Estimation of water yield in the hydrographic basins of southern Ecuador

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Abstract. Humans greatly benefit from natural water resources, also known as hydrological ecosystem services. However, these services may be reduced by population growth, land use changes, and climate change. As these problems become more critical, the need to quantify water resources increases. The estimation of water yield and its distribution are of great importance for the management of water resources. In the present study, the average annual water yield of the hydrographic basins in the southern region of Ecuador was estimated for the 1970–2015 period using the InVEST water yield model based on the Budyko framework. The model estimates annual surface run-off at the pixel, sub-basin, and basin level considering the following variables: precipitation, actual evapotranspiration, land cover/use, soil depth, and available water content for plants. The model was calibrated by varying the ecohydrological parameter Z to reduce error between estimated and observed water yield. The results showed that the modeling of water yield in the majority of the hydrographic basins was satisfactory, allowing the basins to be ranked according to their importance for water production. The Mayo and Zamora basins had the highest water production, corresponding with 934 and 1218 mm year^{-1}, respectively, while the Alamor and Catamayo basins had the lowest water production, corresponding with 206 and 291 mm year^{-1}, respectively. The present study provides an initial estimate of water yield at the basin level in the southern region of Ecuador, and the results can be used to evaluate the impacts of land cover changes and climate change over time.

1 Introduction

Humans receive a variety of benefits from natural water resources, also known as hydrological ecosystem services (HESs). Several of the main HESs include regulation of the water cycle, high water yields, maintenance of water quality, and aquifer recharge. These services can be negatively affected if natural ecosystems are converted to other land uses by human activities (Quintero, 2010). Decades of anthropogenic intervention have altered land covers and uses, resulting in the conversion of natural lands to pastures, crops, deforested areas, urban constructions, and mining operations, among other land uses (Crespo

et al., 2014). As these problems become more critical, effective land use planning is necessary to guarantee the continued provision of HESs. Such planning requires a good understanding of hydrology and can also be used to support key decisions about the management of water resources in the near future (Buytaert et al., 2006b). The uncertainty associated with climate change and its impacts on the water cycle and water availability further incentivize the need to generate detailed inventories

5   of water resources (Tallis and Polasky, 2009).

In Ecuador, few studies have quantified water resources at the hydrographic basin level (Buytaert et al., 2006b; Duque Yaguache and Vázquez Zambrano, 2015). The main challenges for the advancement of hydrological knowledge have been the difficulty of implementing and maintaining observation networks in complex and remote environments and the lack of recognition of ecosystems as water suppliers (Célleri et al., 2009). However, some microbasins have been studied in the wet

10   paramos and tropical mountains of southern Ecuador. Of these studies, several can be highlighted, whose main contributions have been the conceptualization of hydrological processes (Célleri et al., 2009; Célleri and Feyen, 2009; Llambí et al., 2012), water modeling (Balcázar et al., 2016; Buytaert et al., 2006a; Oñate and Aguilar, 2003; Vázquez, 2015), monitoring and quantification of the main climate variables (Campozano et al., 2016; Ochoa-Tocachi et al., 2018), documenting climate variability (Bendix et al., 2008; Buytaert et al., 2006c; Celleri et al., 2007; Fries et al., 2014; Luna-Romero et al., 2018;

15   Rollenbeck and Bendix, 2011), and determining the effect of land use changes on water behavior (Buytaert et al., 2005, 2007; Crespo et al., 2014; Ochoa-Tocachi et al., 2016) as well as the impacts of climate change on hydrology (Breuer et al., 2013; Buytaert et al., 2009, 2010; Buytaert and Bievre, 2012; Mora et al., 2014). Generally, these studies have been developed at small scales over relatively short time frames.

The importance of studying Andean basins rests on their importance as the main providers of water for the Andes highlands

20   as well as for the adjacent, extensive lowlands and a portion of the coastal plains (Buytaert et al., 2006b). Crespo et al. (2014) highlighted that water production in paramo microbasins in their natural state is around 75% of precipitation in terms of quantity. The high water production of these basins is due to the high quantity of precipitation as well as the low water consumption of vegetation. However, the urban growth and concentration of agriculture in the inter-Andean valleys have directly influenced the increase in the demand for water for different uses.

25   The modeling of hydrological services is associated with a considerable implementation effort and data requirement, and the required data may not always be available. For this reason, it is necessary to explore accessible tools that require little information but can still provide a good overall scenario of available hydrological services. In particular, to quantify available water resources, traditional hydrological and ecosystem service tools are available. The InVEST model is one tool for the valuation of ecosystem services developed in 2007 by Stanford University, the World Wildlife Fund (WWF), and the Nature

30   Conservancy (TNC). It contains several sub-models, including a model for estimating water yield. This latter model has a biophysical component that calculates water yield based on landscape features in addition to a valuation component that aims to represent the benefits of the available water supply for humans (Hamel and Guswa, 2015).

The biophysical module used in this work is based on the Budyko hydrological framework. This model estimates annual average run-off at the pixel, sub-basin, and basin level, considering variables such as precipitation, reference

evapotranspiration, land use and cover, soil depth, and available water content for plants. The InVEST water yield model has been widely used throughout the world with satisfactory results in China (e.g., Bai et al., 2012; Geng et al., 2015; Lang et al., 2017; Li et al., 2018; Zhang et al., 2012), Thailand (e.g., Arunyawat and Shrestha, 2016), Spain (e.g., Bangash et al., 2013), Argentina (e.g., Gaspari et al., 2015; Izquierdo and Clark, 2012), and several countries in northeastern Africa (e.g., Belete

5 et al., 2018). Other studies such as those of Sánchez-Canales et al. (2012), Hamel and Guswa (2015), Redhead et al. (2016), and Pessacg et al. (2015) have analyzed the sensitivity, calibration, and validation of the model and have agreed that it produces accurate estimates of water production in hydrographic basins. However, the uncertainty introduced by errors in climate data can be significant and non-spatially heterogeneous, subsequently affecting the estimated spatial distribution of water yield.

Given this context, the objective of the present study was to estimate and map average annual water yield for the 1970–2015

10 period in nine hydrographic basins of the southern region of Ecuador. The largest amount of meteorological, precipitation, and temperature data available for the region was used. Given the interest in water yield from the perspective of ecosystem services, the InVEST water yield model was used to generate explicit spatial estimates of water yield. The results are an initial estimate of water yield at the level of large hydrographic basins in the study area considering a land use and cover map corresponding with the 2013–2014 period. The results can be used to evaluate the future impacts of changes in plant cover and climate change,

15 which would facilitate the local planning and management of water resources in the long term.

2 Materials and methods

2.1 Study area

The study was carried out in nine hydrographic basins of the southern region of Ecuador located in the provinces of El Oro, Loja, and Zamora Chinchipe that, as a whole, form Planning Zone 7 (Zona de Planificación Siete [ZP7]), a political and

20 administrative unit (Figure 1). This unit has an area of ~27491 km^2 and is located between 3°02' and 5°00' N and 78°21' and 80°29' W. The altitude ranges from 0 to ~3500 masl.

Sixteen climate types are present in the study area according to the Thornthwaite climate classification performed by the Instituto Nacional de Meteorología e Hidrología (INAMHI) (Moya, 2006). Some of the main factors that influence the climate are oceanographic phenomena, such as the El Niño–Southern Oscillation and the Humboldt current (Maldonado A., 2001),

25 and the presence of the Andes mountain range. Specifically, the study area coincides with one the lowest sectors of the mountain range known as the inter-Andean depression (Figure 1b). In addition, the region is considered as the limit between the northern and central Andes. The high sectors are extremely wet throughout the year, whereas the downwind slopes, in contrast, are relatively dry. The region is also characterized by an extreme vertical precipitation gradient and the fragmented relief of valleys and mountain ranges, which further influence the significant climate heterogeneity of the region (Richter and

30 Moreira, 2005).
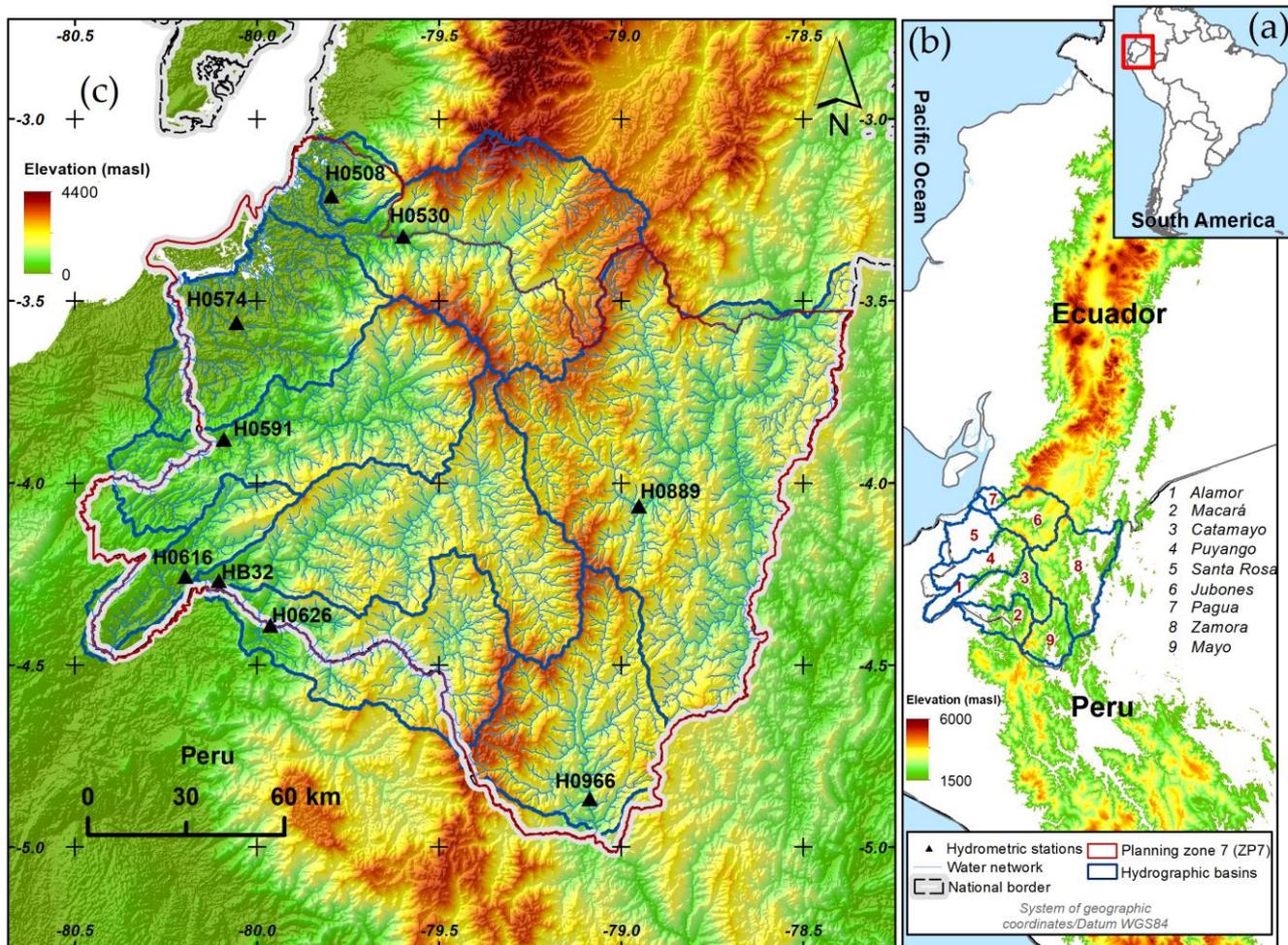
Figure 1: Location of the study area in relation to (a) Southern America, (b) Ecuador and the Andean system. (c) Location of the hydrometric stations in relation to the hydrographic basins.

5   The hydroclimatic variables analyzed in the 1970–2015 period showed that precipitation in the hydrographic basins, except for the Zamora and Mayo basins, presents high spatial-temporal variability (Figure 2

Figure 2: Magnitude and evolution of the hydroclimatic variables per hydrographic basin for the 1970–2015 period. and Figure 3a). The precipitation level varied between ~300 and ~1800 mm year^{-1}. However, in years with El Niño events, the precipitation

10   level reached ~3400 mm year^{-1}. In the Zamora and Mayo basins (Figure 2) located along the Amazon slope, precipitation varied between ~1000 and ~2200 mm year^{-1}. The mean temperatures of the hydrographic basins (Figure 2) along both slopes varied between 14 to 25 °C. At the spatial level, areas near the Andes mountain ranges were colder, whereas the coastal areas were warmer (Figure 3b).
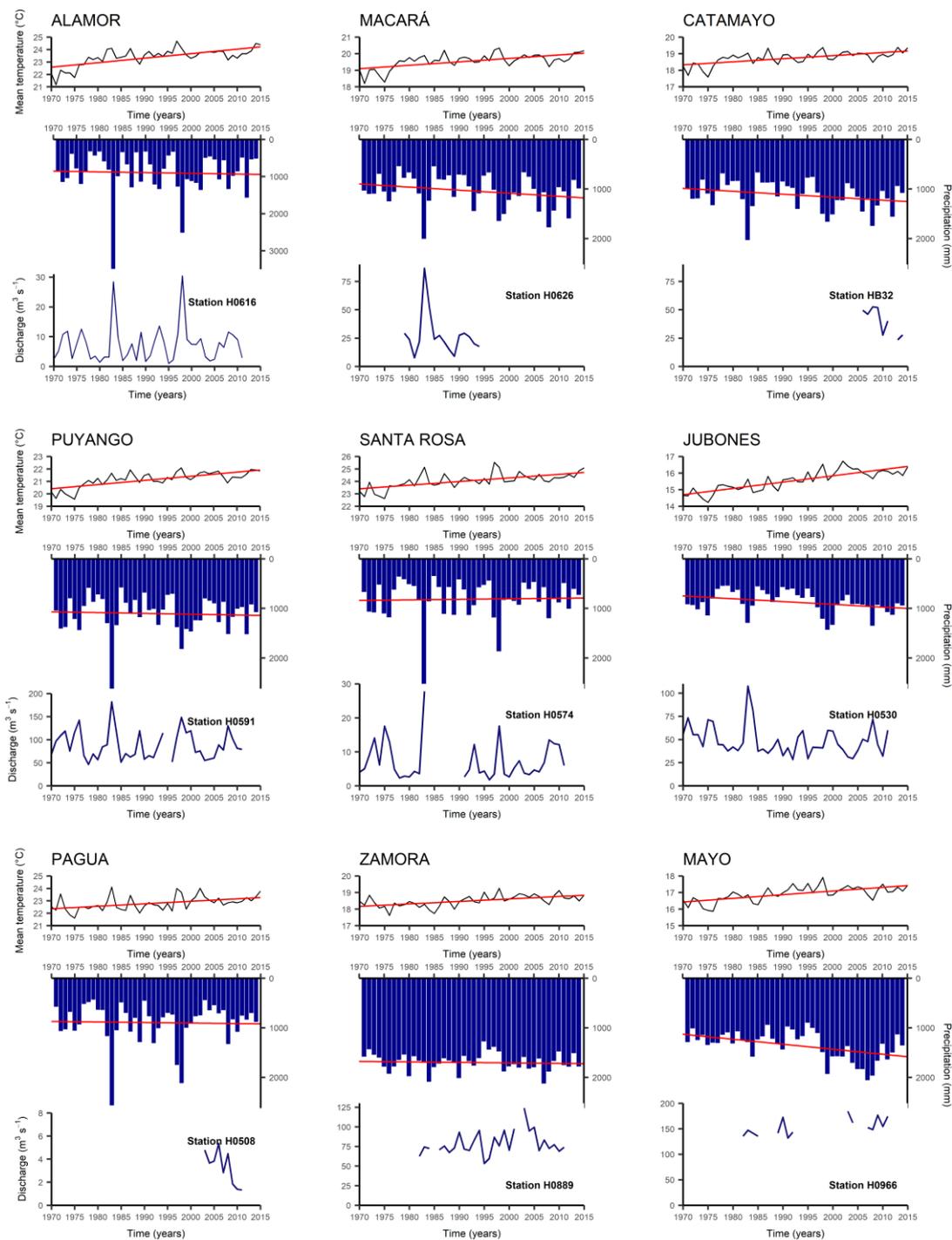
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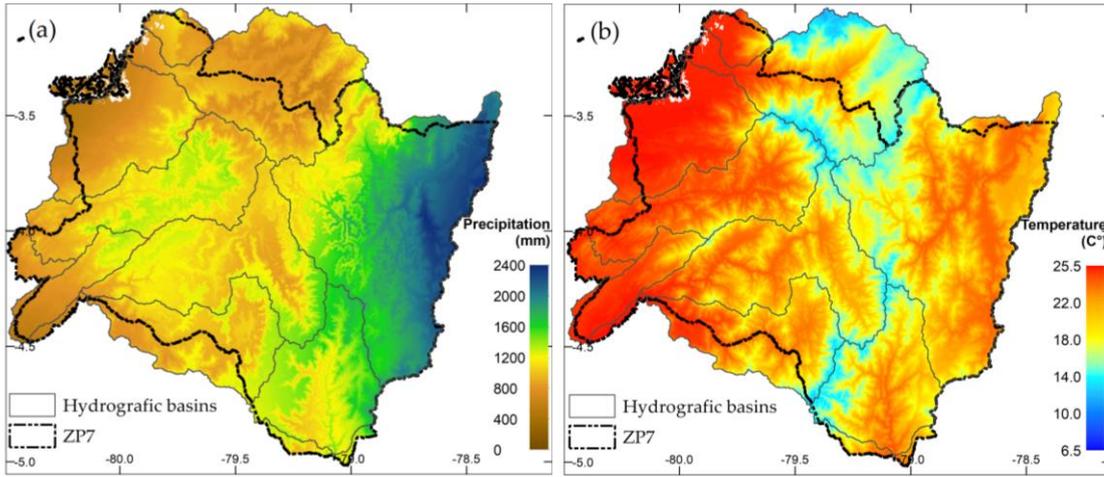
Figure 3: Spatial distribution of (a) average annual precipitation and (b) average annual mean temperature in the study area for the 1970–2015 period.

2.2 InVEST water yield model

The InVEST water yield (WY) model is based on the Budyko curve and on average annual precipitation (Eq. 1). The model calculates average surface run-off (Y) of pixel x in the landscape as follows:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \tag{1}$$

where AET_x is the annual actual evapotranspiration of pixel x, and P_x is annual precipitation of pixel x. The fraction AET_{xj}/P_x is based on the expression of the Budyko curve proposed by Fu (1981, cited in Sharp et al. 2018) and Zhang et al. (2004) (Eq. 2):

$$\frac{AET_x}{P_x} = 1 + \frac{PET_x}{P_x} - \left[1 + \left(\frac{PET_x}{P_x}\right)^{\omega_x}\right]^{1/\omega_x} \tag{2}$$

where PET_x is the potential evapotranspiration, and ω_x is a non-physical parameter that characterizes the natural climate-soil properties proposed by Donohue et al. (2012). PET_x (Eq. 3) and ω_x (Eq. 4) are defined as follows:

$$PET_x = K_{c\,(l_x)} \times ET_{0\,x} \tag{3}$$

$$\omega_x = Z \times \frac{AWC_x}{P_x} + 1.25 \tag{4}$$

where $ET_{0\,x}$ is the reference evapotranspiration of pixel x, and K_c is the evapotranspiration coefficient of vegetation associated with a specific land use/cover (LUC) (l_x). ET_0 reflects local climate conditions as a function of the evapotranspiration of a reference vegetation. K_c adjusts the ET_0 values according to the vegetation type of pixel x.

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AWC_x is the available water content for plants in mm and is defined based on soil texture and effective root depth. AWC_x establishes the quantity of water that can be stored and liberated in the soil for plant use. It is estimated as the product of the fraction of plant available water capacity (PAWC) and of root restricting layer depth and vegetation rooting depth (Eq. 5):

$$AWC_x = Min \ (Rest.layer.depth, root.depth) \times PAWC \tag{5}$$

5   The depth of the root restriction layer is the soil depth at which the penetration of roots is inhibited because of physical or chemical characteristics. The depth of the rooting zone is often determined as the depth above which 95% of root biomass of a particular vegetation type is located. The PAWC is the available water capacity for plants, which is to say, the difference between the field capacity and the wilting point.

The Z value is an empirical constant that captures basin characteristics such as climate, precipitation intensity, and topography.

10   The minimum value of ω_x is 1.25, which is the value for bare soil (when root depth is 0). Three methods were proposed by Sharp et al. (2018) for the determination of Z. The first method is based on the positive correlation between Z and average annual precipitation events per year (N), as Z approximates to N/5 (Donohue et al., 2012). This implies that Z captures precipitation patterns and distinguishes between basins with similar annual precipitation but distinct precipitation intensity (Hamel and Guswa, 2015). The second method is based on solving Z in Eq. 4; the necessary ω values are available at the

15   worldwide level (Liang and Liu, 2014; Xu et al., 2013). The third method, which was used in the present study, determines Z through calibration, which consists of comparing estimated data with observed data.

Finally, for LUCs without vegetation (water bodies, urban areas, etc.), AET is directly calculated from ET_0 values, and the upper limit is determined by precipitation, as follows (Eq. 6)

$$AET_x = Min \ (K_c(l_x) \times ET_{0 \ x}, P_x) \tag{6}$$

20   Accordingly, the WY model calculates average surface run-off per pixel in addition to average surface run-off at the hydrographic sub-basin and basin level. A detailed description of the model can be consulted in Sharp et al. (2018) and Hamel and Guswa (2015).

2.3 Data

The data required by the InVEST WY model are average annual precipitation, annual average reference evapotranspiration

25   (*ETo*), land use/cover (LUC), fraction of plant available water capacity (PAWC), soil depth, and the boundaries of the hydrographic basins (Figure 3) in addition to the biophysical attribute table and the ecohydrological parameter *Z*.
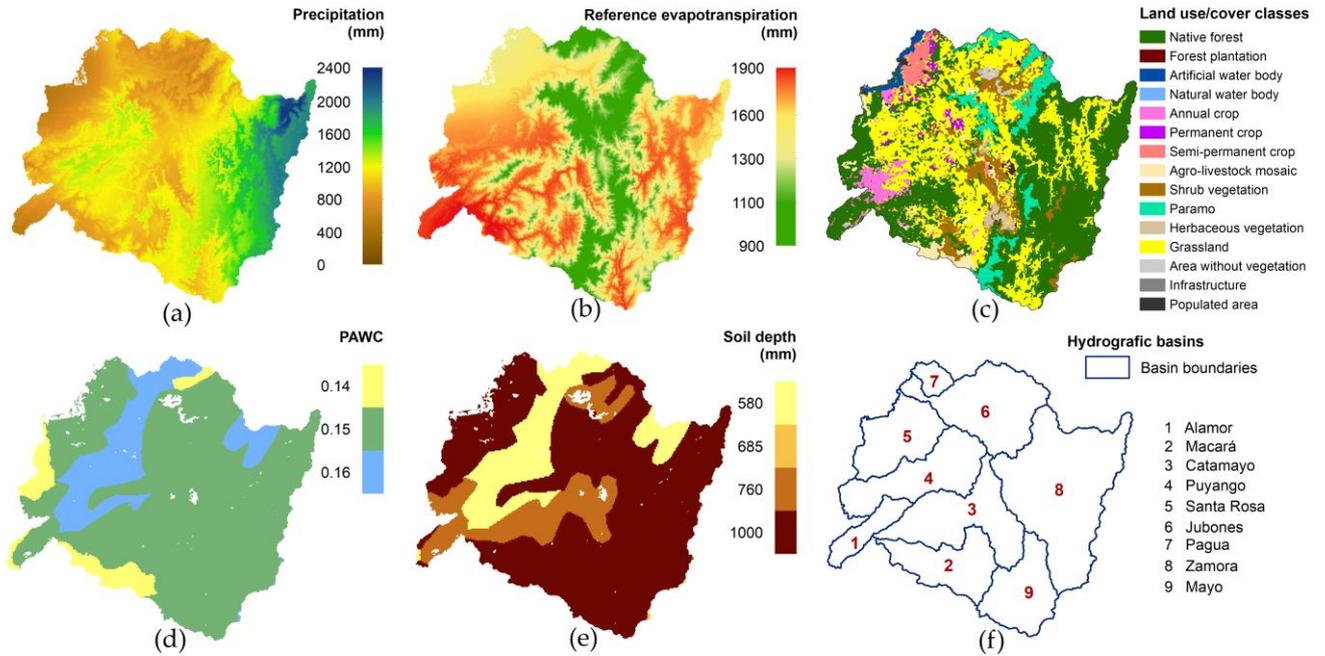
Figure 4: Variables required for the execution of the InVEST water yield model: (a) precipitation (mm), (b) reference evapotranspiration (mm), (c) land use and cover, (d) plant available water capacity fraction, (d) soil depth, and (f) hydrografic basins.

Climate data: The climate data are the most important input variables in the water yield model. Maps of precipitation and of average, minimum, and maximum temperature at a high resolution of 6 arc seconds (~185 m) were generated through interpolation based on observed data using the thin-plate smoothing method in the ANUSPLIN software (Hutchinson, 2006). The climate data were obtained from the network of meteorological stations of the INAMHI, the Servicio Nacional de Meteorología e Hidrología (SENAMHI) of Peru, and the Estación Científica San Francisco (ECSF). Precipitation data from a total of 160 meteorological stations were used in addition to temperature data from 64 stations. The data were recorded in different formats and at distinct temporal scales, so the data were converted to monthly values for the 1970–2015 period. The data were subsequently structured and validated; this process consisted in (1) merging the data according to the recommendations of the World Meteorological Organization (WMO, 2011), (2) detecting gaps in the data using graphs, and (3) identifying atypical values. To identify atypical data in the variables of average, maximum, and minimum temperature, an upper limit of 1.5 times the interquartile range (IQR) was established; meanwhile, for precipitation, considering that the variability in the data is much higher, the limit was set at 3 times the IQR.

The temperature maps were used to estimate ET_0 using the Hargreaves equation (Eq. 7).

$$ET_0 = 0.0023 \ Ra \ \left[\left(\frac{T_{max} + T_{min}}{2} \right) + 17.8 \right] \ (T_{max} - T_{min})^{0.5} \ \left(\frac{mm}{day} \right) \tag{7}$$

where Ra is terrestrial solar radiation in mm day^{-1}, T_{max} is the maximum temperature (°C), and T_{min} is the minimum temperature (°C). Ra was obtained from the databases of Global-Aridity and Global-PET from the Consultative Group on

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International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI) at a resolution of 1.5 arc minutes. The resolution of the Ra map was adjusted to 6 arc seconds. In the study area, the maximum spatial variation of Ra is 0.35 mm (13.22–12.87 mm) in June, and the minimum variation is 0.002 mm in March (15.561–15.563 mm), indicating that the variation of Ra across the study area is relatively small and that the resolution adjustment likely did not affect the estimation of ET_0.

5 **Land use and cover (LUC)**: The database on LUC was obtained from the Ministerio del Ambiente del Ecuador (MAE) at a scale of 1:100000 for 2014. From these data, a raster image was generated based on the level-II classification proposed by MAE and Ministerio de Agricultura, Ganadería, Acuacultura and Pesca (MAGAP) (MAE and MAGAP, 2015) which contained 15 classes of LUC for the study area (Figure 3c).

Depth of the root restriction layer: Data on the root restriction layer were unavailable. For this reason, according to the
10 recommendation of Sharp et al. (2018), soil depth was used. Soil depth data were obtained from the Harmonized World Soil Database (HWSD) version 1.2 (FAO et al., 2012). From this, a raster image was generated. The unit of measurement was millimeters (mm).

Plant available water capacity fraction (PAWC): This parameter was generated based on the AWC and the minimum value of the soil depth or root depth of vegetation (Equation (5)). The AWC and soil depth were obtained from the HWSD databases
15 (FAO et al., 2012), and the root depth was obtained from Allen et al. (1998) and Sharp et al. (2018). The result was a raster image of PAWC with values between 0 and 1 (dimensionless).

Biophysical attribute table: A table containing biophysical attributes for each LUC class (Table 1) was generated in text format (.csv). The attributes are as follows: Id, LUC class, evapotranspiration coefficient (K_c), root depth, and vegetation presence. The values for K_c and root depth were taken from Allen et al. (1998) and Sharp et al. (2018). K_c is used to obtain
20 potential evapotranspiration from ET_0; the value ranges from 0 to 1.5. The field vegetation presence determines which equation will be used to estimate actual evapotranspiration (AET) in the WY model: A value of 1 corresponds with LUCs with vegetation (Eq. 2), and a value of 0 corresponds with LUCs without vegetation (Eq. 6).

Ecohydrological parameter Z: Z is an empirical constant with a value of 1 to 30 that was determined during the calibration, which involved the comparison of estimated data with observed data. At following, the calibration process is described in
25 greater detail.

Table 1: Biophysical attribute table used to execute the water yield model.

Id	LUC classes	K_c	Root depth (mm)	Presence vegetation
1	Native forest	1	5000	1
2	Natural water body	1	-	0
3	Semi-permanent crop	0.6	1000	1
4	Grassland	0.7	1000	1
5	Permanent crop	0.6	1000	1
6	Shrub vegetation	0.5	2000	1
7	Agro-livestock mosaic	0.6	1000	1
8	Populated area	0.3	-	0
9	Area without vegetation	0.3	-	0
10	Artificial water body	1	-	0
11	Paramo	0.7	1500	1
12	Herbaceous vegetation	0.7	1500	1
13	Forest plantation	1	5000	1
14	Annual crop	0.6	900	1
15	Infrastructure	0.3	-	0

2.4 Calibration of the Water Yield model

To calibrate the WY model, as stated above, the ecohydrological parameter Z and observed data (long-term average water flow) collected from nine hydrological stations were used. Unfortunately, hydrometric stations were not present at the outlets of the hydrographic basins; data from these stations are ideal for model calibration. The nine available hydrometric stations were located in sub-basins of the hydrographic basins of the study area (Figure 1 and Figure 2).

The calibration was performed by varying the Z value from 1 to 30 until the error was minimized to the greatest extent possible. In this case, the error is determined by the difference between estimated and observed water yield. Observed water yield was determined from data on daily water flow from INAMHI. The calibration period of each hydrographic sub-basin depended on the availability of observed data from hydrometric stations (Table 2).

Table 2: Information on hydrometric stations and calibration period for the water yield model.

Station code	Hydrometric station	Hydrographic basin	Calibration period	Evaluated years	Excluded years
H0616	Alamor at Saucillo (Dj Celica)	Alamor	1970–2011	42	-
H0626	Macará at Pte. Internacional	Macará	1979–1994	16	-
HB32	Catamayo at Vicin	Catamayo	2006–2014	8	2012
H0591	Puyango at Cpto. Militar (Pte. Carretera)	Puyango	1970–2011	42	1995
H0574	Arenillas at Arenillas	Santa Rosa	1970–2011	34	1984-1990
H0530	Jubones at Ushcurrumi	Jubones	1970–2011	42	-
H0508	Chaguana at Pte. Carretera	Pagua	2003–2011	9	-
H0889	Zamora DJ Sabanilla (at Zamora)	Zamora	1982–2011	28	1985, 2002
H0966	Mayo AJ Qda. Zumbayacu	Mayo	1982–2011	15	1984, 1986-1988, 1993-1995, 1997-2002, 2005-2006

The units for the observed data were cubic meters per second (m^3/s), and the units of the estimated data were millimeters per year (mm year^{-1}). Accordingly, the observed data were transformed to mm year^{-1}.

5   In the hydrographic sub-basins, the diversion of water flow by irrigation systems was additionally considered. Only water flows that could influence the calibration of the model were taken into account (Table 3), such as the Zapotillo irrigation system located before station HB32 that diverts approximately 8 m^3/s. Small water channels that communities use for irrigation were not considered because information was lacking on the diverted water volume and because the diverted quantities were considered minimal.

10   **Table 3: Irrigation systems considered in the calibration of the water yield model.**

Hydrographic basin	Station code	Irrigation channels	Total diverted volume (m^3/s)	Source	Date
Macará	H0626	7	3.29	GADP-Loja (2013)	up to 2012
Catamayo	HB32	7	9.40		

The calibrated Z values were used to obtain the water yield of each hydrographic basin under the assumption that the calibrated value captured the climate characteristics, precipitation intensity, and topography of the basins.

3 Results

3.1 Calibration of the water yield model

The calibration of the model provided an analysis of the sensitivity of water yield with respect to ecohydrological parameter Z (Figure 5). The extreme values of Z, 1 and 30, led to different simulations of water yield. For example, in the case of the Alamor in Saucillo (H0616) station, the Z values of 1 and 30 led to errors of 95% and 35%, respectively, with respect to the Z value of 13 at which the error was minimized to 0.58%. The lowest Z values had higher errors in the simulations of water yield than the highest Z values.
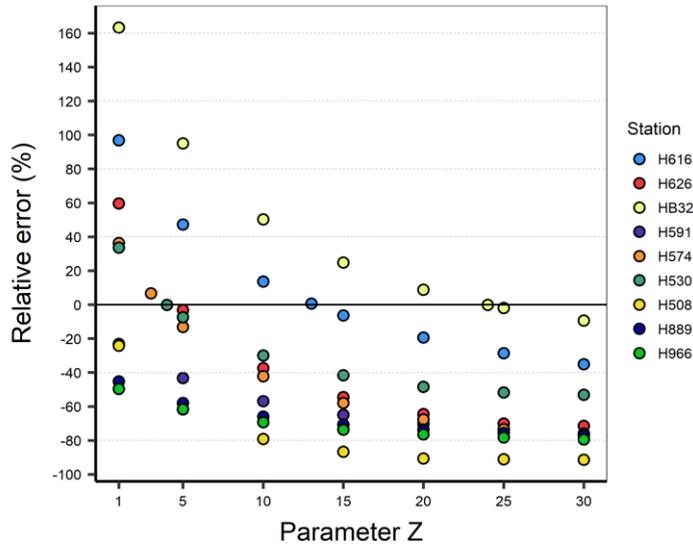

Figure 5. Calibration of the model as a function of ecohydrological parameter Z.

The model was calibrated for five hydrographic sub-basins with Z values ≥ 3 and errors of less than 7%. Meanwhile, the remaining four sub-basins could not be satisfactorily calibrated, as water production was underestimated in these sub-basins by 20% to 50% (Table 4).

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Table 4: Summary of the calibration process per hydrographic sub-basin.

Station code	Hydrometric station	Area (Km²)	P (mm)	ET₀ (mm)	PET (mm)	AET (mm)	Z	Obs. WY (mm)	Est. WY (mm)	Relative error (%)
H0616	Alamor at Saucillo (Dj Celica)	585	1108	1660	1157	725	13	381	383	0.58
H0626	Macará at Pte. Internacional	2509	986	1544	1124	595	5	360	349	−3.21
HB32	Catamayo at Vicin	4172	1251	1536	1170	833	24	303	303	0.1
H0591	Puyango at Cpto. Militar (Pte. Carretera)	2728	1149	1585	1153	375	1	1008	775	−23.18
H0574	Arenillas at Arenillas	493	1009	1678	1302	533	3	447	477	6.61
H0530	Jubones at Ushcurrumi	3636	870	1249	810	447	4	423	422	−0.10
H0508	Chaguana at Pte. Carretera	190	789	1505	1169	352	1	576	437	−24.19
H0889	Zamora DJ Sabanilla (at Zamora)	1422	1343	1240	1070	399	1	1724	994	−45.23
H0966	Mayo AJ Qda. Zumbayacu	2564	1424	1363	1189	422	1	1987	1001	−49.60

ET₀: reference evapotranspiration, PET: potential evapotranspiration, AET: actual evapotranspiration, Obs. WY: observed water yield, Est. WY: estimated water yield, P: precipitation, Km²: square kilometres, mm: millimetres
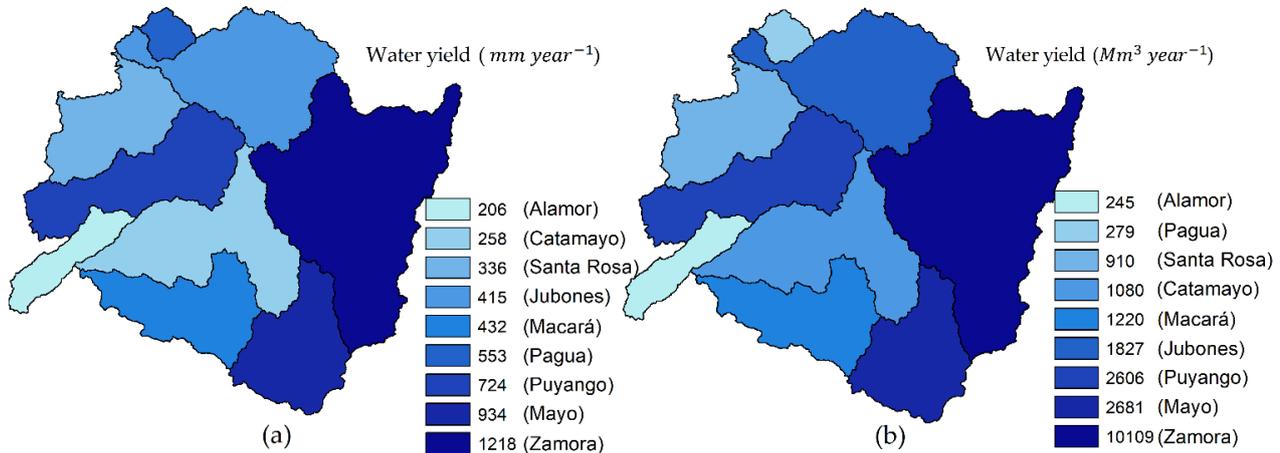
3.2 Water yield

5 The water yield varies from 206 mm in Alamor basin to 1218 in Zamora basin. The Amazon basins (Zamora and Mayo) have the highest water production, and the basins located in the Andean mountains and valleys (Alamor and Catamayo) have the lowest water production (Table 5 y Figure 6).

Table 5: Average annual water yield per hydrological basin (1970–2015).

Id	Hydrographic basin	Area (Km²)	P (mm)	ET₀ (mm)	PET (mm)	AET (mm)	Est. WY (mm)	Volume (Mm³)
1	Alamor	1187	899	1752	1436	693	206	245
2	Macará	2824	1039	1577	1193	607	432	1220
3	Catamayo	4187	1121	1528	1167	863	258	1080
4	Puyango	3601	1106	1629	1240	382	724	2606
5	Santa Rosa	2708	842	1603	1263	505	336	910
6	Jubones	4402	875	1284	861	460	415	1827
7	Pagua	505	906	1457	1075	352	553	279
8	Zamora	8297	1701	1518	1376	482	1218	10109
9	Mayo	2869	1356	1390	1211	421	934	2681

10 ET₀: reference evapotranspiration, PET: potential evapotranspiration, AET: actual evapotranspiration, Est. WY: estimated water yield, P: precipitation Km²: square kilometres, mm: millimetres, Mm³: million cubic meters

Precipitation and ET_0 were similar in some basins, for example, Macará and Catamayo; however, the AET differed, generating distinct water yields (Table 5). This can mainly be attributed to the influence of K_c in the estimation of AET. The value of K_c depends on the type of vegetation cover. Lower values of K_c correspond with lower values of AET and, consequently, with higher values of water production (and vice versa). The model assumes that all water in excess of water lost due to AET is water production.

Figure 5: Spatial distribution of average annual water yield in the hydrographic basins of the study area from 1970–2015: (a) surface run-off depth (mm) and (b) water volume (Mm³).

Water production at the pixel level is shown in Figure 7 which illustrates the zones of high and low water production per hydrographic unit. Comparing water yield with the spatial distribution of precipitation (Figure 3), the water yield generally increases in areas of high precipitation. For example, the highest precipitation occurs in the eastern portion of the Zamora basin, where the water production also tends to be higher.
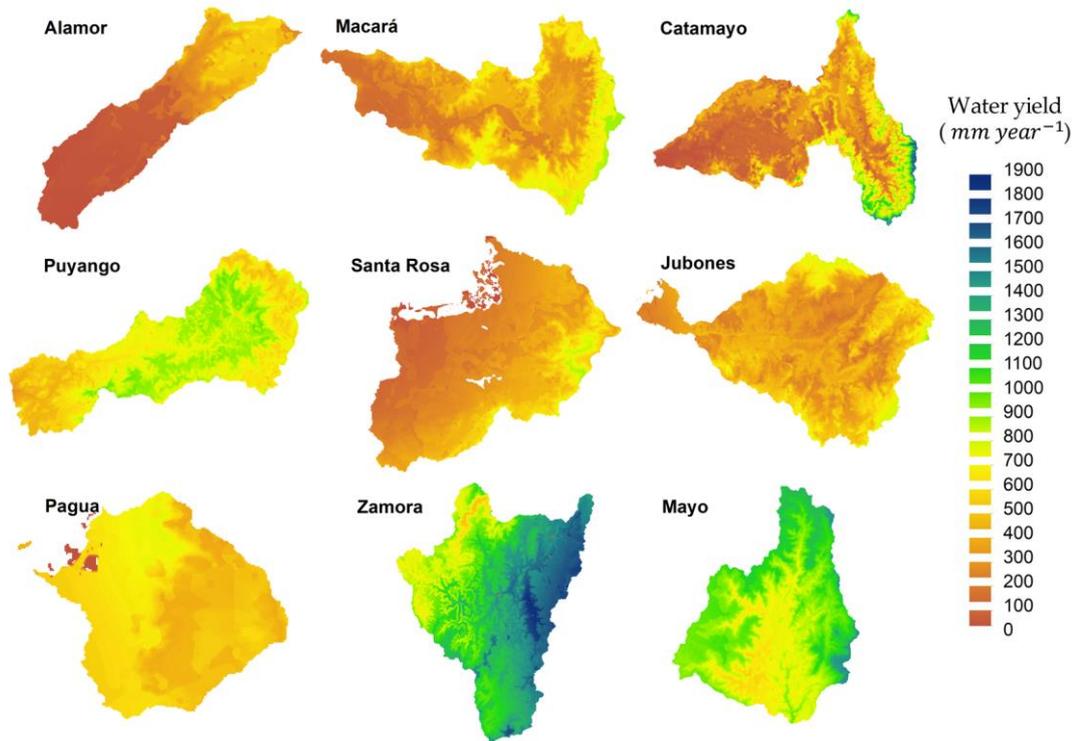
Figure 6: Spatial distribution of average annual water yield in the hydrographic basins of the study area from 1970–2015.

4 Discussion

Calibration of the Water Yield model

5 The Z empirical parameter remains uncertain according to several studies (Hamel and Guswa, 2015; Pessacg et al., 2015; Redhead et al., 2016). High Z values correspond with areas that receive a greater number of rainfall events per year, whereas low Z values indicate few rainfall events per year. However, in the present study, despite the satisfactory calibration of five hydrographic basins, stations H016 (Jubones), H0626 (Macará), and H0574 (Santa Rosa) were calibrated with low Z values, indicating that these zones are arid, even though precipitation occurs during the entire year in the high part of the Jubones

10 basin. This can be attributed to the forcing of the Z parameter with the objective of minimizing the error between simulated and observed water yield.

The high variation of calibrated basins in the Z parameter (3 to 24) can be attributed to the unique characteristics of the basins in regard to plant cover, soil properties, and topography despite their proximity. The w variable modulates these characteristics and is conditioned by the AWC-precipitation relationship and the empirical factor Z. This latter factor captures the intensity

15 of precipitation and the topography of the basin, which are not described by available water content (AWC) and annual precipitation.

15

Water yield was underestimated for the stations that were unable to be calibrated. This is possibly due to the precipitation data, as precipitation is the variable most sensitive to the estimation of water yield according to several previous studies (Goyal and Khan, 2016; Hamel and Guswa, 2015; Redhead et al., 2016; Sánchez-Canales et al., 2012). Notably, Rollenbeck and Bendix (2011) evaluated a set of local area weather radar (LAWR) images in southern Ecuador and found that precipitation reached

5   4000 mm in the high mountains. However, the images obtained in the present study from the interpolation indicated a precipitation level of 2400 mm for this same area.

As previously mentioned, the underestimation of precipitation is possibly due to the low density of meteorological stations in the high mountain zones that receive the highest quantity of precipitation as well as the complex orography of the study area. The presence of the Andes mountain range directly influences precipitation, and the present study area corresponds with one

10   of the lowest sectors of the mountain range known as the inter-Andean Depression (Richter and Moreira, 2005). In a study, Cuervo-Robayo et al. (2014) developed climate surfaces for Mexico using the thin-plate smoothing method, and the results were generally satisfactory. However, the authors similarly indicated that high standard error values were mostly found for mountain ranges.

In another study in an Andean basin of Argentina, Pessacg et al. (2015) evaluated different precipitation data sets with distinct

15   spatial and temporal resolutions; the calibration of the model varied per precipitation database. Notably, these authors found that precipitation errors of ± 30% led to errors in water yield of 50% to 150% (-45% to -60%) in some sub-basins.

Water yield

The basins located in the Amazon region had the highest water production. These basins are influenced by masses of hot air with high humidity proceeding from evaporative processes in wetlands and evapotranspiration in rain forests, which both

20   generate significant precipitation through processes of adiabatic cooling (Pourrut et al., 1995). Overall, in this region, precipitation is uniformly distributed throughout the year. However, in the Mayo basin, there is a slight decrease in precipitation from the months of June to October.

Meanwhile, the basins located in the Andean mountains and valleys to the southwest of the mountain chain are generally wet in the high parts and dry in the low parts as a result of the Foehn effect (Emck, 2007). A clear example of this phenomenon

25   occurs in the Valley of Catamayo (northeast of the Catamayo basin), which has a completely arid climate as a result of the Foehn effect and easterly winds. The driest months are June to August, which have very little or no precipitation. Meanwhile, the short wet season is characterized by intense rains that arrive with humid air masses originating from the South. Additionally, the Valley of Vilcabamba (southeast of the Catamayo basin) show a similar pattern. However, its climate is semi-arid (with a similar seasonality) because of its proximity to the Cordillera Real and the slightly weaker Foehn effect (Rollenbeck and

30   Bendix, 2011).

Another study in the southern region of Ecuador (Aguirre et al., 2015) evaluated water production as an ecosystem service in ZP7. Specifically, average water production was calculated seasonally (for the rainy and dry season) using a run-off equation. The results showed greater water production in the northwestern zone (Zamora basin) and lower production in the coastal

zones and Andean valleys, which is in agreement with the results of the present study. However, the influence of vegetation cover was also evidenced: The model was able to capture variation in water yield with respect to LUC. Precipitation and ET_o in some basins were similar, whereas the AET was different (Table 5) as a consequence of the influence of the K_c of each LUC class in the estimation of AET.

5   The main limitations of the InVEST water yield model are its inability to consider seasonal or sub-seasonal variability as well as infrastructure for ground water or for redistributing water flow. However, the model is deterministic and is based on simplifications of widely accepted hydrological relationships. It has the advantage of being based on relatively simple code that users can understand and adjust as necessary (Vigerstol and Aukema, 2011). Based on this simplified representation of the hydrological process, the InVEST Water Yield model can be used to quantify and map related ecosystem services relatively

10   rapidly (Lüke and Hack, 2018).

5 Conclusions

The orographic complexity and lack of available high-quality hydrometric data complicated the calibration of the Z parameter and, subsequently, the validation of the model. The large variations in the Z parameter across the hydrographic basins can mainly be attributed to the forcing of Z to minimize errors between simulated and observed water yield. This forcing was

15   carried out because of the possible underestimation of precipitation. It appears that precipitation errors in the simulation of water yield were not absorbed by the Z parameter.

The modeling of water yield in the majority of hydrographic basins was satisfactory. The model allowed the order of importance of the basins in terms of water production to be determined despite underestimating precipitation. The basins with the highest water production were Zamora and Mayo, highlighting the importance of these basins in the study area.

20   However, because water yield was underestimated in some of the hydrographic basins of the study area, it is necessary to explore different algorithms for estimating precipitation and temperature at different spatial and temporal resolutions in order to determine the most ideal method for evaluating water yield in the southern region of Ecuador.

In the present study, point climate data were used and subsequently interpolated. These data mostly originated from meteorological stations located in the low parts of valleys. For this reason, to generate more accurate estimations of annual

25   water yield in the study area, it is necessary to increase the density of meteorological stations and to improve the spatial distribution of these stations.

Different Budyko approaches, including the framework used in the present study, have been developed for calculating long-term water balance (Hamel and Guswa, 2015). Further research studies should examine the effects of land use and cover changes on water production as well as the effects of climate changes in future projections.

30   In conclusion, the obtained results are an initial estimate of the water yield at the hydrographic basin level of the southern region of Ecuador. The results may have applications in different fields, including water supply services, hydroelectric energy production, in the identification of protection areas and the mitigation of water risk. In particular, these results can be used to

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evaluate the impacts of land use changes and climate change and to thereby facilitate the planning and local management of water resources in the long term.

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