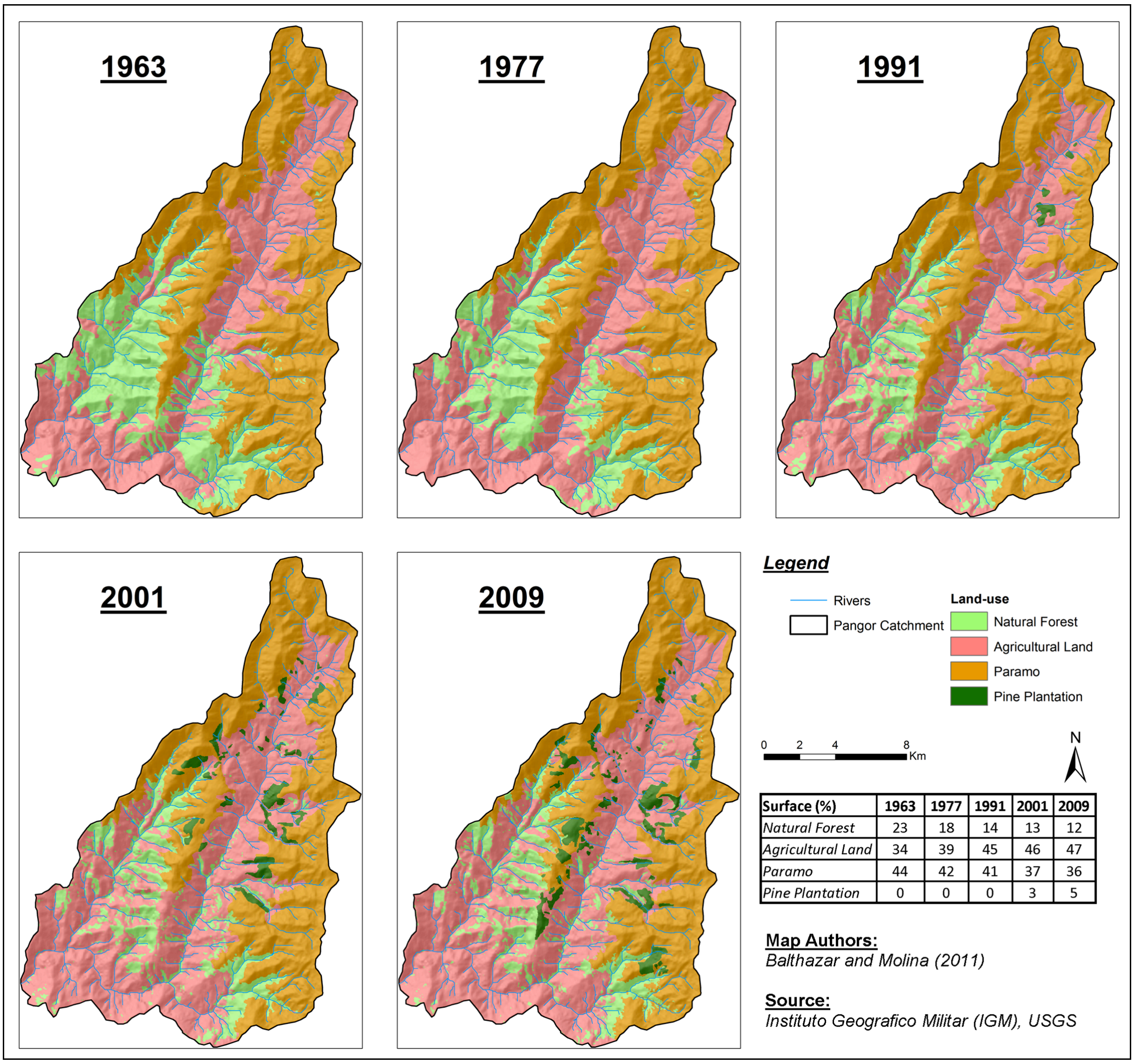
In this study, we identified four major land-use categories: (1) Natural forest composed by the tropical montane cloud forest, (2) Agricultural land, which consists of rangeland and cropland, (3) Páramo grassland and (4) Pine plantations. In general, land use consists of about 47% agricultural land and 36% páramo grassland, with lesser amounts of natural forest (12%) and pine plantations (5%).

Land use/land cover maps between 1963 and 2009 (fig. 1) highlight the expansion of the agricultural frontier, the clearing of natural forest (about 50%) and the rapid conversion of páramo grassland to pine plantations. In Table 3 is summarized the main changes occurred from 1963 to 2009.

Table 3

Area km²	1963	1977	1991	2001	2009	Change km²	Change %
Agricultural land	95	111	128	133	133	38	40
Natural forest	64	52	39	36	34	- 30	- 47
Páramo	124	120	115	105	102	- 22	- 18
Pine plantations	0	0	1	9	14	14	100

Fig.1



Surface (%)	1963	1977	1991	2001	2009
Natural Forest	23	18	14	13	12
Agricultural Land	34	39	45	46	47
Paramo	44	42	41	37	36
Pine Plantation	0	0	0	3	5

Fig.1. Time series of land use/land cover maps of the Pangor catchment in the central part of Ecuador

3.2. Streamflow analysis

Fig. 2

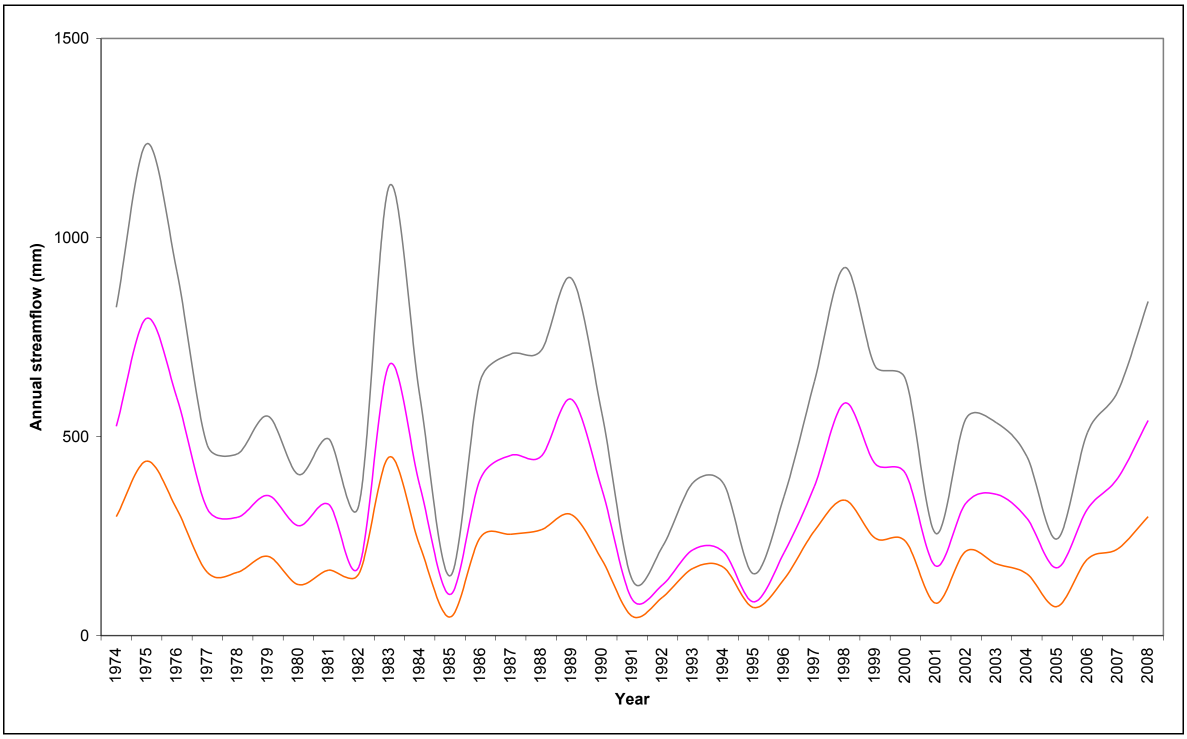


Fig. 2. Streamflow (gray line), baseflow (purple line), and stormflow (orange line)

Fig. 3

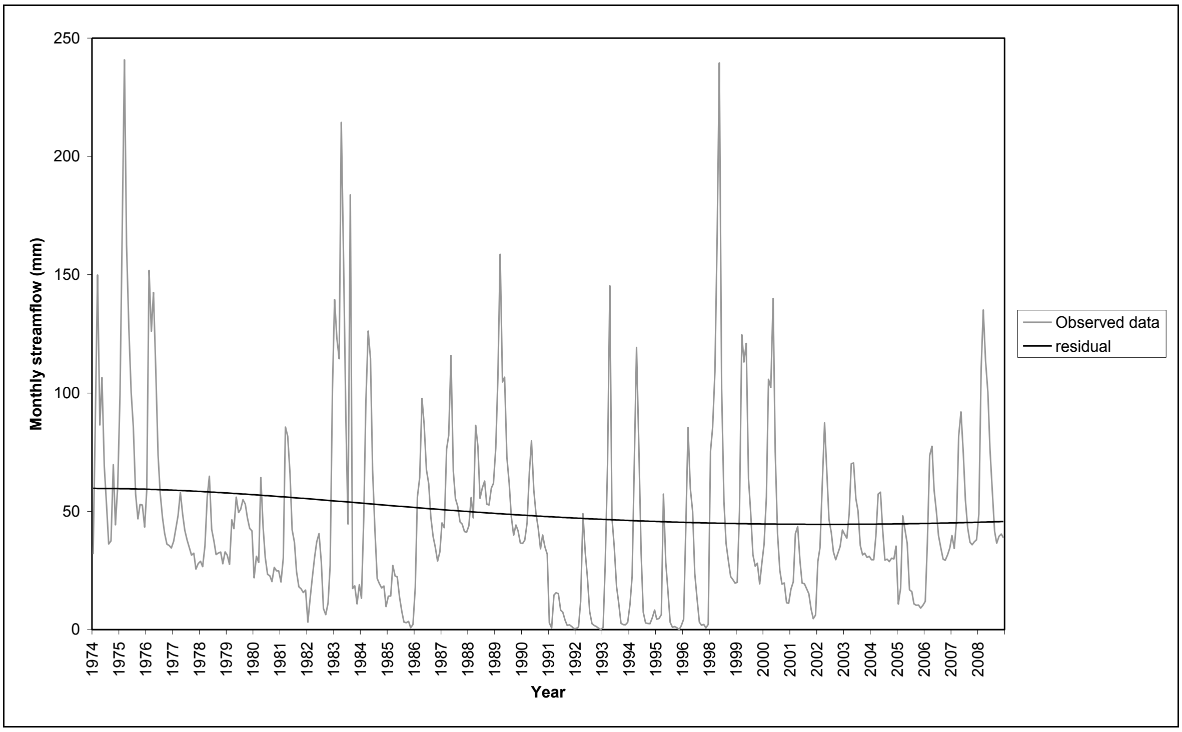


Fig.3. EMD analysis of monthly streamflow. Residual or trend (black line) and observed monthly streamflow (gray line).

Time series analysis of streamflow applying the Empirical Mode Decomposition method (EMD) indicates a trend of decreasing streamflow between 1974 and 2008 as a result of land use change that occurred in the Pangor catchment during the last 50 years.

4. Publication in preparation

During the time of my short-term contract (full- time 4 months and part-time 5 months) allowed me to acquire sufficient information to achieve the goals of the research project. A publication is in preparation, which will be submitted to an international journal during the next few months. Below is indicated the potential article with the authors and the title:

Molina, A., Van Rompaey, A., Lambin, E., Balthazar, V., Brisson, E., Vanacker, V., 2011. Longer-term effects of land use change on streamflow in the Ecuadorian Andes. Journal of Hydrology, in preparation.

5. References

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Lillesand, T.M. and Kiefer, R.W., 2000. Remote sensing and image interpretation. John Wiley and Sons, Inc.

Peel, M.C and McMahon, T.A., 2006. Recent frequency component changes in interannual climate variability. Geophysical Research Letters 33, doi:10.1029/2006GL025670.

Poveda, G., Mesa, O.J., 1997. Feedbacks between hydrological processes in tropical South America and large-scale ocean-atmospheric phenomena. Journal of Climate 10, 2690–2702.

Restrepo, J.D., Kjerfve, B., 2000. Magdalena river: interannual variability (1975–1995) and revised water discharge and sediment load estimates. J. Hydrol. 235, 137–149.

Willems, P., 2009. A time series tool to support the multi-criteria performance evaluation of rainfall-runoff models. Enviromental Modelling & Software 24, 311-321.