CHAPTER 6

Participatory Monitoring of the Impact of Watershed Interventions in the Tropical Andes

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Introduction

This chapter documents the efforts of building the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA). First, we explain the background and motivations that led to the formation of a diverse consortium of institutions with a joint interest. Then we present

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the methodological approach that the monitoring network has adopted. Lastly, we discuss in brief the main results, the most relevant milestones and breakthroughs, and the major challenges remaining and perspectives in the scientific, technological and social domains. We argue that the correct use of the generated knowledge, from community level to national governance entities, proves crucial to increase catchment intervention efficiency and improve water resources management.

The tropical Andes are hotspots for ecosystem services provision and environmental change. The naturally high diversity of geographical and climatic characteristics results in equally variable and non-stationary hydrometeorological features (Vuille et al., 2000). These characteristics are closely related to the large portfolio of ecosystem services, especially in terms of the scale and variability of the discharge of rivers that support up- and downstream livelihoods. However, this region suffers from extensive data scarcity and an acute lack of understanding on how to leverage ecosystem services to support human development (Célleri and Feyen, 2009; Balvanera et al., 2012). One of the reasons for this is that the official national monitoring networks do not have an ecosystem assessment focus, and tend not to cover remote headwater areas (Célleri et al., 2010; Buytaert et al., 2016), and therefore are not ideal to study the nature, distribution and evolution of ecosystem services. These issues, in combination with rapid changes in land use and climate, as well as increasing population and water demand, put severe pressure on water resources (Buytaert and De Bièvre, 2012).

Changes in land use and land cover, which are driven by anthropogenic pressure from local users and by increasingly intensive watershed management, have a large impact on hydrology and ecosystem services. In the last decades, local research has delivered relevant knowledge about the natural hydrological regime of Andean catchments and the impacts of several human activities that are commonly detrimental to water yield and hydrological regulation, e.g., Luteyn (1992), Inbar and Llerena (2000; 2004), Díaz and Paz (2002), Hofstede (2002), Bruijnzeel (2004), Farley et al. (2004), Buytaert et al. (2002; 2004; 2005; 2006a; 2006b; 2007), Célleri et al. (2007), Favier et al. (2008), Quichimbo (2008), Tobón (2009), Crespo et al. (2010; 2011; 2012), Carlos et al. (2014), Córdova et al. (2015), Mosquera et al. (2015), Padrón et al. (2015), Ochoa-Tocachi et al. (2016a; 2016b). However, the effectiveness of different interventions in the region, be it in a context of ecosystem management, payment for ecosystem services, adaptation to climate change or investment in green infrastructure in watersheds, is far off from being thoroughly assessed or even fully understood. For instance, many catchment conservation strategies and common restoration efforts, such as re- or afforestation, have not been evaluated properly for their hydrological benefits and are often based on a very limited local evidence base. Additionally, those which consider the necessity of generating new knowledge about the natural environment, such as several climate change adaptation initiatives in mountain areas, are responding to information gaps by putting significant efforts in glacier monitoring. But the information gap for an effective watershed management in high-elevation and headwater areas persist, as such monitoring sites cannot capture the impact of interventions.

Emerging from a local awareness about the need for better information on ecosystem services, a partnership of academic and non-governmental institutions triggered the use of participatory hydrological monitoring to address this gap. In 2009, they formed the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA), which leverages the growing availability of inexpensive and robust sensor technology (Buytaert et al., 2014). The iMHEA network is a consortium of institutions interested in generating and strengthening the hydrological knowledge of Andean ecosystems to improve decision making on water resources management in this region. Increasing the knowledge of hydrology and meteorology in Andean catchments involves the implementation of new monitoring, in a way that ensures optimal complementarity with existing monitoring networks (Célleri et al., 2010). The iMHEA recognizes the role of water and environment authorities and of the offices of hydrology and meteorology as the rectors of water resources management in each country, and as a way to complement their efforts of data generation, they propose a bottom-up approach in which civil institutions can contribute with local scale and headwater monitoring.

The iMHEA network uses a design based on a 'trading-space-for-time approach' (Célleri et al., 2010; Buytaert et al., 2014; Ochoa-Tocachi et al., 2016b) illustrated in Fig. 6.22. This concept relies on strengthening the statistical significance of an intervention signal by monitoring several catchments in a regional setting (Buytaert and Beven, 2009; 2011; Oudin et al., 2010; Singh et al., 2011; Sivapalan et al., 2011; Wagener and Montanari, 2011). The increased number of monitoring sites also allows for a robust regionalization of the results by covering different ecosystems with diverse physiographic characteristics and contrasting land uses and degrees of conservation/alteration (Ochoa-Tocachi et al., 2016b). The proposal recommends the use of paired catchments, which allows comparisons on the short-term; however, single catchments can be monitored to analyze long-term changes using a baseline of several years to capture inter annual climatic variations and analyze non-stationarity.

In this way, the establishment of a 'minimum' hydrological monitoring in several sites is of a higher priority than implementing detailed monitoring in few locations. Such an indispensable monitoring consists of the measurement of rainfall and stream flow at high temporal resolution

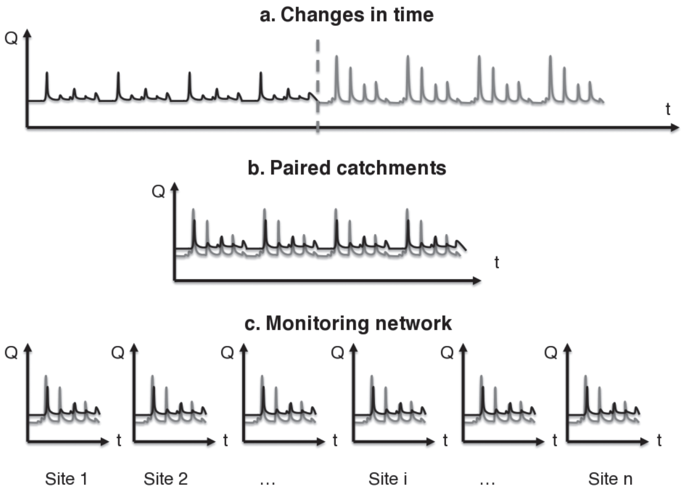
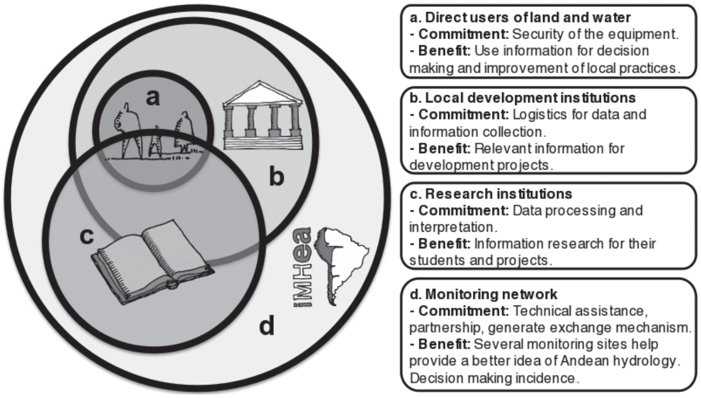


Fig. 6.22 Concept of space-for-time substitution. (a) Long-term monitoring allows to identify trends and changes in time when a perturbation has occurred. (b) Paired catchments reduce the monitoring length by adding a spatial variable to the analysis and comparing watersheds under contrasting conditions. (c) The replication of the perturbation in several sites or the consideration of different conditions in a monitoring network provides a robust framework in which to analyze impacts and facilitate the regionalization of results.

and at micro-catchment scale. To maximize the usefulness of these data for national hydrometeorological offices and local partners, the selected sites are commonly located in areas with low density of stations. The generated data will potentially have different characteristics and quality, which is determined by the specific purposes of the local partner; however, the high-spatial and short-temporal resolution of these data is highly compatible to the long-term and low-spatial density of national networks (Buytaert et al., 2016).

iMHEA aims to tackle data-scarcity in the Andean region by generating information using a participatory environmental monitoring framework. As such, iMHEA is not a formal network but is aimed mostly at promoting exchange of information and experience, and involves the movement of resources from different partners and funding sources. The good quality of the data is achieved through a partnership with research institutions (Célleri et al., 2010). Therefore, the entry threshold for local partners to the network is relatively low and accessible. The monitoring system includes an institutional agreement between local communities and users of water and land, local governments and institutions of development, research groups and universities, and monitoring networks at national and regional scales (Fig. 6.23). The engagement and experience of local users are critical for the success of monitoring activities, and the interaction between the several



a. Direct users of land and water
- **Commitment:** Security of the equipment.
- **Benefit:** Use information for decision making and improvement of local practices.

b. Local development institutions
- **Commitment:** Logistics for data and information collection.
- **Benefit:** Relevant information for development projects.

c. Research institutions
- **Commitment:** Data processing and interpretation.
- **Benefit:** Information research for their students and projects.

d. Monitoring network
- **Commitment:** Technical assistance, partnership, generate exchange mechanism.
- **Benefit:** Several monitoring sites help provide a better idea of Andean hydrology. Decision making incidence.

Fig. 6.23 Institutional agreement in a participatory monitoring framework. The diverse partners in the network commit to different activities depending on their capacities and resources and obtain benefits for their own objectives and purposes.

different stakeholders is necessary to achieve long-term sustainability. The involvement of local universities and research groups working in the areas of influence guarantees scientific rigor and robustness in the generated data. This interaction between the general public and traditional scientists is often referred to as citizen science (Buytaert et al., 2014), and has a strong potential to tackle data-scarcity in remote regions, such as the tropical Andes.

Lastly, a key element of the philosophy of iMHEA is that "information that is not shared is useless". Therefore, as a fundamental principle, the generated data and the derived knowledge is shared in common standards and at different levels. The information produced at a local scale can be used to draw regional conclusions about the hydrology of the Andes. This monitoring system aims to generate data at mid- and long-term to allow analyses of hydrological changes in time and consistent support of decision making. The iMHEA holds annually an Assembly of stakeholders to provide a space for reflection and action, as well as organizes international courses on Andean hydrology and hydrological monitoring for diverse audiences. Consequently, the newly generated information and knowledge can be useful and usable to achieve the objectives of water and land users, local partners, research groups and national institutions.

In this chapter, we present the methodological guidelines for a participatory hydrological monitoring of Andean ecosystems. The objectives of this hydrological monitoring system are to ensure that the observatories in each watershed will generate standardized data that can be used in future studies and assessments of ecosystem services. Such objectives are: (i) to increase the knowledge about hydrological ecosystem services in Andean watersheds, especially but not limited to water availability and hydrological regulation; and (b) to increase the knowledge about the impacts of watershed interventions (i.e., changes in land use and land cover, adaptation measures, deforestation, afforestation, restoration, etc.). Once good base information about hydrological processes and their relations exists, different models can be calibrated adequately with these data to support extrapolation and regional analyses (Ochoa-Tocachi et al., 2016b).

Hydrological Monitoring Setup

Monitoring methodology

In order to support the technical aspects of setting up the monitoring and to maximize the compatibility and consistency of data produced by each location, a core team within iMHEA designed a detailed monitoring protocol (Fig. 6.24).

The minimum variables to be monitored are:

- Catchment physiographic characteristics.
- Rainfall inside the catchment.
- Stream flow at the outlet of the catchment.

With this information, a simple water balance equation can be used to estimate the total amount of water consumed by vegetation, evaporated from free water surfaces, infiltrated to the deeper soil strata and stored in the soils. The length of monitoring (at least one hydrological year) and the impermeable rocks generally found beneath the soils of Andean catchments (Buytaert et al., 2007), allows the assumption of equilibrium in the sub surface storage volumes. Therefore, the difference between rainfall and stream flow can be considered as a good approximation of the evapotranspiration in the catchment.

However, such assumption may not necessarily be true in all cases. Deep permeable soils may occur in some regions sustaining large aquifers (Buytaert et al., 2006b; Favier et al., 2008). Therefore, a careful selection of the catchments, ideally with the assessment of an experienced hydrologist, would help minimize potential issues due to the simplification of the water balance or to monitor those elements that influence greatly on such balance (Fig. 6.25(a)).

At the same time, this protocol recommends the monitoring of the hydrological variables using automatic electronic equipment supported by manual measurements. It has been observed that automatic measurements are more cost-effective than manual measurements (Célleri et al., 2010; Buytaert et al., 2014). Nevertheless, electronic equipment is also prone to failure or decalibration, in which cases the use of manual measurements guarantees a correct quality control and validation of the generated information.

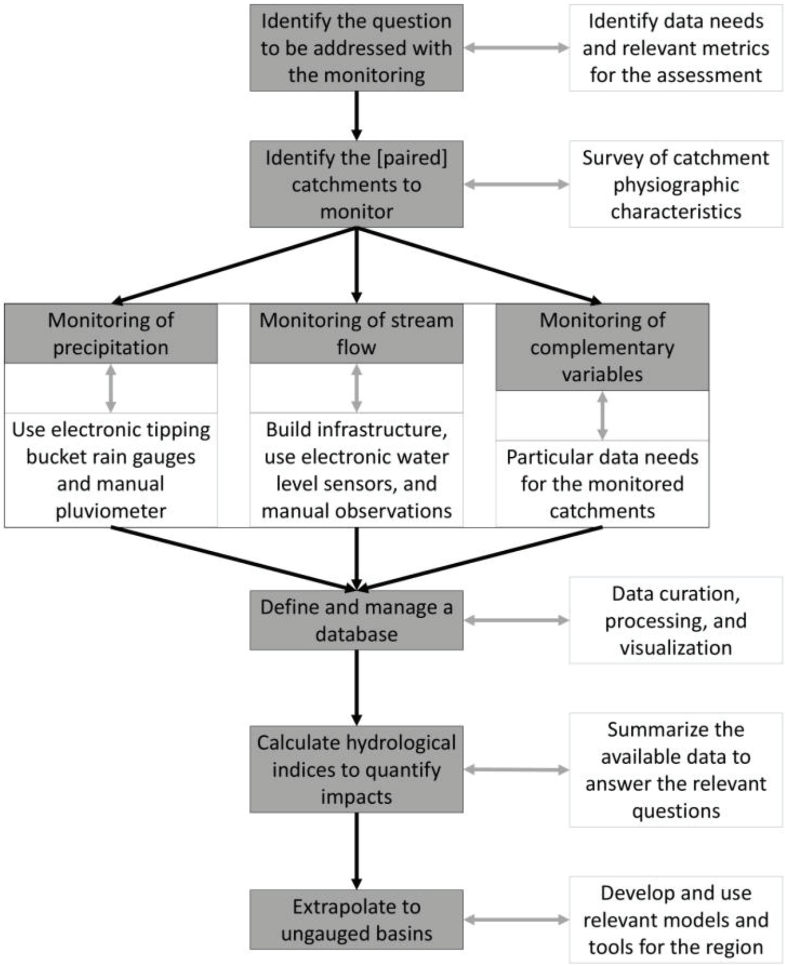


Fig. 6.24 Flowchart of procedure steps for the evaluation of watershed interventions. These steps are explained in detail in the monitoring protocol.

~~Physiographic Catchment~~ Characteristics

The main physical catchment attributes must be surveyed at the beginning of the monitoring project. The outlet of the catchment is defined at the point where the flow gauging station will be located. The key physiographic characteristics are: (i) those necessary to understand the functioning of the catchment (e.g., area, elevations, slopes, soils); and (ii) those necessary to compare with other catchments (e.g., land use and land cover, watershed interventions, special features). Generally, this characterization is done thoroughly once at the beginning of the project, due to the slow rate of

Fig. 6.25. Pictures ~~of equipment and catchments in the iMHEA network~~: (a) Selection of monitoring catchments in Tambobamba, Peru, by a group of hydrologists, local partners and users of land and water. Photo: Boris Ochoa-Tocachi, 2011. (b) Example of a tipping bucket rain gauge with a resolution of 0.2 mm installed in Lloa, Ecuador. Photo: BOT, 2014. (c) Local partners of iMHEA installing a rain gauge in Piura, Peru. The rain gauge accuracy is revised using static and dynamic calibration methods on a regular basis. Photo: BOT, 2012. (d) A weir located at the outlet of an iMHEA catchment in Ica, Peru. The V-shaped section of the weir allows an accurate monitoring of low flows. Photo: Junior Gil-Rios, 2015. (e) A weir located at the outlet of an iMHEA catchment in Huaraz, Peru. The composite triangular-rectangular section allows the monitoring of high flows. Photo: JGR, 2014. (f) A weather station is located at a central location between the iMHEA catchments in Lloa, Ecuador. The monitoring of several climatic variables, in this case temperature, relative humidity, solar radiation, wind velocity and direction and rainfall, allows for a more accurate calculation of evapotranspiration. Photo: BOT, 2014. (g) Example of a tipping bucket rain gauge in Lloa, Ecuador, with some litter retained in the filter. Photo: BOT, 2014. (h) Hydrological monitoring of two catchments under different levels of conservation/alteration in Cochabamba, Bolivia. A local farmer contrasts visually (left) a highly degraded catchment produced by cultivation and overgrazing, against (right) a relatively conserved catchment situated closely to the former. In what we refer to as the 'Placebo iMHEA effect', local users recognize the relevance of monitoring impacts, even before seeing any data. ~~This has supported the implementation of new monitoring sites and the implementation of water conservations practices more smoothly.~~ Photos: Luis Acosta, 2012. (i) Highly seasonal catchment in Tambobamba, Peru. In puna, the landscape is markedly different during the (left) dry season and the (right) rain season. Photos: BOT, 2012, 2013. (j) An International Course on Andean Hydrology and Hydrological Monitoring organized by Nature and Culture International, CONDESAN, the University of Piura, Peru, and iMHEA in Piura in 2013. Photo: BOT, 2013. (k) A group of farmers in a meeting with local decision makers and hydrologists from iMHEA in Pacaipampa, Peru. Photo: BOT, 2012.

change in such parameters, but it can be updated periodically if necessary (e.g., annually).

The main characteristics are:

- Catchment area and shape (indicating the calculation method, for instance, using a topographical map at 1:10,000 scale or GPS surveying).
- Elevation map, maximum and minimum points (location of the flow gauging station).
- Average catchment and riverbed slopes (indicating the calculation method).
- Initial characterization of land use and land cover (indicating the areal percentage of land cover, the land uses identified in the catchment, and the identification method).
- Soils and geology maps and characteristics (especially soil hydrophysics).
- Special features that can influence in the occurring hydrological processes (e.g., permeable bedrocks), or in other hydrological ecosystem services (e.g., important sediment transport and deposition due to the presence of roads).

This information can be organized using a standard iMHEA Inventory Form for each monitored catchment. A map of the catchment(s) at an appropriate scale must contain these elements, including the location of any equipment, monitoring points and operational routes.

Monitoring of Precipitation

Rainfall is the main component of precipitation in Andean catchments (Padrón et al., 2015), and is monitored using electronic tipping bucket rain gauges (Fig. 6.25(b)) and validated with manual measurements using a pluviometer. The rain gauges must have a resolution of at least 0.254 mm (0.1 in), but typically 0.2 mm and ideally 0.1 mm. Each rain gauge provides event rainfall data (time to tip), which is then aggregated at fixed time intervals depending on the posterior analysis. Such aggregation can be done simply by counting the number of tips during a time period or using linear interpolation (Ciach, 2003) or other techniques, for instance, a composite cubic spline interpolation on the cumulative rainfall curve (Sadler and Brusscher, 1989; Wang et al., 2008).

A correct measurement of precipitation, which implies regional representativeness, is conditioned by several factors such as reducing wind effects (World Meteorological Organization, 2012). The location of rain gauges must be chosen in such a way that wind velocity at the flume is as low as possible. When possible, both the rain gauge and the manual pluviometer should be protected against wind effects in all directions using natural or artificial elements but located at a distance of at least twice the height of such elements to avoid rainfall interception. Additionally, the rain gauge must be leveled and installed at a standard height of 1.50 m above the ground (Fig. 6.25(c)).

The manual pluviometer must have a ruler with minimum graduations of 0.2 or 0.1 mm (i.e., the same as the automatic rain gauge resolution). To ensure accurate measurements, the maximum error of such graduations must not exceed ± 0.05%. In areas with snowfall occurrence, the equipment must be located above the maximum expected snow height accumulation in the ground. Additionally, an antifreeze substance must be used to melt ice and snow falling in the pluviometer without exceeding one third of its total capacity. On the other hand, to avoid evaporative losses from the pluviometer, the equipment must minimize heat absorption (e.g., using clear colors that reflect most on the incident sunlight), and could use a thin layer of oil (≈ 8 mm) to prevent evaporation.

Monitoring of Stream Flow

Discharge is usually estimated as a function of water level at a gauging station, which has the function to facilitate the generation of continuous and systematic measurements to calibrate a stage-discharge curve (World Meteorological Organization, 2008). The water level is monitored using automatic electronic sensors, mainly pressure transducers and ultrasonic devices, and validated with manual observations. The gauging station must feature a control section (e.g., a weir or a stable river section) with known geometric characteristics unchanged over time, and able to contain the total discharge at the outlet of the catchment (Fig. 6.25(d)). The manual observations must be obtained using a ruler with graduations of 1 mm.

In mountain streams with moderate flows, such as those in Andean catchments, the discharge can be monitored using a sharp-crested weir equipped with automatic pressure transducers. The composite weir would feature a V-shaped section for low flows and a triangular-rectangular section for high flows (Fig. 6.25(e)). In lowland streams with sustained high flows and important sediment transport, such as those in Andean-Amazonian catchments, a weir is not recommended. After an appropriate hydrological assessment, the gauging station can be placed in a completely stable natural river section or building a canal structure such as a Parshall flume to avoid sediment deposition. The use of ultrasonic water level sensors is also recommended in this case.

The World Meteorological Organization (2008) recommends the following for the location of the flow gauging station:

- Identify a straight reach of approximately 100 m upstream and downstream to the monitoring station. This is sometimes impractical in Andean catchments, where reach lengths of approximately 10 m have been sufficient to provide stable values of discharge.

- The total flow must be confined in the control section for the entire range of water stage, avoiding the occurrence of subsurface flow.
- The control section must avoid erosion, sediment deposition and changes in geometry.
- The riverbanks must be stable and sufficiently tall to contain floods.
- In the case of using a weir, the water level must be monitored upstream of the control section at a distance of at least three times the maximum water level above the crest to avoid effects from the contraction of the water sheet.
- The velocity of water approaching the weir must be less than 0.15 m s^{-1}.
- Strong water level fluctuations in the stream surface must be avoided.
- The station should be sufficiently secure and accessible to allow taking measurements even when there is presence of ice, solids, sediments or high floods.

To calibrate the stage-discharge curve (World Meteorological Organization, 2012), simultaneous measurements of discharge and water level are needed along a range of flow rates. Although a control structure can be used in the gauging station, the theoretical equation needs to be calibrated under operational conditions to reduce errors in the estimation of discharge (USDI Bureau of Reclamation, 2001). When flows are low, a volumetric method can be sufficient to estimate the discharge by dividing a measured volume over a period time. When flows are moderate and laminar, the discharge can be measured using the velocity-area method dividing the gauging section in several subsections and measuring velocity at different depths. When flows are high and turbulent, a dilution gauging method can be used, for instance, using table salt and measuring the electric conductivity that is related to substance concentration and discharge. In all cases, the discharge measurements must be repeated consecutively at least three times recording the water level, date and time of each observation.

Other monitored variables

Although not required ~~by the iMHEA protocol~~, many iMHEA partners engage in monitoring of other variables, which provide added value for their particular management context. Examples include (i) monitoring of other meteorological variables such as temperature, humidity and wind speed/direction, (ii) soil properties, (iii) geological characterization and, (iv) tracer monitoring.

An approximation of evapotranspiration can be obtained using rainfall and stream flow on an annual basis, shorter-term time scales would require local meteorological data to improve the calculation, e.g., (Córdova et al., 2015). These data generally include air temperature, relative humidity, solar radiation, wind velocity and direction and air pressure. A weather station can be located at a central location within a catchment or a group of catchments, generating data at least at an hourly basis (Fig. 6.25(f)).

At the same time, the effects of different watershed interventions on local hydrological ecosystem services are strongly linked to their impacts on soil properties. For example, soil compaction under overgrazing (Sarmiento, 2000; Díaz and Paz, 2002; Quichimbo, 2008) or enhanced soil infiltration in forested catchments (Bruijnzeel, 2004; Tobón, 2009; Beck et al., 2013a). Therefore, an extensive characterization of soil properties can improve the understanding of local hydrological processes. Similarly, an accurate identification of geologic influences (e.g., permeable rocks, aquifers, faults) can improve the posterior interpretation of results. This characterization can be complemented with tracer monitoring, for instance, using natural occurring isotopes (Mosquera et al., 2015).

Considerations for the Monitoring Design and Operation

Spatial scale, density and coverage of monitoring stations

It is important to obtain data at scales that are hydrologically representative of the ecosystems in the surrounding area. Commonly, the catchment of interest hosts various ecosystems or land uses (e.g., grasslands, forests, degraded areas, plantations), and thus the observed variables may not capture the hydrological signals of individual characteristics. In this case, it is difficult to attribute the stream flow response to a single land use or land cover that impacts on the hydrological functioning of an ecosystem.

Ideally, a catchment must host a homogeneous land use and land cover; however, this may be problematic in practice, especially for large catchments. For instance, Bosch and Hewlett (1982) found that impacts on stream flow due to changes in forest cover of less than 20% cannot be detected. Therefore, this protocol recommends that the monitored catchments must be smaller than 15 km^2 and have a single land use or land cover in at least 80% of their areas.

Similarly, other problems are present in small catchments (< 0.2 km^2). For example, in high Andean grasslands with significant wetland areas, sub surface water flow can become important. As only a fraction of the total discharge is effectively measured, the unmonitored circulation of water in the soil without draining to a common stream would invalidate the assumption considered to close the water balance. Another problem of small catchments is their regional representativeness, for instance, in terms of slopes, shape, storage capacity, or water yield, e.g., Mosquera et al. (2015), which could complicate the extrapolation of results to larger catchments

(Ochoa-Tocachi et al., 2016b). In any case, the design must ensure that the total outflow can be monitored at the outlet of the catchment, avoiding zero-order basins, i.e., catchments without a permanent, defined discharge canal.

In terms of equipment, the number of stations necessary to measure rainfall depends on the catchment area and the expected spatial rainfall variability therein. For instance, Buytaert et al. (2006a) and Célleri et al. (2007) have found great differences in precipitation at small distances in mountain catchments of southern Ecuador. In these cases, a sub- or an over-estimation of total rainfall can lead to an erroneous application of the water balance equation, and thus to draw mistaken conclusions about the impacts of different watershed interventions. Furthermore, Padrón et al. (2015) argue that tipping bucket rain gauges may underestimate total precipitation by around 15% when rain falls mainly as low intensity events.

As a general rule, at least 2 rain gauges must be installed in each catchment even when these are small (< 1 km^2). Most of the iMHEA monitoring sites are equipped with 3 rain gauges at representative low, middle and high elevation points within the catchments (Ochoa-Tocachi et al., 2016a). This also allows to validate and correct the measurements or fill data gaps when one of the sensors fails, for example, due to battery or memory issues or inlet obstructions.

Frequency of Automatic Data Acquisition

Due to the rapid hydrological response of small catchments to precipitation events, flows can reach peak values in only a few minutes. Therefore, the frequency of data logging must be high, minimum at an interval of 15 minutes, but ideally 5 minutes. Most of the iMHEA's sites generate data at a high temporal resolution of 5 minutes, in order to identify impacts on the short-term hydrological regulation that can pass unnoticed on daily aggregated indices (Ochoa-Tocachi et al., 2016a).

Data stored by automatic sensors must be gathered approximately once a month. Although the most advanced sensors may have the capacity to store large amounts of data, the tough climatic conditions of Andean catchments increase the need of sensor maintenance. For example, some technicians have reported obstructions in the rain gauge flumes due to the presence of forest litter or small animals even in shorter periods (Fig. 6.25(g)). Another problem can be the limited capacity of batteries and data loggers to function for longer periods. Both issues may result in the loss of important data between the visits.

Monitoring Design for Impact Evaluation

Two general approaches are common to assess the impacts of land use and land cover change ~~(LUCC)~~ or other watershed interventions on local hydrology (McIntyre et al., 2014): long-term analysis and paired catchments. However, in both cases quantifying these impacts is complicated by the difficulty of distinguishing the effects of changes in land use from those that are due to natural climatic variability or other confounding factors (Ashagrie et al., 2006; Bulygina et al., 2009). In long-term analysis, even though the same catchment is monitored before and after the change, the influence of natural climatic variability may be different during the two considered periods (Lørup et al., 1998). This is solved in the second approach by monitoring the paired catchments under the same climatic conditions and different land uses. However, all watersheds are unique and land use is not the only factor that affects their hydrological responses (Bosch and Hewlett, 1982; Thomas and Megahan, 1998; Beven, 2000; Brown et al., 2005; Adams et al., 2012; Biederman et al., 2015). In iMHEA, although some sites have robust combined before-after-intervention-reference setup (Fig. 6.26), impact of an intervention is evaluated based on spatial comparison rather than changes over time. On balance, the ability of paired catchments to deliver more rapid answers, makes it the preferred approach.

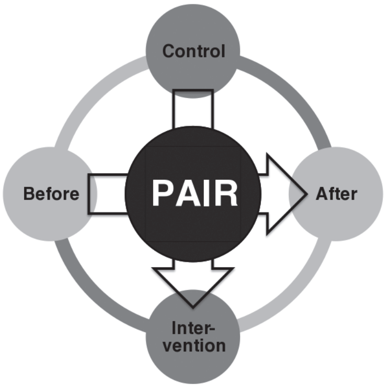


Fig. 6.26 The ideal design of the paired catchments involves the temporal (before-after) and spatial (control-intervention) dimensions. Although the definition of a baseline is more robust under this design, a simpler setup of 'control-intervention' has proved useful in many cases.

Paired-Catchment Monitoring

To understand the impacts of contrasting watershed interventions (e.g., different land use types), this protocol recommends the use of paired catchments. This design is based on the comparison of the hydrological responses of two catchments, where one acts as a reference of a particular state and the other represents the intervention to be assessed. For example, natural vs cultivated catchments, degraded vs restored catchments or forested vs grassland catchments. Each catchment must be equipped following the guidelines previously indicated.

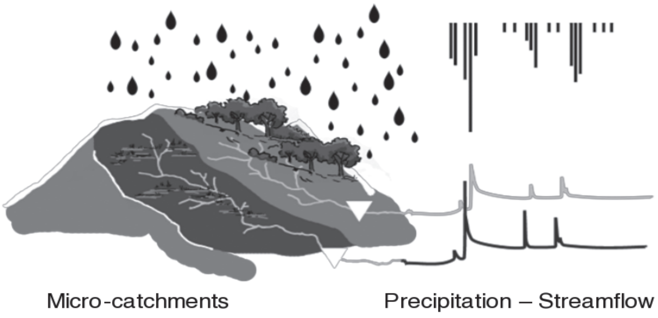


Fig. 6.27 Conceptual representation of the paired catchment setup. Under this design, catchments are commonly collocated to minimize climatic differences. The resulting hydrographs that characterize their hydrological responses are compared to identify the impacts of different watershed interventions.

Under this design, catchments are selected in such a way that their size, topography, soils, climate and other factors are as similar as possible, ~~being~~ the watershed intervention ~~the~~ only significant difference ~~between them~~. In this way, the discrepancies found (if present) in discharge values or in the water balance can be attributed to such differences (Fig. 6.27). To limit the variability in climatic and soil conditions, the catchments must be located as close as possible to each other. This also reduces the efforts in maintenance and operation works.

Au.: Pl rephrase, meaning not clear

A major advantage of the paired catchment design is that important differences in their hydrological responses can be identified in relatively short time periods (e.g., 1 year), feeding rapidly into the decision-making process. A careful analysis and interpretation of the results is necessary to avoid an erroneous attribution of hydrological response impacts that are due to other confounding factors.

Figure 6.28 shows an example of a paired catchment design in northern Ecuador. The two selected catchments, Quebrada del Volcán (221 ha) and Quebrada Kachiyaku (179 ha), are equipped with 1 weir with pressure transducers and 2 rain gauges each, and 1 meteorological station that has been placed in a central location (Fig. 6.25(f)). The monitoring is projected to be maintained on the long-term to understand the ongoing hydrological processes of these ecosystems, identify differences due to land use and land cover, and to characterize subsurface water exchange mechanisms between the catchments.

Long-Term Monitoring

To understand changes in the hydrological response of a catchment over time (i.e., non-stationarity), ~~a single catchment can be monitored using the recommended instrumentation~~. Although the principle of this protocol

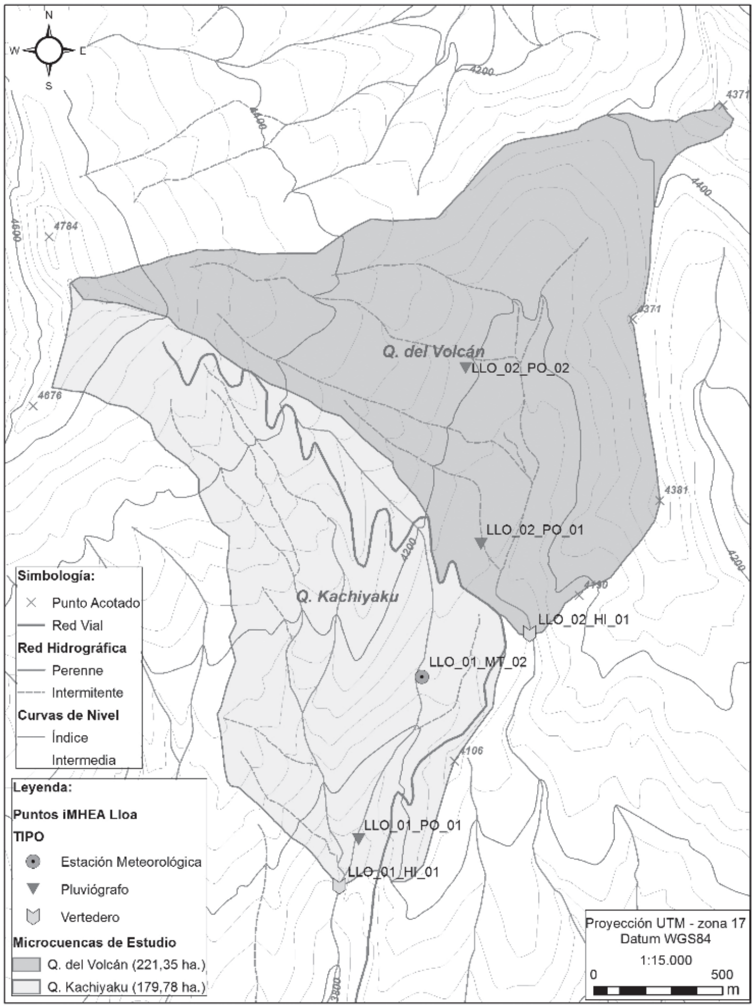


Fig. 6.28 ~~Example of the iMHEA paired catchments monitored in Lloa, Ecuador.~~ This site aims to understand the hydrological processes occurring in the humid páramo of northern Ecuador, including the impacts of grazing exclusion, restoration efforts and deep water infiltration in the soils.

is to draw significant conclusions in the short term using space-for-time substitution, the long-term monitoring of the individual catchments can reveal important information. For example, many restoration efforts will show results after several years, which can be contrasted to an initial baseline. Under this design, the sustainability of the monitoring sites is extremely important, and surely benefits from a participatory approach and a strong institutional agreement.

It is important to differentiate between controlled interventions (e.g., restoration efforts) and uncontrolled changes (e.g., climate change), and between immediate impacts (e.g., infrastructure construction) and sustained changes (e.g., land-use change). Moreover, the monitoring should be set up ideally before the change to be assessed in order to generate a robust baseline that allows for a meaningful comparison of long term effects. A sensible combination of the paired catchment setup in the long term may reveal significant results of the evaluated interventions (Fig. 6.22).

Data Processing and analysis

Defining and managing a database

A quality control of the generated data must be done immediately after the data has been downloaded at every visit in order to identify errors (e.g., data outside the expected measurement range, such as negative water level values) or suspicious measurements (e.g., extreme rainfall intensities). Data must be curated thoroughly before their use in any posterior analysis. These data should feed a structured and organized database that could potentially have different purposes and users (Buytaert et al., 2012).

The high-resolution time series aggregated at different time intervals (5, 15, 60 minutes, or 1 day) may represent a large amount of information in the long term. However, it is imperative to store the finest resolution data to avoid losing important information that can be used in other studies not necessarily thought at the beginning of the project. For instance, a local partner may need daily values that can be obtained by aggregating the high-resolution data; however, disaggregating information from a larger to a shorter interval is not impossible without very restrictive assumptions that could invalidate the results or input large uncertainties. Furthermore, the high-resolution data can capture rapid hydrological processes and changes therein that can be omitted in aggregated indices (Ochoa-Tocachi et al., 2016a).

Hydrological Indices to Quantify Impacts

Hydrological indices are commonly used to summarize the hydrological response of a catchment, its state of conservation, and the impact of alterations. A large set of indices (also referred to as 'signatures' ~~in hydrological literature~~) exist in the scientific literature, e.g., Walsh and Lawler (1981), Hughes and James (1989), Poff and Ward (1989), Richards (1989; 1990), Poff (1996), Poff et al. (1997), Richter et al. (1996; 1997; 1998), Clausen and Biggs (1997; 2000), Wood et al. (2000), Gippel et al. (2001), Baker et al. (2004), Mathews and Richter (2007), Beck et al. (2013a). Poff and Ward (1989) and Richter et al. (1996) defined five main components of the flow regime: (i) magnitude, (ii) frequency, (iii) duration, (iv) timing, and (v) rate of change in flow events. Olden and Poff (2003) have extended this classification with sub categories for average, low and high flows, and analyzed index redundancy and multicollinearity.

In the Andes, the great spatial variability of climatic conditions and the only recent development of research on Andean hydrology have delayed the development of indices to evaluate the hydrological response of these catchments. However, the emergent generation of large amounts of data requires the synthesis of information in a reduced set of hydrological indices that can reflect clearly the impacts of human interventions. Moreover, decision makers and local stakeholders require the presentation and visualization of results and the quantification of ecosystem services, including the associated uncertainty, in a common and understandable language. For instance, the water yield can be characterized by the runoff ratio, whereas the hydrological regulation is usually quantified in means of the base flow index and the slope of the flow duration curve (Sawicz et al., 2011; Ochoa-Tocachi et al., 2016b; Visessri and McIntyre, 2016). The calculation and use of hydrological indices to evaluate ecosystem functioning are simpler than other types of indicators (Pyrce, 2004), such as hydraulic evaluations, habitat assessment or holistic approaches.

To optimize the available information, indices must be selected in such a way that they are relatively independent (Sefton and Howarth, 1998; Bulygina et al., 2009), well-defined to minimize ambiguity (Olden and Poff, 2003), and susceptible to represent the impact of changes in the catchment (Archer et al., 2010). The use of indices to characterize the impacts of land-use change on the hydrological response of Andean catchments can be seen in Ochoa-Tocachi et al. (2016a).

Data Processing

Different methods exist to interpolate the tipping bucket rainfall data, but a commonly used method uses a composite cubic spline interpolation applied to the cumulative rainfall curve and then aggregated at different time steps. This allows a smoother estimation of rainfall intensities than simply counting the number of tips in a determined interval of time, which is deemed more realistic (Fig. 6.29). A 1-minute or 5-minutes moving window can be used to extend the calculation of rainfall intensities for different event durations under consideration. The normalized seasonality index (Walsh and Lawler, 1981) ranging from 0 (non-seasonal) to 1 (extremely seasonal) can be used to compare rainfall regimes between several catchments.

The discharge data must be normalized prior to any comparison between catchments, for instance, dividing by the catchment area (units of mm or $l\ s^{-1}\ km^{-2}$). For the calculation of some indices (e.g., runoff ratio) or

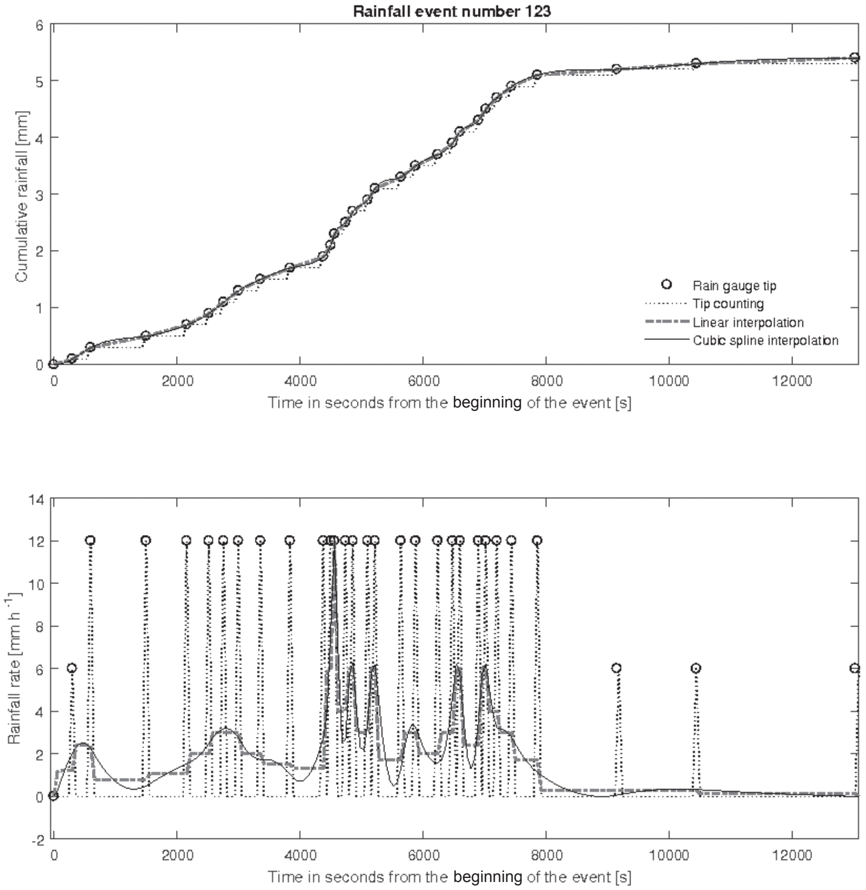


Fig. 6.29 Example of the calculation of 1-minute rainfall intensities based the tipping bucket rain gauge data. The simple tip counting provides a good calculation of rainfall totals but fails to provide realistic intensity estimations. Linear and polynomial interpolation techniques can be used to obtain a continuous time series of rainfall intensities that are considered a more accurate representation of real conditions.

to apply the water balance equation, flow units are transformed to match the rainfall units (mm). Daily flows can be used to calculate Flow Duration Curves (FDC) and corresponding percentiles. Three indices are commonly considered in several hydrological studies and for watershed management:

- The Runoff Ratio (RR), calculated as the relation between average annual discharge and average annual rainfall, and represents an indication of water yield.
- The Base Flow Index (BFI), calculated as the ratio between base flow to total flow, e.g., Chapman (1999), Kabubi et al. (2005), Willems (2014),

and can be associated to the short-term hydrological regulation at event scale.

- The slope of the FDC, calculated between the 33rd and 66th flow percentiles in logarithmic scale, commonly used as an indicator of hydrological regulation (Olden and Poff, 2003; Ochoa-Tocachi et al., 2016b). For example, a steep slope may indicate high flashiness in the hydrological response to precipitation events, whereas a flatter curve may represent a buffered behavior and larger storage capacity (Buytaert et al., 2007; Yadav et al., 2007).

Extrapolation to Ungauged Areas

Although several stakeholders are interested in data for specific watersheds, it is impractical to monitor every single catchment due to several constraints, such as the limited amount of resources. However, it is possible to regionalize the results obtained from the monitoring of individual catchments to a broader context based on their hydrological similarity (Sawicz et al., 2011) in contrast to their physical similarity, see also Muñoz et al. (2016). The objective of such relationships is not only to reduce the monitoring efforts (Correa et al., 2016), but to estimate and predict the hydrological response of ungauged catchments and the effects of different watershed interventions before their implementation. This allows for approximating several impacts by relating the information generated in a group of representative sites, including a quantification of the uncertainty associated with these estimations.

Regional analyses are used to generalize results from data gathered in the few monitored sites to ungauged basins and to account for differences due to catchment uniqueness and spatial variability (Sivapalan, 2003; Beck et al., 2013b). Two examples of regional models that are widely used in other regions are the BFIHOST in the UK (Boorman et al., 1995) and the Curve Number in the US (USDA, 1986). Predictions in ungauged basins can be done through different methods (Parajka et al., 2013; Visessri and McIntyre, 2016), from which two regionalization approaches are widely used (Bulygina et al., 2009; 2011; 2012):

- relationships between catchment attributes and model parameters, e.g., Lamb and Kay (2004), McIntyre et al. (2005), Parajka et al. (2005), Lee et al. (2006), Wagener and Wheater (2006), Young (2006), Beven (2007), Wagener (2007), Buytaert and Beven (2009); and,
- relationships between catchment attributes and hydrological indices, e.g., Berger and Entekhabi (2001), Brandes et al. (2005), Mazvimavi et al. (2005), Shamir et al. (2005; 2005), Bárdossy (2007), Yadav et al. (2007), Longobardi and Villani (2008), Oudin et al. (2010), Zhang et

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al. (2008), Peña-Arancibia et al. (2010), van Dijk (2010), Krakauer and Temimi (2011), Ahiablame et al. (2013), Visessri and McIntyre (2016).

The second approach has been implemented to the iMHEA network of paired catchments, where significant relationships were found between variables that describe land use and land cover and most of the tested hydrological indices (Ochoa-Tocachi et al., 2016b). Combining the paired catchment setup with the common regionalization approach ~~proved~~ useful to improve both approaches (Fig. 6.30). Therefore, this design is seen as a useful strategy to optimize data collection to support and improve watershed interventions in data-scarce regions, such as the tropical Andes.

Current State of the iMHEA Network and Preliminary Results

Using a design based on a trading-space-for-time approach, over 30 catchments are currently being monitored for precipitation and stream flow by 18 local stakeholders in 15 sites located in Bolivia, Peru, Ecuador and Venezuela (Fig. 6.31). Where possible, one catchment is chosen such that it is representative for a reference state, while a second catchment represents the practice to be evaluated. The reference state may refer to either a conserved condition in contrast to ~~LUCCD~~, or a degraded catchment without restoration activities or watershed management (Fig. 6.25(h)). The network focuses on small, homogeneous headwater catchments (between 0.2 km^2 and 10 km^2) with a single land use or intervention in at least 80% of its area. As observed in Buytaert et al. (2016), the data generated by iMHEA is highly complementary to that of hydrometeorological stations. Figure 6.32 shows rainfall data in the Piura Basin from SENAMHI, the National Service of Meteorology and Hydrology of Peru, with stations located from 0 to 3000 masl and from iMHEA with stations between 2500 and 3800 masl. It is clear that the estimated rainfall trend (linear regression) as fitted on the SENAMHI stations underestimates precipitation in the highlands, and that the definition of climatic zones in official documents, e.g., Autoridad Nacional del Agua (2012) is far from realistic without the inclusion of the newly generated data.

As expected, the analyzed data clearly reflect the dominant regional climate patterns and the extraordinary wide spectrum of hydrological response behavior of the tropical Andes. Ochoa-Tocachi et al. (2016a) have summarized this range contrasting the perennially humid, highly buffered stream flow behavior of wet páramos with the strongly seasonal, flashy stream flow response of the drier puna (Table 6.12; Fig. 6.33). Rainfall seasonality is controlled by latitude, with minimum values of the seasonality index observed in the transition between the páramo and the puna biomes, especially in the region of the Andes where elevations are the lowest facilitating air fluxes. In other areas, the influence of the

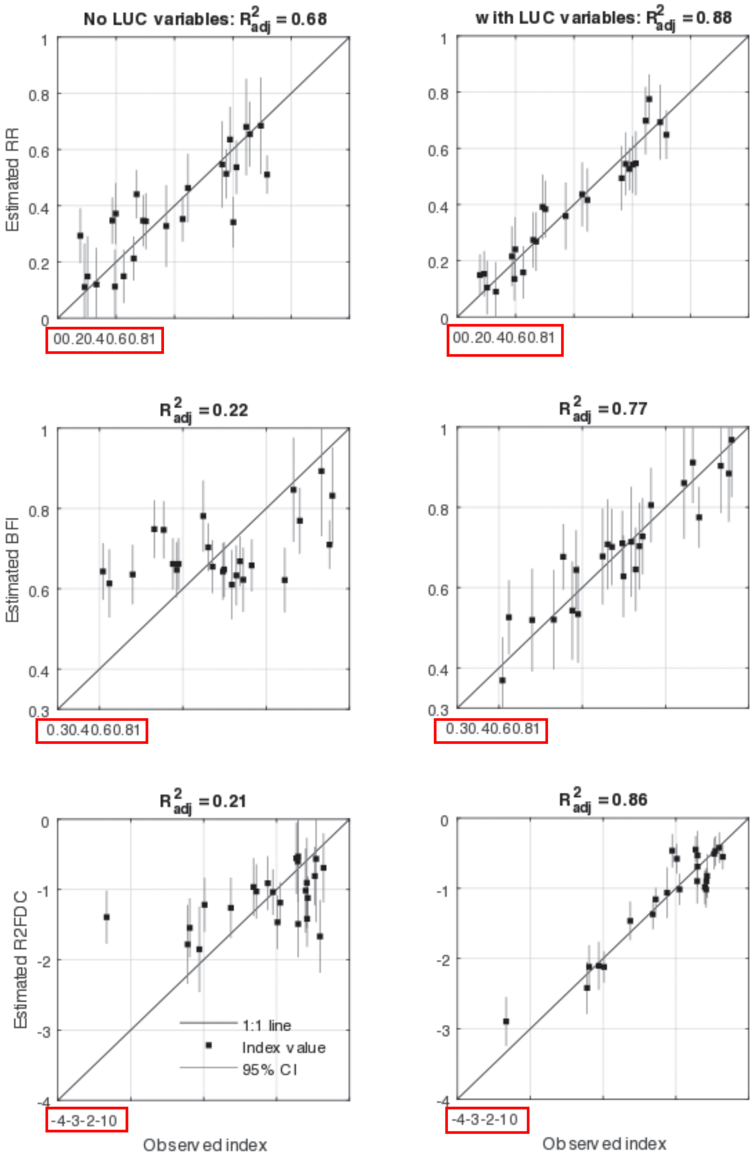

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Fig. 6.30 Effects of including land use and land cover variables in the regional regressions derived using the iMHEA catchments. As shown for the runoff ratio, the base flow index and the slope of the flow duration curve, the inclusion of land use and land cover variables improve the regression performance and reduce the associated uncertainty significantly.

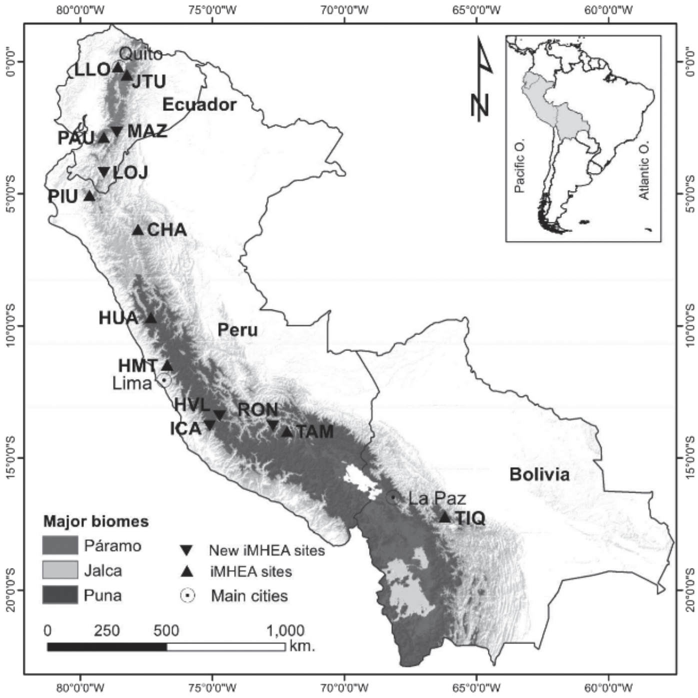

Fig. 6.31 Map of the tropical Andes and location of the iMHEA monitoring sites. Those represented a black up-pointing triangle where included in an assessment of the impacts of land use on the hydrological response of Andean catchments (Ochoa-Tocachi et al., 2016a), and where used to test the usefulness of paired catchments to regionalize land-use signals on stream flow (Ochoa-Tocachi et al., 2016b).

Amazonian warm and humid air masses contrasts to the cold and dry Pacific regime, generating notorious dissimilarities in both sides of the Cordillera (Fig. 6.25(i)). Despite these differences, natural Andean catchments are characterized by high runoff ratios, indicating large water yields (Buytaert et al., 2007; Mosquera et al., 2015), and ~~flat profiles~~ of the FDC, which are associated with a good hydrological regulation capacity and a base flow dominated response (Buytaert et al., 2006b; Crespo et al., 2011).

Similarly, the impacts of land use are found to be influenced by several factors, such as the catchments' physiographic characteristics, the original and replacement vegetation cover and soil properties and changes therein. Such impacts commonly result in more variable stream flows and in reduced water yields and worse hydrological regulation (Ochoa-Tocachi et al., 2016a). Despite the hydrological properties of the original biome, the

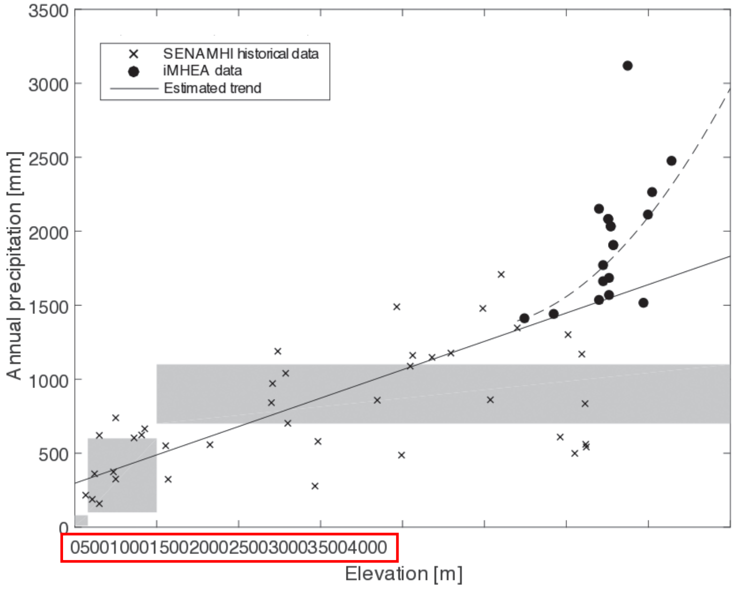

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Fig. 6.32 Rainfall data from SENAMHI and iMHEA showing the complementarity of information generated by multiple sources in a polycentric approach (Buytaert et al., 2016).

effects of common human activities in the different Andean catchments are consistent (Fig. 6.34). It has been observed that cultivation increases flashiness and reduces low flows in particular (Sarmiento, 2000; Buytaert et al., 2007). Grazing effects depend on animal density and may pass unnoticeable in aggregated indices (Crespo et al., 2011), but they have the largest effect on the hydrological regulation. The afforestation of grasslands with exotic vegetation affects the entire range of discharges (Buytaert et al., 2007). Even though the specific magnitudes of such changes are variable, these trends are consistent in the different Andean biomes studied by the iMHEA network (Ochoa-Tocachi et al., 2016a).

An important case in point is afforestation with exotic species. When large extensions of Andean highlands were forested with pine, local authorities tried to replicate a successful experience to recover degraded lands occurred in Cajamarca, Peru. However, most frequently, pine plantations are introduced in non-degraded areas and, as seen in humid páramo studies (Buytaert et al., 2007), they change water and organic carbon retention and hydrological response features. We find similar trends in afforested jalcas and punas, including important reductions in water yield, mainly produced by higher evapotranspiration and canopy interception, and major impacts on discharge, especially over low flows (Ochoa-Tocachi et al., 2016a). Despite the negative evidenced impacts of afforestation on total

Table 6.12 Summary of the iMHEA catchment characteristics for the selected sites in Fig. 6.30.

Code Units	Ecosystem [type]	Altitude [m]	Area [km²]	Land-use [type]	Monitoring period [dates]
LLO Lloa					
LLO_01	Páramo	3825–4700	1.79	Overgrazed	10/01/2013–27/01/2016
LLO_02	Páramo	4088–4680	2.21	Grazed	10/01/2013–27/01/2016
JTU Jatunhuaycu					
JTU_01	Páramo	4075–4225	0.65	Overgrazed	14/11/2013–15/02/2016
JTU_02	Páramo	4085–4322	2.42	Overgrazed	15/11/2013–15/02/2016
JTU_03	Páramo	4144–4500	2.25	Natural	13/11/2013–16/02/2016
PAU Paute					
PAU_01	Páramo	3665–4100	2.63	Natural	24/05/2001–16/08/2005
PAU_02	Páramo	2970–3810	1.00	Natural	29/02/2004–31/07/2007
PAU_03	Páramo	3245–3680	0.59	Afforested	29/05/2004–31/07/2007
PAU_04	Páramo	3560–3721	1.55	Cultivated	27/10/2001–14/10/2003
PIU Piura					
PIU_01	Páramo	3112–3900	6.60	Natural	05/07/2013–12/12/2015
PIU_02	Páramo	3245–3610	0.95	Grazed	06/07/2013–13/12/2015
PIU_03	Páramo	3425–3860	1.31	Overgrazed	11/04/2013–23/10/2015
PIU_04	Forest	2682–3408	2.32	Natural Forest	23/06/2013–14/01/2016
PIU_07	Dry puna	3110–3660	7.80	Overgrazed	11/07/2013–15/01/2015
CHA Chachapoyas					
CHA_01	Jalca	2940–3200	0.95	Afforested	18/08/2010–07/12/2015
CHA_02	Jalca	3000–3450	1.63	Natural	18/08/2010–07/12/2015
HUA Huaraz					
HUA_01	Humid puna	4280–4840	4.22	Natural	10/09/2012–20/06/2014
HUA_02	Humid puna	4235–4725	2.38	Grazed	10/09/2012–20/06/2014
HMT Huamantanga					
HMT_01	Dry puna	4025–4542	2.09	Overgrazed	28/06/2014–03/03/2016
HMT_02	Dry puna	3988–4532	1.69	Overgrazed	26/06/2014–03/03/2016
TAM Tambobamba					
TAM_01	Humid puna	3835–4026	0.82	Afforested	12/04/2012–02/01/2013
TAM_02	Humid puna	3650–4360	1.67	Natural	12/04/2012–16/04/2013
TIQ Tiquipaya					
TIQ_01	Humid puna	4140–4353	0.69	Cultivated	02/04/2013–25/01/2016
TIQ_02	Humid puna	4182–4489	1.73	Natural	18/02/2013–25/01/2016

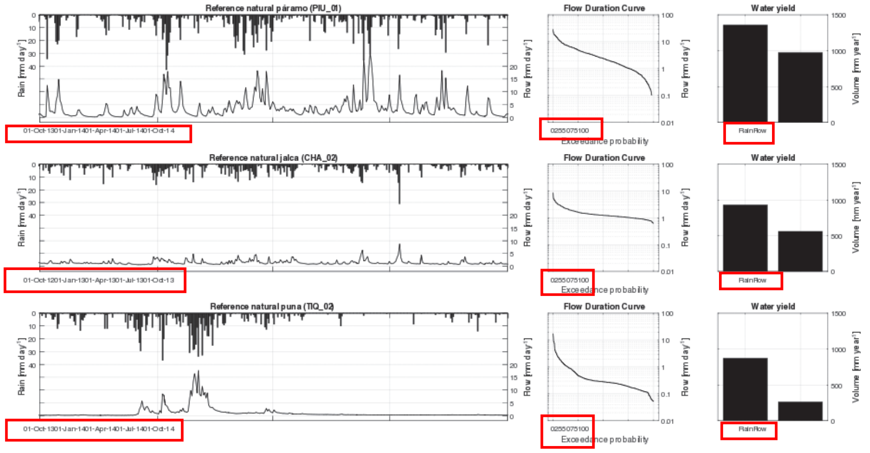

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Fig. 6.33 ~~Hydrological response in a year of natural Andean catchments in different biomes from Ochoa-Tocachi et al. (2016a): (left) daily time series of rainfall and stream flow show different regimes and seasonality mainly driven by latitude; (middle) the flow duration curves show smooth profiles with (right) large specific discharges with respect to input precipitation.~~

water production and local biodiversity (Hofstede et al., 2002), this practice is still part of large regional efforts generally supported by the Ministries of Agriculture of Andean countries. In the last years, local awareness has increased recognizing such practices as productive interventions rather than mistakenly camouflaging them as conservation efforts. This has made it possible to improve the identification of 'more suitable' areas of intervention and changing the approach towards the implementation of conservation agriculture in degraded lands by leveraging the enhancement in soil infiltration produced by tree roots to avoid or reduce erosive processes (Bruijnzeel, 2004; Tobón, 2009; Beck et al., 2013a). However, adequate watershed interventions using afforestation with exotic species in remote Andean catchments is still far from being solved.

In the context of growing investment in climate change adaptation under compensation schemes for ecosystem services in Peru,[1] iMHEA has started to deliver useful information to multi-scale and multi-stakeholder decision-making activities, especially in previously sub-represented ecosystems. For example, the identification of livestock impacts on hydrological regulation in puna highlands provides also quantitative and complementary information on hydrological benefits of overgrazing elimination. Livestock grazing increases soil bulk density, which results in reduced hydraulic conductivity, increased overland flow and lower water yields (Díaz and

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[1] http://www.leyes.congreso.gob.pe/Documentos/Leyes/30215.pdf

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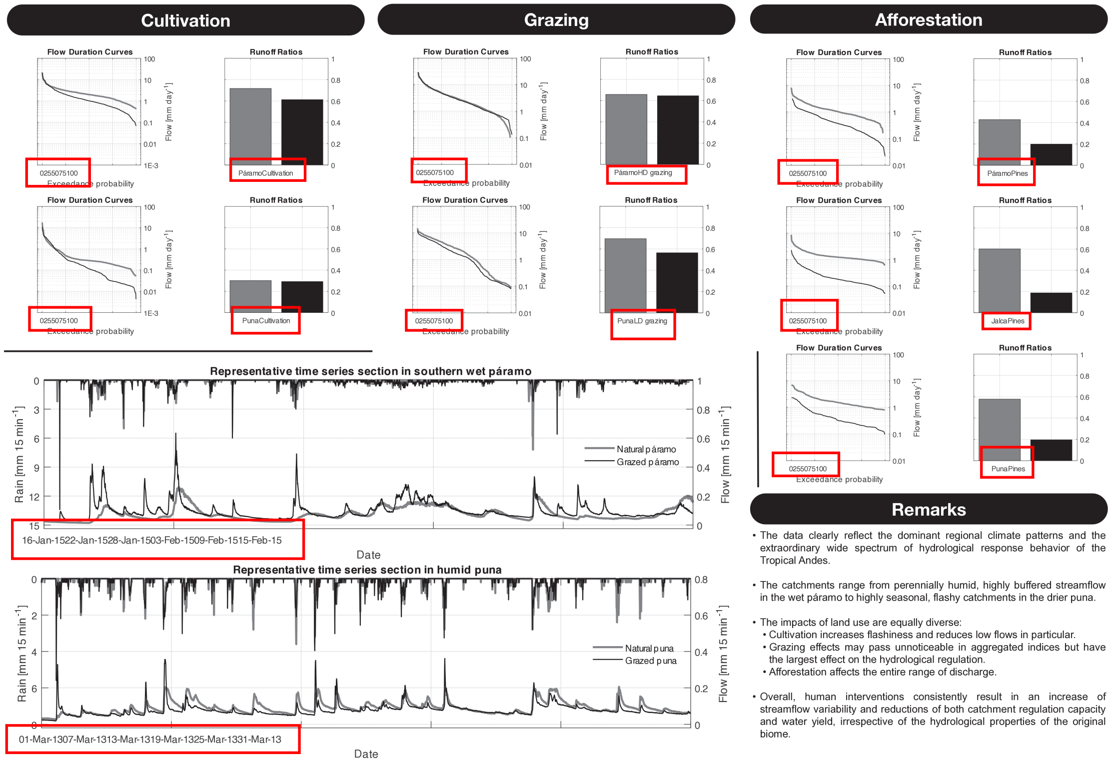

- The data clearly reflect the dominant regional climate patterns and the extraordinary wide spectrum of hydrological response behavior of the Tropical Andes.
- The catchments range from perennially humid, highly buffered streamflow in the wet páramo to highly seasonal, flashy catchments in the drier puna.
- The impacts of land use are equally diverse:
  - Cultivation increases flashiness and reduces low flows in particular.
  - Grazing effects may pass unnoticeable in aggregated indices but have the largest effect on the hydrological regulation.
  - Afforestation affects the entire range of discharge.
- Overall, human interventions consistently result in an increase of streamflow variability and reductions of both catchment regulation capacity and water yield, irrespective of the hydrological properties of the original biome.

Fig. 6.34 Impacts of land use change showing consistent trends in the different Andean biomes analyzed, despite the differences in hydrological regime. In the case of livestock grazing, the impacts are noticeable in the high-resolution time series (bottom left) rather than in the aggregated indices (top middle).

Paz, 2002; Quichimbo, 2008; Crespo et al., 2010). In areas where seasonality and hydrological regulation are critical, water companies build expensive gray infrastructure to secure water for large cities downstream during long dry seasons. Recent changes in legislation now encourage companies to fight catchment degradation to improve natural hydrological regulation capacity. The sites provide a new generation of hydrological information that allows for economic analyses to study green infrastructure feasibility and cost-benefit comparisons between gray and green investments (Gammie and De Bièvre, 2015). For example, Fig. 6.35 shows a comparison of a set of gray and green infrastructure options for Lima, Peru.

The iMHEA initiative has now ~~called~~ the attention of major donors in the context of strengthening capacity for climate change adaptation, and green infrastructure investments in general, as they require evidence of the benefits of their investments. Other initiatives that are adopting the approach are the booming Water Funds in Latin America and the green

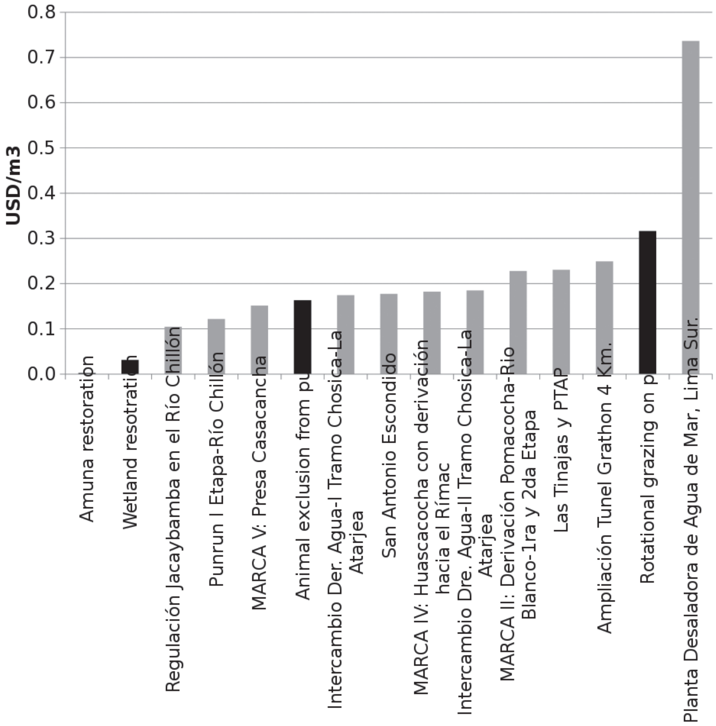

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Fig. 6.35 Comparison of gray and green infrastructure in terms of Costs per Effectiveness (USD m^{-3}) from Gammie and De Bièvre (2015). The iMHEA has started to feed hydrological data into economic analyses to support large scale interventions, such as those to ensure water supply for Lima, Peru.

infrastructure investments as they are promoted by recently approved Peruvian legislation, being even compulsory in the case of water utilities of medium and large cities.

Conclusions

The research builds upon several years of extensive study, as part of the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA), to characterize the hydrology of tropical Andean catchments. By using data from a network of micro-catchments distributed from Ecuador to Bolivia, the iMHEA aims to tackle the scarcity of data and knowledge about the hydrology of high Andean catchments and the impacts of land use and cover change and degradation on their hydrological response and water yield, as well as those of many watershed interventions. By 'trading space-for-time', we find consistent impacts and trends in the different monitored biomes.

We recognize that a fixed common solution to the diversity of hydrological issues in the Andes does not exist, but the methodology proposed by the iMHEA has proved crucial to increase and strengthen the knowledge of Andean hydrology. Knowledge of hydrological change at this scale is limited but key, and this research output will significantly help decision makers inform policies related to development and conservation. Also, this network is an illustration of how information generated from participatory monitoring schemes, such as iMHEA, proves to be extremely relevant to overcome data-scarcity. The participatory nature of the network allows also for more rapidly feeding into decision-making processes and to promote mechanisms, opportunities and spaces to reflect, exchange experiences and provide feedback more easily (Fig. 6.25(j) and 6.25(k)). The results provided by iMHEA may be used to improve water resources management and the effectiveness of water conservation measures, and to support further research in the Andean region. Furthermore, the advent of new technologies and methods, as well as new questions that have been raised in the last years, involves a faster evolution of the network, but it certainly strengthens the route started a couple of years ago with promising and highly expected results.

As noted in Ochoa-Tocachi et al. (2016b), this methodology can be applied to evaluate human interventions both after their implementation (in the monitored catchments) and before (predicting responses in ungauged catchments). As the available database for human intervention assessment grows, including more catchments covering different ecosystems, characteristics and contrasting land use types and watershed interventions, more robust extrapolations can be expected with a better quantification of uncertainty. This approach is useful to generate information about the impact of human interventions on catchment hydrology, especially in data-scarce regions, but with potential application in other regions of the world.

Acknowledgments

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References

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~~Adams, H. et al.~~ 2012. Ecohydrological consequences of drought- and infestation-triggered tree die-off: Insights and hypotheses. Ecohydrology 5: 145–159.

Adhikary, S., Yilmaz, A. and Muttil, N. 2015. Optimal design of rain gauge network in the Middle Yarra River catchment, Australia. Hydrological Processes 29(11): 2582–2599.

~~Ahiablame, L. et al.~~ 2013. Estimation of annual baseflow at ungauged sites in Indiana USA. Journal of Hydrology 476: 13–27.

Archer, D., Climent-Soler, D. and Holman, I. 2010. Changes in discharge rise and fall rates applied to impact assessment of catchment land use. Hydrology Research 41(1): 13–26.

~~Ashagrie, A. et al.~~ 2006. Detecting the influence of land use changes on discharges and floods in the Meuse River Basin—the predictive power of a ninety-year rainfall-runoff relation? Hydrology and Earth System Sciences 10: 691–701.

Autoridad Nacional del Agua. 2012. Diagnóstico de la Gestión de los Recursos Hídricos de la Cuenca Chira-Piura, Piura: Ministerio de Agricultura, Autoridad Nacional del Agua, Peru.

Baker, D., Richards, R., Loftus, T. and Kramer, J. 2004. A new flashiness index: Characteristics and applications to midwestern rivers and streams. Journal of the American Water Resources Association (JAWRA) 40(2): 503–522.

~~Balvanera, P. et al.~~ 2012. Ecosystem services research in Latin America: The state of the art. Ecosystem Services 2: 56–70.

Bárdossy, A. 2007. Calibration of hydrological model parameters for ungauged catchments. Hydrology and Earth System Sciences 11(2): 703–710.

~~Beck, H. et al.~~ 2013a. The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. Hydrology and Earth System Sciences 17(7): 2613–2635.

~~Beck, H. et al.~~ 2013b. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. Water Resources Research 49(12): 7843–7863.

Bendix, J. 2000. Precipitation dynamics in Ecuador and northern Peru during the 1991/92 El Niño: a remote sensing perspective. International Journal of Remote Sensing 21: 533–548.

Bendix, J., Rollenbeck, R. and Reudenbach, C. 2006. Diurnal patterns of rainfall in a tropical Andean valley of southern Ecuador as seen by a vertically pointing K-band Doppler radar. International Journal of Climatology 26(6): 829–846.

Berger, K. and Entekhabi, D. 2001. Basin hydrologic response relations to distributed physiographic descriptors and climate. Journal of Hydrology 247(3-4): 169–182.

Beven, K. 2000. Uniqueness of place and process representations in hydrological modelling. Hydrology and Earth System Sciences 4(2): 203–213.

Beven, K. 2007. Towards integrated environmental models of everywhere: uncertainty, data and modelling as a learning process. Hydrology and Earth System Sciences 11: 460–467.

~~Biederman, J. et al.~~ 2015. Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies. Water Resources Research 51: 9775–9789.

~~Bond, B. et al.~~ 2002. The zone of vegetation influence on baseflow revealed by diel patterns of streamflow and vegetation water use in a headwater basin. Hydrological Processes 16: 1671–1677.

Boorman, D., Hollist, J. and Lilly, A. 1995. Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom, IH Report 126, Wallingford: Institute of Hydrology.

Bosch, J. and Hewlett, J. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55: 3–23.

Bradley, R.S., Vuille, M., Diaz, H.F. and Vergara, W. 2006. Threats to water supplies in the tropical andes. Science 312: 1755–1756.

Bradshaw, C., Sodhi, N., Peh, K. and Brook, B. 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. Global Change Biology 13(11): 2379–2395.

Brandes, D., Hoffmann, J. and Mangarillo, J. 2005. Base flow recession rates, low flows, and hydrologic features of small watersheds in Pennsylvania, USA. Jorunal of the American Water Resources Association 41(5): 1177–1186.

Brauman, K., Daily, G., Duarte, T. and Mooney, H. 2007. The nature and value of ecosystem services: An overview highlighting hydrologic services. Annual Review of Environment and Resources 32: 67–98.

~~Brown, A. et al.~~ 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310: 28–61.

Bruhns, K.O. 1994. Ancient South America. New York: Cambridge University Press.

Bruijnzeel, L. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems and Environment 104: 185–228.

Bulygina, N., McIntyre, N. and Wheater, H. 2009. Conditioning rainfall-runoff model parameters for ungauged catchments and land management impacts analysis. Hydrology and Earth System Sciences 13: 893–904.

Bulygina, N., McIntyre, N. and Wheater, H. 2011. Bayesian conditioning of a rainfall-runoff model for predicting flows in ungauged catchments and under land use changes. Water Resources Research 47(2): W02503.

~~Bulygina, N. et al.~~ 2012. Integrating different types of information into hydrological model parameter estimation: Application to ungauged catchments and land use scenario analysis. Water Resources Research 48(6): W06519.

~~Buytaert, W. et al.~~ 2002. Impact of land use changes on the hydrological properties of volcanic ash soils in South Ecuador. Soil Use and Management 18: 94–100.

Buytaert, W., De Bièvre, B., Wyseure, G. and Deckers, J. 2004. The use of the linear reservoir concept to quantify the impact of changes in land use on the hydrology of catchments in the Andes. Hydrology and Earth System Sciences 8(1): 108–114.

Buytaert, W., De Bièvre, B., Wyseure, G. and Deckers, J. 2005. The effect of land use changes on the hydrological behaviour of Histic Andosols in south Ecuador. Hydrological Processes 19: 3985–3997.

~~Buytaert, W. et al.~~ 2006a. Spatial and temporal rainfall variability in mountainous areas: A case study from the south Ecuadorian Andes. Journal of Hydrology 329(3-4): 413–421.

~~Buytaert, W. et al.~~ 2006b. Human impact on the hydrology of the Andean páramos. Earth Science Reviews 79(1-2): 53–72.

Buytaert, W., Iñiguez, V. and De Bièvre, B. 2007. The effects of afforestation and cultivation on water yield in the Andean páramo. Forest Ecology and Management 251(1-2): 22–30.

Buytaert, W. and Beven, K. 2009. Regionalization as a learning process. Water Resources Research 45: W11419.

~~Buytaert, W. et al. 2010.~~ Uncertainties in climate change projections and regional downscaling in the tropical Andes: Implications for water resources management. Hydrology and Earth System Sciences 14: 1247–1258.

Buytaert, W. and Beven, K. 2011. Models as multiple working hypotheses: hydrological simulation of tropical alpine wetlands. Hydrological Processes 25(11): 1784–1799.

Buytaert, W. and De Bièvre, B. 2012. Water for cities: The impact of climate change and demographic growth in the tropical Andes. Water Resources Research 48: W08503.

Buytaert, W., Baez, S. and Bustamante, M. 2012. Web-based environmental simulation: Bridging the gap between scientific modeling and decision-making. Environmental Science & Technology 46: 1971–1976.

~~Buytaert, W. et al.~~ 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. Frontiers in Earth Science 2(26)~~.~~

Au.: Page number missing

~~Buytaert, W. et al.~~ 2016. Citizen science for water resources management: Toward polycentric monitoring and governance? Journal of Water Resources Planning and Management (ASCE) 142(4): 01816002.

Cain, S.F.I., Gregory, D.A., Loheide, S.P. and Butler, J.J.J. 2004. Noise in pressure transducers readings produced by variations in solar radiation. Ground Water 42(6): 939–944.

Carlos, G., Munive, R., Mallma, T. and Orihuela, C. 2014. Evaluation of the infiltration rate in farm, forestry and grazing land in the Shullcas River's basin. Apuntes de Ciencia & Sociedad 4(1): 32–43.

Célleri, R., Willems, P., Buytaert, W. and Feyen, J. 2007. Space-time rainfall variability in the Paute Basin, Ecuadorian Andes. Hydrological Processes 21: 3316–3327.

Célleri, R. and Feyen, J. 2009. The hydrology of tropical andean ecosystems: Importance, knowledge status, and perspectives. Mountain Research and Development (MRD) 29(4): 350–355.

Célleri, R. 2010. Estado del conocimiento técnico científico. pp. 24–45. *In*: Quintero, M. (ed.). Servicios Ambientales Hidrológicos en la RegiónAndina. Lima: CONDESAN & Instituo de Estudios Peruanos.

~~Célleri, R. et al.~~ 2010. Understanding the hydrology of tropical Andean ecosystems through an Andean Network of Basins. Goslar-Hahnenklee, IAHS Publication, pp. 209–212.

Chapman, T. 1999. A comparison of algorithms for stream flow recession and base flow separation. Hydrological Processes 13: 701–714.

Ciach, G. 2003. Local random errors in tipping-bucket rain gauge measurements. Journal of Atmospheric and Oceanic Technology 20: 752–759.

Ciach, G. 2003. Local random errors in tipping-bucket rain gauge measurements. Journal of Atmospheric and Oceanic Technology 20: 752–759.

Clausen, B. and Biggs, B. 1997. Relationships between benthic biota and hydrological indices in New Zealand streams. Freshwater Biology 38(2): 327–342.

Clausen, B. and Biggs, B. 2000. Flow variables for ecological studies in temperate streams: Groupings based on covariance. Journal of Hydrology 237(3-4): 184–197.

~~Córdova, M. et al.~~ 2015. Evaluation of the Penman-Monteith (FAO 56 PM) method for calculating reference evapotranspiration using limited data. Mountain Research and Development 35(3): 230–239.

~~Correa, A. et al,~~ 2016. Continuous versus event-based sampling: how many samples are required for deriving general hydrological understanding on Ecuador's páramo region? Hydrological Processes, 30(South American Hydrology): 4059–4073.

~~Crespo, P. et al,~~ 2010. Land use change impacts on the hydrology of wet Andean páramo ecosystems. IAHS-AISH Publication 336: 71–76.

~~Crespo, P. et al,~~ 2011. Identifying controls of the rainfall-runoff response of small catchments in the tropical Andes (Ecuador). Journal of Hydrology 407(1-4): 164–174.

~~Crespo, P. et al,~~ 2012. Preliminary evaluation of the runoff processes in a remote montane cloud forest basin using mixing model analysis and mean transit time. Hydrological Processes 26(25): 3896–3910.

~~Cuevas, J.G. et al,~~ 2010. Are diurnal fluctuations in streamflow real? Journal of Hydrology and Hydromechanics 58(3): 149–162.

Díaz, E. and Paz, L. 2002. Evaluación del regimen de humedad del suelo bajo diferentes usos, en los páramos Las Ánimas (Municipio de Silvia) y Piedra de León (Municipio de Sotará), Departamento del Cauca, Popayán: Fundación Universitaria de Popayán.

Etter, A. and van Wyngaarden, W. 2000. Patterns of landscape transformation in Colombia, with emphasis in the Andean region. Ambio 29: 432–439.

Farley, K., Kelly, E. and Hofstede, R. 2004. Soil organic carbon and water retention after conversion of grasslands to pine plantations in the ecuadorian andes. Ecosystems 7: 729–739.

~~Favier, V. et al.~~ 2008. Evidence of groundwater flow on Antizana ice-covered volcano, Ecuador. Hydrological Sciences Journal 53(1): 278–291.

Fekete, B.M. and Vörösmarty, C.J. 2007. *The* current status of global river discharge monitoring [illegible] potential new technologies complementing traditional discharge measurements. Brasilia, IAHS Publication~~.~~

~~Freeman, L.A. et al,~~ 2004. Use of submersible pressure transducers in water-resources investigations. Techniques of Water-Resources Investigations 8(A3).

Gammie, G. and De Bièvre, B. 2015. Assessing Green Interventions for the Water Supply of Lima, Peru. Cost-Effectiveness, Potential Impact, and Priority Research Areas. Washington, DC: Forest Trends Association.

Gippel, C. 2001. Hydrological analyses for environmental flow assessment. pp. 873–880. *In*: Ghasemi, F. and Whetton, P. (eds.). Proceedings MODSIM 2001, International Congress of Modelling and Simulation. Canberra: Modelling and Simulation Society of Australia & New Zealand, The Australian National University.

Gribovszki, Z., Szilágyi, J. and Kalicz, P. 2010. Diurnal fluctuations in shallow groundwater levels and streamflow rates and their interpretation—A review. Journal of Hydrology 385: 371–383.

Gribovszki, Z., Kalicz, P. and Szilágyi, J. 2013. Does the accuracy of fine-scale water level measurements by vented pressure transducers permit for diurnal evapotranspiration estimation? Journal of Hydrology 488: 166–169.

Groisman, P. and Legates, D. 1994. The accuracy of the United States precipitation data. Bulletin of the American Meteorological Society 75: 215–227.

Hannah. 2011. Large-scale river flow archives: Importance, current status and future needs. Hydrological Processes 25(7): 1191–1200.

Harden, C.P. 2006. Human impacts on headwater fluvial systems in the northern and central Andes. Geomorphology 79: 249–263.

~~Hofstede, R. et al,~~ 2002. Impact of pine plantations on soils and vegetation in the Ecuadorian High Andes. Mountain Research and Development 22: 159–167.

Hughes, J. and James, B. 1989. A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. Australian Journal of Marine and Freshwater Research 40: 303–326.

Au.: Is it chapter title or Name of the book?

Include reference Guallpa and Celleri, 2013.

Inbar, C. and Llerena, C. 2000. Erosion processes in high mountain agricultural terraces in Peru. Mountain Research and Development 20(1): 72–79.

Inbar, M. and Llerena, C. 2004. Procesos de erosión en andenes agrícolas andinos en la cuenca del río Santa Eulalia, Lima, Perú. pp. 141–148. *In*: Llerena, C., Inbar, M. and Benavides, M. (eds.). Conservación y Abandono de Andenes. Lima: Universidad Nacional Agraria La Molina, University of Haifa.

IUCN. 2002. High Andean Wetlands, s.l.: International Union for Conservation of Nature.

Kabubi, J., Mutua, F., Willems, P. and Mngodo, R. 2005. Low Flow Analysis using Filter Generated Series for Lake Victoria Basin, Cairo: FRIEND/NILE conference.

Körner, C. and Ohsawa, M. 2005. Mountain systems. pp. 681–716. *In*: Hassan, R., Scholes, R. and Ash, N. (eds.). Ecosystems and Human Well-being: Current State and Trends. s.l.: The Millenium Ecosystem Assessment.

Krakauer, N. and Temimi, M. 2011. Stream recession curves and storage variability in small watersheds. Hydrology and Earth System Sciences 15: 2377–2389.

Lamb, R. and Kay, A. 2004. Confidence intervals for a spatially generalized, continuous simulation flood frequency model for Great Britain. Water Resources Research 40: W07501.

Lee, H., Mcintyre, N. and Young, A. 2006. Predicting runoff in ungauged UK catchments. Proceedings of the Institution of Civil Engineers Water Management 159(2): 129–138.

Longobardi, A. and Villani, P. 2008. Baseflow index regionalization analysis in a mediterranean area and data scarcity context: Role of the catchment permeability index. Journal of Hydrology 355(1-4): 63–75.

Lørup, J., Refsgaard, J. and Mazvimavi, D. 1998. Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. Journal of Hydrology 205(3-4): 147–163.

Luteyn, J.L. 1992. Páramos: why study them? pp. 1–14. *In*: Balslev, H. and Luteyn, J.L. (eds.). Páramo: An Andean Ecosystem Under Human Influence. London: Academic Press.

Lü, Y., Hu, J., Sun, F. and Zhang, L. 2015. Water retention and hydrological regulation: harmony but not the same in terrestrial hydrological ecosystem services (in Chinese). Acta Ecologica Sinica 35(15): 5191–5196.

Include reference Manz et al., 2017.

~~Manz, B. et al~~. 2016. High-resolution satellite-gauge merged precipitation climatologies of the Tropical Andes. Journal of Geophysical Research: Atmospheres 121: 1190–1207.

Mathews, R. and Richter, B. 2007. Application of the indicators of hydrologic alteration software in environmental flow setting. JAWRA Journal of the American Water Resources Association 43(6): 1400–1413.

Include reference Martinez et al., 2017.

Mazvimavi, D., Meijerink, A., Savenije, H. and Stein, A. 2005. Prediction of flow characteristics using multiple regression and neural networks: A case study in Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C 30(11-16): 639–647.

~~McIntyre, N. et al~~. 2005. Ensemble predictions of runoff in ungauged catchments. Water Resources Research 41: ~~DOI: Volume 41: p.~~ W12434.

Au.: Pl check

~~McIntyre, N. et al~~. 2014. Modelling the hydrological impacts of rural land use change. Hydrology Research 45(6): 737–754.

McLaughlin, D. and Cohen, M. 2011. Thermal artifacts in measurements of fine-scale water level variation. Water Resources Research 47: W09601.

~~Molina, A. et al~~. 2007. Runoff generation in a degraded Andean ecosystem: Interaction of vegetation cover and land use. Catena 71: 357–370.

~~Molina, A. et al~~. 2015. Multidecadal change in streamflow associated with anthropogenic disturbances in the tropical Andes. Hydrology and Earth System Sciences 19: 4201–4213.

Mora, D. and Willems, P. 2012. Decadal oscillations in rainfall and air temperature in the Paute River Basin–Southern Andes of Ecuador. Theoretical and Applied Climatology 108(1): 267–282.

~~Mosquera, G. et al~~. 2015. Runoff from tropical alpine grasslands increases with areal extent of wetlands. Catena 125: 120–128.

Include reference Muñoz et al., 2016.

~~Muñoz, E. et al.~~ 2016. Unraveling complex hydrogeological processes in Andean basins in south-central Chile: An integrated assessment to understand hydrological dissimilarity. Hydrological Processes 30(South American Hydrology): 4934–4943.

~~Ochoa-Tocachi, B. et al.~~ 2016a. Impacts of land use on the hydrological response of tropical Andean catchments. Hydrological Processes 30(South American Hydrology): 4074–4089.

Ochoa-Tocachi, B., Buytaert, W. and De Bievre, B. 2016b. Regionalization of land-use impacts on streamflow using a network of paired catchments. Water Resources Research 52: 6710–6729.

~~O'Connell, P. et al.~~ 2004. Review of Impacts of Rural Land Use and Management on Flood Generation, Impact Study Report, London: Defra/Environment Agency R&D Technical Report (FD2114).

Olden, J. and Poff, N. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19(2): 101–121.

Oudin, L., Kay, A., Andréassian, V. and Perrin, C. 2010. Are seemingly physically similar catchments truly hydrologically similar? Water Resources Research 46: W11558.

Padrón, R., Wilcox, B., Crespo, P. and Célleri, R. 2015. Rainfall in the Andean Páramo: New insights from high-resolution monitoring in southern Ecuador. Journal of Hydrometeorology 16: 985–996.

Parajka, J., Merz, R. and Blöschl, G. 2005. A comparison of regionalisation methods for catchment model parameters. Hydrology and Earth System Sciences 9: 157–171.

~~Parajka, J. et al.~~ 2013. Prediction of runoff hydrographs in ungauged basins. pp. 53–69. *In*: ~~Blöschl, G. et al.~~ (eds.). Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales. Cambridge,: Cambridge University Press.

Peña-Arancibia, J., van Dijk, A., Mulligan, M. and Bruijnzeel, L. 2010. The role of climatic and terrain attributes in estimating baseflow recession in tropical catchments. Hydrology and Earth System Sciences 14(11): 2193–2205.

Poff, N. and Ward, J. 1989. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46(10): 1805–1818.

Poff, N. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependance in some hydrological descriptors. Freshwater Biology 36: 71–91.

~~Poff, N. et al.~~ 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience 47(11): 769–784.

Pyrce, R. 2004. Hydrological low flow indices and their uses. *In*: Watershed services Centre Report, 04-2004, Peterborough: Trent University, Symons Campus.

Quichimbo, P. 2008. Efecto de la forestación sobre la vegetación y el suelo, Cuenca: Universidad de Cuenca.

Richards, R. 1989. Measures of flow variability for great lakes tributaries. Environmental Monitoring and Assessment 13(2-3): 361–377.

Richards, R. 1990. Measures of flow variability and a new flow-based classification of great lakes tributaries. Journal of Great Lakes Research 16(1): 53–70.

Richter, B., Baumgartner, J., Powell, J. and Braun, D. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10(4): 1163–1174.

Richter, B., Baumgartner, Wigington and Braun, D. 1997. How much water does a river need? Freshwater Biology 37(1): 231–249.

Richter, B., Baumgartner, J., Braun, D. and Powell, J. 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research & Management 14(4): 329–340.

Roa-García, C.E. and Brown, S. 2009. Assessing water use and quality through youth participatory research in a rural Andean watershed. Journal of Environmental Management 90: 3040–3047.

Roa-García, M.C., Brown, S., Schreier, H. and Lavkulich, L. 2011. The role of land use and soils in regulating water flow in small headwater catchments of the Andes. Water Resources Research 47: W05510.

Sadler, E. and Brusscher, W. 1989. High-intensity rainfall rate determination from tipping-bucket rain gauge data. Agronomy Journal 81: 930–934.

Sarmiento, L. 2000. Water balance and soil loss under long fallow agriculture in the Venezuelan Andes. Mountain Research and Development 20(3): 246–253.

~~Sawicz, K. et al.~~ 2011. Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. Hydrology and Earth System Sciences 15: 2895–2911.

Sefton, C. and Howarth, S. 1998. Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. Journal of Hydrology 211(1-4): 1–16.

Shamir, E., Imam, B., Gupta, H. and Sorooshian, S. 2005. Application of temporal streamflow descriptors in hydrologic model parameter estimation. Water Resources Research 41: W06021.

~~Shamir, E. et al.~~ 2005. The role of hydrograph indices in parameter estimation of rainfall–runoff models. Hydrological Processes 19(11): 2187–2207.

~~Singh, R. et al.~~ 2011. A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate—accounting for changing watershed behavior. Hydrology and Earth System Sciences 15(11): 3591–3603.

Sivapalan, M. 2003. Prediction in ungauged basins: A grand challenge for theoretical hydrology. Hydrological Processes 17: 3163–3170.

~~Sivapalan, M. et al.~~ 2011. Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. Water Resources Research 47: W02522.

Thomas, R. and Megahan, W. 1998. Peak flow responses to clear-cutting and roads in small and large basins, Western Cascades, Oregon: A second opinion. Water Resources Research 34(12): 3393–3403.

Tobón, C. 2009. Los Bosques Andinos y el Agua. Serie investigación y sistematización #4. Quito: Programa Regional ECOBONA—INTERCOOPERATION & CONDESAN.

Include reference Ulloa et al., 2017.

USDA. 1986. Urban Hydrology for Small Watersheds, Report TR-55, Washington DC: United States Department of Agriculture.

USDI Bureau of Reclamation. 2001. Water Measurement Manual., s.l.: Water Resources Research Laboratory, US Department of the Interior.

van Dijk, A. 2010. Climate and terrain factors explaining streamflow response and recession in Australian catchments. Hydrology and Earth System Sciences 14(1): 159–169.

Visessri, S. and McIntyre, N. 2016. Regionalisation of hydrological responses under land-use change and variable data quality. Hydrological Sciences Journal 61(2): 302–320.

~~Viviroli, D. et al.~~ 2007. Mountains of the world, water towers for humanity: typology, mapping, and global significance. Water Resources Research 43: W07447.

Vuille, M., Bradley, R.S. and Keiming, F. 2000. Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. Journal of Geophysical Research 105(D10): 12447–12460.

Wagener, T. and Wheater, H. 2006. Parameter estimation and regionalization for continuous rainfall-runoff models including uncertainty. Journal of Hydrology 320: 132–154.

Wagener, T. 2007. Can we model the hydrological impacts of environmental change? Hydrological Processes 21: 3233–3236.

Wagener, T. and Montanari, A. 2011. Convergence of approaches toward reducing uncertainty in predictions in ungauged basins. Water Resources Research 47(6): W06301.

Walsh, R. and Lawler, D. 1981. Rainfall seasonality: description, spatial patterns and change through time. Weather 36(7): 201–208.

Wang, J., Fisher, B. and Wolff, D. 2008. Estimating rain rates from tipping-bucket rain gauge measurements. Journal of Atmospheric and Oceanic Technology 25: 43–56.

White, S. and Maldonado, F. 1991. The use and conservation of national resources in the Andes of southern Ecuador. Mountain Research and Development 11: 37–55.

White, W.N. 1932. A method of estimating ground-water supplies based on discharge by plants and evaporation from soil-results of investigation in Escalante Valley, Utah. Water Supply Paper 659(A): 1–105.

Willems, P. 2014. Parsimonious rainfall–runoff model construction supported by time series processing and validation of hydrological extremes—Part 1: step-wise model-structure identification and calibration approach. Journal of Hydrology 510: 578–590.

~~Wohl, E. et al.~~ 2012. The hydrology of the humid tropics. Nature Climate Change 2: 655–662.

Wondzell, S., Gooseff, M. and McGlynn, B. 2009. An analysis of alternative conceptual models relating hyporheic exchange flow to diel fluctuations in discharge during baseflow recession. Hydrological Processes 24(6): 686–694.

Wood, P., Agnew, M. and Petts, G. 2000. Flow variations and macroinvertebrate community responses in a small groundwater-dominated stream in south-east England. Hydrological Processes 14(16-17): 3133–3147.

World Meteorological Organization. 2008. Guide to Hydrological Practices, Volume I, Hydrology—From Measurement to Hydrological Information. Sixth edition, 2008 ed. Geneva: Chairperson, Publications Board, World Meteorological Organization (WMO).

World Meteorological Organization. 2012. Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8. 2008 edition, updated in 2010 ed. Geneva: Chairperson, Publications Board, World Meteorological Organization (WMO).

Yadav, M., Wagener, T. and Gupta, H. 2007. Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins. Advances in Water Resources 30: 1756–1774.

Young, A. 2006. Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. Journal of Hydrology 320: 155–172.

Zhang, Z., Wagener, T., Reed, P. and Bhushan, R. 2008. Reducing uncertainty in predictions in ungauged basins by combining hydrologic indices regionalization and multiobjective optimization. Water Resources Research 44: W00B04.

~~Zulkafli, Z. et al. 2016.~~ Projected increases in the annual flood pulse of the Western Amazon. Environmental Research Letters 11: 014013.