Water, Climate and Land Use in a Non-Stationary Tectonically-Active Humid Tropical Environment

A Dissertation

Presented in Partial Fulfillment of the Requirements for the

Degree of Doctor of Philosophy

with a

Major in Water Resources

with an emphasis in Science and Management

in the

College of Graduate Studies

University of Idaho

by

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December 2014

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Authorization to Submit Dissertation

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Abstract

In the tropics, ongoing departure from the long-term climate average is more rapid and significant than anywhere on the planet, predicted to reach unprecedented conditions as early as 2020. Moreover, low latitudes harbor the majority of developing nations with limited capital available for monitoring water resources and climate change. As climate change intensifies, the interaction between altered precipitation regimes and modified vegetation and soil associated with expanding agricultural and pastoral land use can reduce the intrinsic resilience of watersheds and the ecosystems and societies they support.

In this dissertation I provide insight into how climate change and land use affect watershed hydrology and channel morphology in the data-poor humid mountain tropics. I identified a unique expression of geomorphic equilibrium in mountain river channels relative to conventional metrics of geomorphic balance derived from temperate and semi-arid regions. Using physically based modeling of surface and subsurface hydrology paired with the field-based channel measurements, I evaluated the response exhibited by watersheds in tectonically active steep mountain terrain under existing and altered climate and land cover scenarios. Watersheds converted from forest to pasture exhibit greater peak flow events, lower base flow and reduced resilience to increased rainfall intensity. My efforts provide a rapid and inexpensive procedure for deciphering the effects of land use and climate change without need for long-term datasets or a spatially comprehensive description of subsurface heterogeneity, allowing local resource management efforts to broaden to the watershed scale.

Acknowledgements

I would like to thank my mentors and advisors who helped make this project a reality. Alex Fremier stuck with me from the beginning and truly provided the insight and clarity I needed to complete this dissertation. Jan Boll provided essential guidance, particularly though the hydrologic modeling phase of the project. Both Alex and Jan visited my field sites in Costa Rica, often standing in the rain unfazed while providing me crucial feedback. Brian Yanites agreed to join my committee later in the project, but offered invaluable advice leading to a major breakthrough when I most needed it. I could not have initiated any of this work without the help of Fabrice DeClerck who provided me with relevant regional context and aided my site selection and transportation woes. And, I would not have been able to complete this research without the constant support of Nilsa Bosque-Pérez, always available to help navigate the occasional turbulence of interdisciplinary research and education. This work was funded by a National Science Foundation (NSF) Integrative Graduate Education and Research Traineeship (IGERT) (Grant No. 0903479).

The long, rainy, albeit beautiful field days exploring the mountain rainforest rivers of central Costa Rica were made enjoyable and extremely productive because of the assistance and company of Amilkar Moncada. I also appreciated field assistance from Claudia Medellín Moreno and Aline Ortega-Pieck. Information lent by Frederico Gómez at the Instituto Costarricense de Electricidad greatly aided the watershed modeling, providing data from stream gauges and weather stations in the study region. Thanks to Dave Shelley for finding a way to sell my somewhat trustworthy motorcycle.

I would like to thank my friends and colleagues Kristen Welsh-Unwalla, Levi Keesecker, and Renée Hill for unending support and constant collaboration over the period of this research. Chapter 3 is the interdisciplinary dissertation chapter we jointly wrote in conjunction with faculty from the University of Idaho and Washington State University – a product of deep discussion, interactions with the people and places of rural Costa Rica, and countless ideas and iterations. We thank Alex Fremier, Jan Boll, Barbara Cosens and Nilsa Bosque-Pérez for their support and contributions throughout the process. We sincerely appreciate the support and collaboration of ASADA and CAAR representatives from the Tuis and Pejibaye River basins in Costa Rica. We thank J.D. Wulfhorst for his contributions to methodological development and review of the manuscript. We are also grateful for Nicole Sibelet and Isabel Gutiérrez for providing comments on the manuscript. Additionally, we thank Amilkar Moncada again for his assistance with fieldwork.

The Palouse Basin Aquifer study by the University of Idaho Water Resources Program was funded in part by the Palouse Basin Aquifer Committee. We are grateful for the collaboration with Dr. Allyson Beall (WSU), Dr. Fritz Fiedler (UI), Dr. Charles Harris (UI) and the first cohort of students to enter the Water Resources Program: Katherine Bilodeau, Matthew Reeves, Matthew Darrington, Luke Marchant, and Sandra Richartz, whose theses are available on the Palouse Basin Integrated Basin Analysis website: http://wrbasins.nkn.uidaho.edu/palouse_digital_resources.

Most importantly, the support from my wife Amy Martin, including fieldwork assistance and allowing me to be away from home for months at a time, kept me going over the last four years. I must also acknowledge my parents for instilling my passion for the natural world, a thirst to understand how it all works, and an ethic to respect diverse people and places.

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CHAPTER 1

Highly erosive flow regimes and high-resolution sampling in the humid tropics of Costa Rica refine predictions of geomorphic equilibrium

Abstract

In the absence of conventional expressions of fluvial geomorphic equilibrium, we identified unique evidence of equilibrium morphology in three mountain watersheds of central Costa Rica characterized by steep channels, high weathering rates, and a humid tropical climate. We measured morphological and hydraulic variables at a high spatial resolution in 73 stream reaches to evaluate geomorphic signals of equilibrium. We found that metrics such as consistent bankfull discharge, strong downstream hydraulic geometry relationships, and critical bed shear stress values did not indicate equilibrium conditions. However, regularly distributed sediment patches – wider zones of coarse-grained alluvial fill in an otherwise bedrock channel – were aligned with sediment size and shear stress values, explaining the pattern of channel width:depth and suggesting that these systems are functioning with morphological stability. Differences in the signature of equilibrium morphology among the studied basins signify that changes in watershed hydrology associated with land cover conversion alter the geomorphic expression of equilibrium by intensifying channel scour and downstream sediment transport.

Introduction

The equilibrated graded stream is the hypothesized expression of a self-organized balanced condition for river channels (Makin 1948). The bankfull channel, for example, is the geomorphic expression of equilibrium because it maintains the downstream transport of incoming sediment driven by channel-forming discharge (Leopold et al. 1964). However, the graded stream concept assumes relatively constant exogenous factors (such as tectonic activity, base level change, land cover conversion, and climate). When these factors influence channel and floodplain form by altering water and sediment delivery, other geomorphic proxies of equilibrium are necessary.

The graded stream concept emerged from studies in alluvial channels of temperate regions (Mackin 1948, Leopold et al 1964). The seasonal hydrological stationarity allow these inputs to maintain regularity in channel form within Schumm and Lichty's (1965) 'graded' timescale (Mackin 1948, Leopold et al. 1964). Multiple empirical observations of equilibrium emerged from these ideas and have defined fluvial geomorphology: bankfull channel dimensions and discharge, median grain size initiation of motion at bankfull flow and downstream hydraulic geometry (DHG).

Fundamental fluvial geomorphic thought stresses that the frequency and magnitude of channel-shaping flows strongly influence channel geometry (Leopold et al. 1964), and equilibrium morphology reflects the accrual of these flow events over time. Stationary flow and sediment regimes generate the bankfull channel shape. Additionally, in equilibrated rivers, the critical bed shear stress required to detach bedload sediment roughly correlates with the shear stress applied to the streambed at bankfull discharge (Howard 1980 cited in Wohl 2010). Transporting bedload is a critical mechanism for shaping channels, partially explaining the relationship between bankfull discharge and channel forming flow. Based on the DHG concept, discharge also strongly controls the variability in channel width and depth; where well-developed DHG exists, the system has reached a detectable degree of equilibrium (Wohl 2004). Thus, well-developed DHG and a uniform bankfull discharge that generates critical bed shear stress represent stable channel morphology maintained by stationary watershed and climate conditions.

Although the driving forces shaping river channels are universal, observed channel morphology might not express conventional signatures of equilibrium because of actively changing or extreme flow and sediment regimes. Where disequilibrium exists, morphology reflects its absence through inconsistent morphological patterns. However, in environments characterized by significant tectonic activity, humid climate and steep terrain, the amplified hydraulic driving forces responsible for geomorphic change may develop unique morphological expressions. Such extreme environments should also exhibit a distinct capacity to influence geomorphic adjustments to land cover conversion and associated shifts in watershed hydrology such as increases in runoff-generated peak flow events (Spaans et al. 1989, Germer et al. 2010, Hanson et al. 2004, Toohey 2012, Chapter 2).

Thus, in extreme fluvial environments, conventional proxies for equilibrium may not accurately signify system balance, implying disequilibrium conditions. For example, mountain river systems defined by tightly coupled hillslope-channel processes, dynamic flow regimes, and a limited sediment supply punctuated by pulses of mass wasting can counteract the establishment of stability analogous to lowland or topographically muted headwater basins. Yet, stable channel morphology does develop along steep channels in response to sediment and discharge inputs, resulting in particular reach types (e.g. step-pool, pool-riffle) (Montgomery and Buffington 1997, Montgomery 1999) that maximize boundary roughness relative to stream power and sediment supply (Wohl and Merritt 2008).

In humid tropical settings, abundant precipitation and high rates of physical and chemical weathering create unique conditions for development of distinctive geomorphic characteristics (Scatena and Gupta 2011) and river channel stability. Humid climates can generate recurrent flood pulses that produce relatively frequent channel-shaping flows (Pike et al. 2010), seemingly driving more rapid channel adjustment. Moreover, humid tropical climates in steep terrain generate strong hydraulic forcing where weathering rates are rapid. Yet watershed and river dynamics research has historically focused on temperate and semi-arid systems, and consequently there exists a tendency to apply these results in diverse regions where watersheds have evolved to unique climates (Panama – Wohl 2005, Puerto Rico – Pike et al. 2010). As a result, few process-based studies on steep (≥0.002 m/m) mountain river channel morphology in the humid tropics exist, in part because of the limited resources available for monitoring (Revkin 2007). And, few studies have explicitly addressed the concept of geomorphic equilibrium (*sensu* Schumm 1977) or the applicability of the dominant discharge and hydraulic geometry concepts (*sensu* L. Leopold et al. 1964) in high gradient rivers of the humid tropics (but see Wohl 2005, Pike et al. 2010). The widespread use of the concepts with limited formal evaluation in this end-member system calls for a more specific evaluation.

In this paper, we propose that where hydraulic forcing is strong ($\Omega : d_{84} > 10{,}000$ W m^{-1} m^{-1}) (Wohl 2004) but bankfull and DHG indicators are inconsistent, system stability is not explained by conventional metrics. Within the context of three humid tropical mountain watersheds, we first assessed the expression of conventional proxies of morphological equilibrium in three end-member fluvial systems by quantifying the capacity of the systems to hydraulically shape existing channel morphology. Second, we evaluated alternative geomorphic signals of equilibrium in systems with excessive driving forces by elucidating longitudinal patterns of morphological and hydraulic variables. Lastly, we resolved land use influences on river system equilibrium by examining variations in morphological and hydraulic patterns among watersheds experiencing a gradient of land use intensity. Indicators of system equilibrium are vital for assessing watershed response in regions lacking long-term monitoring, particularly where land cover conversion continues to extend into headwater basins experiencing unprecedented climate change.

Methods

Description of Study Watersheds

Three watersheds (HUC level 3 – 10,000ac) located in the Talamanca Mountains of central Costa Rica were chosen based on similar drainage area, shape, elevation gradient, average channel slope, climate, geology and the proximity to one another (Table 1). Two of the watersheds, Gato and Atirro, lie within the Reventazón Watershed draining to the Atlantic, and the third, Platanillo, drains into the Pacuare Watershed, also emptying into the Atlantic (Fig. 1a). The geology of the region has not been comprehensively mapped and is described as mixed Pliocene volcanic and Tertiary sedimentary rocks (Linkimer 2003, Montero et al. 2013). Tectonic activity in the region is dominated by strike-slip faulting and has created a pull-apart basin at the outlet of the Atirro basin, part of the 150km-long Atirro-Río Sucio fault system of east-central Costa Rica (Montero et al. 2013).

The study watersheds represent a gradient of land use (Fig. 1b), allowing an analysis of land use effects on present channel morphology. Gato is within a forest reserve with <0.1% land cover conversion and no known roads. Atirro has 2.5% non-forest land cover, with deforestation including roads within or adjacent to the riparian zone. Plantanillo is intensely modified with 41% of the watershed experiencing modified land cover including agriculture, pasture, and urban uses (Peréz 2009). The land use has been present for decades and supports local livelihoods.

The region encompassing the three watersheds has a rainfall average of 5.25m annually (Instituto Costarricense de Electricidad (ICE)). An elevational precipitation gradient, evident in records from meteorological stations in and near Gato and Atirro watersheds, ranges from 7.07m at an elevation of 1700m to 4.62m at an elevation of 873m (Fig. 2). Although rain falls almost daily at higher elevations in the study region, a drier season reduces precipitation during the months of February through April (Fig. 3). Complete annual records are limited in the climate and discharge data from 2002-2012, but a precipitation gradient from west to east is indicated by a decline in precipitation between stations at similar elevations including the Alto Gato and Cuencas stations and the La Esperanza and Platanillo stations (Fig. 2 & Table 2).

Field Data Collection

In the following, we describe the measurement and assessment of hydraulic driving forces and expression of conventional proxies for morphological equilibrium in the three river segments. We evaluated hydraulic forces based on field-based indicators of bankfull discharge, the ratio of stream power at bankfull discharge to d_{84}, sediment transport capacity at bankfull discharge, shear stress at bankfull discharge, and the strength of downstream hydraulic geometry relationships. These metrics provide insight into thresholds of channel reworking. They also provide the raw data for identifying alternative signatures of equilibrated channel morphology, and enable a cursory evaluation of river channel resilience to land use-induced changes to sediment and flow regime.

We recorded channel geometry at 24-25 reaches characterized by step-pool and plane bed morphology (Montgomery and Buffington 1997) along a 2.5km river segment in each of the three neighboring watersheds (73 sites in total, Fig. 4). We selected transect locations at a 100m interval to randomly capture local variability as well as regional trends as opposed to intentionally selecting sites based on reach morphology, i.e. pool, step or riffle. At each transect, we identified the level of bankfull flow based on a combination of topographic inflection, vegetation characteristics, erosional features and flood-deposited debris (*sensu* Wohl 2005 and Pike et al. 2010). We used a clinometer to verify the horizontal agreement of bankfull stage on both banks. We then stretched a tape across the channel to measure distance while a level line of twine was also secured to accurately measure depth below bankfull stage across the channel. At each topographic undulation we recorded a height measure using a stadia rod. We recorded the distance, substrate type and water depth (when present) to reproduce the bankfull and day-of channel geometry. Where multiple channel threads were present, we only measured the active channel; in other words, channel width does not include vegetated islands dividing channel threads. We recorded a water surface slope measure from the transect location to a point 40-60m upstream, depending on visibility and channel width, using a tripod-mounted surveyor's sighting level.

To capture sediment distribution for each site, we randomly selected 100 clasts along a random walk across the transect channel (Wolman 1954). We measured the median grain axis and classified into one of 24 size categories from very large boulder (2048-4096mm) to silt/clay (<0.1mm), including presence of bedrock in the channel.

We measured the day-of velocity with a flow meter (FlowWatch) along each transect at 60% depth. We used the bankfull perimeter to calculate bankfull stream velocity and discharge by applying the estimated Manning's *n* coefficient based on channel substrate and Manning's equation for velocity at each transect (recommended by Williams 1978). We used the day-of Manning's *n* coefficient to calculate bankfull discharge with the understanding that bankfull flow experiences lower n values (*sensu* Wohl and Wilcox 2005).

Data analysis

Evaluating Hydraulic Driving Force

In order to determine the strength and consistency of hydraulic forcing along the studied segments, we calculated several metrics of stream power and channel geometry. First, we calculated deviation from the average bankfull discharge for all transects in the segment. We then compared the pattern of deviation in bankfull discharge against channel features such as such as a bedrock boundary, multiple thread channel, gradient, w:d ratio, hydraulic radius, d_{50}/d_{84}. Second, in an effort to identify evidence of larger-scale channel evolution, we compared the w:d ratio for each transect to knickpoint location on longitudinal profiles derived from a 10m digital terrain model (DEM) and field-measured channel gradient. Third, we calculated downstream hydraulic geometry relationships for the 24-25 channel transects in each segment with least-squares log-linear regression between bankfull channel geometry measurements (i.e. width, depth and slope) and the bankfull discharge calculated from the field-identified bankfull stage. Fourth, we calculated the ratio of stream power to d_{84} for each site and compared the ratio to the 10,000 W m^{-1} m^{-1} threshold of hydraulic forcing (Wohl 2004). Lastly, we calculated the relationship between flow competence and bankfull discharge as the difference between bankfull shear stress and the critical shear stress of the d_{84} grains for each transect, assuming sediment is mobile when shear stress exceeds critical shear stress. Shear stress is estimated as:

$$\tau * = \rho g h S \qquad (1)$$

critical shear stress as:

$$\tau *_c = 0.045(\rho_s - \rho) g d_{50}^{0.6} d_{84}^{0.4} \qquad (2)$$

and critical depth as:

$$h = 0.045\left(\frac{\rho_s - \rho}{\rho}\right) d_{50}^{0.6} d_{84}^{0.4} S^{-1} \qquad (3)$$

where ρ_s is sediment density (2650 kg m^{-3}), ρ is water density, g is acceleration due to gravity (9.8 m s^{-2}), R is hydraulic radius (m), d50 is the median grain size (m) and d84 is near the maximum grain size (Lorang and Hauer 2007).

We also calculated the transport capacity of bankfull discharge with the simplified Meyer-Peter Mueller bedload equation (Meyer-Peter and Müller, 1948):

$$g_b = 0.253(\tau^* - \tau^*_c)^{3/2} \qquad (4)$$

where g_b is the mass rate of transport per unit width of channel (kg/m).

Identification of Alternative Equilibrium Expressions

We identified longitudinal patterns of morphological and hydraulic variables to identify alternative expressions of equilibrated channel morphology. Width:depth ratios and shear stress values at bankfull discharge were extracted for each transect along the three segments. We generated plots of these values in addition to the distribution of d_{84} along the three segments to explore relationships among the driving hydraulic shear force and channel w:d at bankfull discharge and bed sediment size. Also, given the significant fluctuation in bankfull discharge values along the three study segments, we used HEC-RAS (United States Army Corps of Engineers) to derive hydraulic geometry using a reference discharge of 20cms, and repeated the above analysis for Atirro under the reference discharge.

Land Use Effects on Channel Stability

We examined variations in morphological and hydraulic patterns among the three watersheds across a gradient of land use intensity. We analyzed the DHG and river competence results in relation to the land use intensity in each watershed to determine if effects of land use on channel morphology were evident. The strength of DHG relationships, expressed as the coefficient of determination between bankfull discharge and bankfull width, depth and velocity, was compared among the three watersheds. We noted differences in longitudinal patterns of channel gradient and w:d ratio in addition to sediment distribution and shear stress at bankfull discharge. We recorded the presence of bedrock along channel transects during random walk surveys, and we compared the abundance of bedrock exposure among the three river segments relative to alluvial reaches.

Results

Valley and Channel Characteristics

Wide, shallow channels with cobble to boulder size bedload and minimal gravel and sand lag deposits generally characterize the morphology of the channels in the three study basins. Segmentation of the watersheds exists only in the Platanillo basin within and beyond the studied reaches. Tropical mountain rivers typically show a lack of segmentation relative to their temperate counterparts carved by glaciation (Wohl 2005). However, a strike-slip fault bisects the Platanillo basin, which apparently generated segmentation along the elongated basin in the form of flat wide plains truncated by steeper, narrow canyons up and downstream of the fault zone. Floodplain development is minimal except in lower reaches of the basins of Atirro and Gato, whereas the floodplain along the fault zone in the middle reaches of the Platanillo Basin supports urban and agricultural development. Separated by a canyon stretch below the large mid-basin floodplain, a much smaller floodplain extends along a 700m stretch in the upper study reaches of studied Platanillo segment where the valley is less confining than the upstream and downstream reaches. Two slight terraces (<1m above the floodplain) run along the river left section of valley. Besides these floodplains in Platanillo and the lower reaches of Gato, steep hillslopes typically connect to the channel banks in the studied reaches, although vertical terrace scarps up to 10m high extend above the high-water marks in both Atirro and Platanillo. In Gato, ongoing bank erosion is evident as well, but in contrast to the other two basins, terraces are heavily vegetated and disconnected from the channel by narrow floodplain along several reaches. The active bank erosion in Gato, indicated by undercutting of the bank walls at the high flow stage up to one meter below bank tops, signifies abandonment of the narrow floodplain and channel incision. All three studied river segments occasionally bifurcate into two channel threads for distances up to ~150m. Heavily vegetated islands separate the channel threads, and in certain reaches, evidence of flow over the islands is clear, meaning a high roughness coefficient at bankfull discharge relative to day-of flow.

In all three river segments, reaches are characterized by either wide, coarse-grained sediment deposits spread across the active channel or more constricted, bedrock-lined channels. Bedrock channels are most prevalent in Platanillo, lining four of the 24 study reaches relative to a single bedrock reach in both Atirro and Gato. In particular, the bedrock channel in Atirro cuts through weathered limestone (Fig. 5g). Between the 2012 and 2013 field seasons, extensive scouring of the bedrock channel in Atirro occurred, demonstrating the dynamic nature of these systems (Fig. 5a-f). However, the degree of bedrock weathering is variable in the three river segments. The uppermost bedrock reach in Platanillo (PL3 and PL4) showed clear signs of erosion between field seasons in addition to abandonment of a side channel (Fig. 6a-d), but lower bedrock reaches were not as severely affected by the wet season flows (Fig. 6e). Atirro and Platanillo channels changed considerably between field seasons, indicated by significant bank erosion and channel widening as well as movement of d_{95} bedload, channel abandonment and lateral thalweg shifts. Large wood is present in all three rivers, although rarely appears to force channel morphology.

Channel Morphology

Field indicators of bankfull flows signified inconsistent discharge values along each of the three measured river segments (Fig. 7). Analysis of the residuals from each site's bankfull discharge relative to the average bankfull discharge value for the entire river segment did not reveal a correlation with any local controls such as bedrock exposure, multiple channel threads, valley confinement, or any morphological characteristics including channel width, depth, slope and sediment size distribution. Manning's roughness coefficients, derived from the day-of velocity and wetted perimeter at each transect, were also inconsistent. Estimated bankfull discharge did not follow a consistent or slightly increasing value in a downstream direction.

The ratios of bankfull width to depth express the strongest pattern among all morphological measurements. A longitudinal alternating pattern of wide, shallow to narrow, deep channel geometry appears in all three of the measured segments (Figs. 7 & 8). There is a weak tendency for bankfull discharge to fall below the segment's average bankfull discharge in wider, shallower reaches, especially when the outlying largest bankfull discharge deviation value is removed from each segment. This trend appears primarily in Atirro and Platanillo.

Progressive increases and decreases in the deviation of bankfull discharge from average along three or more consecutive sites are evident in Atirro and Platanillo. Applying a reference discharge of 20cms in HEC-RAS through the Atirro segment removed the bias imposed with use of bankfull discharge, and refined this longitudinal trend (Fig. 8). From 1.5 to 2 wavelengths are captured in each studied segment, although the trend is not regular. Measures of channel slope also express a graduated alternating pattern. Steeper slopes tend to appear where the channel is wide and shallow, but overall slope and w:d do not strongly correlate (Fig. 7).

Downstream Hydraulic Geometry and River Competence

Downstream hydraulic geometry relationships are weak along the study segments (Fig. 9) while stream power, shear stress and sediment transport rate at bankfull discharge are large enough to force for channel reworking (Table 3). The bankfull discharge values derived from the active channel at each transect yield no strong downstream hydraulic geometry relationships (Table 4 and Fig. 9). The downstream hydraulic geometry exponents range from 0.15-0.24 (width), 0.14-0.19 (depth), and 0.07-0.17 (velocity), lower compared to global averages of 0.5 (width), 0.4 (depth), and 0.2 (velocity) (Park 1977). However, in all 73 of the study reaches, the ratio of bankfull stream power to d_{84} breaches the 10,000 W m^{-1} m^{-1} threshold shown to indicate fluvial forcing of channel morphology (Wohl 2004). DHG relationships are considered well-developed in mountain channels when the coefficient of determination (r^2) between discharge and at least two of the three DHG variables is 0.5 or greater (Wohl 2004). The shear stress imposed by bankfull discharge at all reaches also exceeds the d_{84} critical shear stress, often by 100 Nm^{-2} or more (Table 3). The sediment transport rate ranges from 1,432 to 326,167 kg/s at bankfull discharge, a measure of capacity dependent on available sediment.

Sediment Distribution

Applying a reference discharge to the Atirro segment in HEC-RAS revealed a positive correlation between sediment size distribution and shear stress at the reference discharge ($R^2 = 0.69$) (Figs. 8 & 10). Generally, total bed shear stress increased in association with d_{84}. However, bedrock reaches, e.g., AT24 and AT21, exhibited high shear stress and the lowest d_{84} values measured along the segment (fig. 8). Bed shear stress and d_{84} exhibited a negative correlation with w:d ratios, and these relationships demonstrated the same exception in bedrock-lined reaches (Fig. 8).

Platanillo and Atirro had more erratic d_{84} and d_{95} sediment distribution longitudinally than Gato (Fig. 11). Both the Atirro (minorly) and Plantanillo (majorly) watersheds had riparian land use, often on steep valley slopes running directly to the stream banks (Fig. 1). Reaches representing equal basin area among the three watersheds do not provide a sufficient sample size to statistically determine whether channels are wider or deeper in the two basins experiencing land use relative to the forested Gato basin. However, the magnitude of observed incision in both Atirro and Platanillo was not evident in Gato. In all three river segments, incorporation of colluvial boulders was apparent.

Discussion

The application of dominant discharge and equilibrium concepts in extreme environments can shed light onto their limits. The 2.5km extent of river segment sampling may be too short to express DHG trends or consistent bankfull morphology, suggesting low spatial limits to the application of these concepts, at least in the three studied systems. Local, reach-scale resistance to hydraulic driving forces may prevent a consistent channel-forming discharge, and the high spatial resolution sampling was expected to capture this noise. Factors unique to individual sites such as recent colluvial deposits or bedrock exposure may resist hydraulic driving forces, influencing what discharge is required to modify channel morphology. On the other hand, efforts to describe systems outside the range of variability where these concepts were developed can overlook unique components or processes critical to explaining system dynamics. The intrinsic ability of these systems to adjust and reach an equilibrium state should be strengthened by the amount of stream power carving through weathering bedrock. Thus, conventional metrics of channel stability may simply not represent equilibrium at the high spatial resolution at which we sampled, or equilibrium may take another form in these end-member type systems.

Equilibrium Proxies in Extreme Fluvial Environments

We designed this study to identify patterns of channel morphology that serve as proxies for process-driven system stability in an extreme fluvial environment. We chose a high spatial resolution sampling methodology in an effort to find evidence of both the local-scale influence on channel morphology and the larger spatial threshold at which hydraulic forcing is expressed geomorphically. Channel morphology is shaped by flows that can move bed and bank material, which in mountain rivers means cobble and gravel-size sediment and implies bedload transport rather than suspended load (Knighton 1988, Emmett and Wolman 2001, Lenzi et al. 2006, Pike et al. 2010). Channel-forming flow in the humid tropics can be more frequent than observed in temperate regions, shown for instance to occur multiple times per year in the mountains of northeastern Puerto Rico (Pike et al. 2010). We anticipated a consistent bankfull discharge along channel segments as found in the studied channels of the Luquillo National Forest, Puerto Rico (Pike et al. 2010). However, neither a consistent channel-forming discharge nor well-developed DHG emerged from the full suite of morphological measurements. These results triggered interest in what constitutes equilibrium in extreme fluvial environments.

Given that basin area, discharge per unit area, stream power, and sediment transport capacity in our three study systems were well above the threshold of hydraulically forced channel morphology (Brummer and Montgomery 2003, Wohl 2004), we expected well-developed equilibrium morphology. If we consider the stream power and shear stress generated by the flow regime of these systems, there should be no question that these channels are predominantly shaped by hydraulic driving forces rather than controlled by resistant boundary conditions; hydraulic forces dominate local-scale resistance where the ratio of stream power to d_{84} is well above the 10,000 W m^{-1} m^{-1} threshold (Wohl 2004, Pike et al. 2010).

Intensifying the hydraulic driving forces acting on the channels, tectonic activity in the Reventazón Basin is driving both regional uplift and subsidence (Montero et al. 2013). Base level lowering influences the erosion rate of upstream watersheds, and although the erosion rate has not been quantified in the study region, the active pull-apart basin at the mouth of Atirro basin suggests ongoing base level lowering (Montero et al. 2013). The climatic and tectonic conditions should drive hydraulic overpowering of local scale resistance and develop a morphology that reflects the accrual of these forces over time.

An Alternative Equilibrium State

Our high spatial resolution sampling revealed a unique geomorphic expression of balanced geomorphic processes. Representing a repeating morphological pattern, the widening effect that the bed sediment patches impose on otherwise bedrock channel morphology in a system experiencing base level lowering was demonstrated along the studied river segments (Fig. 7) (*sensu* Yanites and Tucker 2010). Also, given the rapid morphological adjustment observed in the channels relative to temperate and semi-arid regions, a shorter temporal perspective for visualizing equilibrium was appropriate in these extreme fluvial systems (Figs. 5 & 6).

An alternating trend in w:d along the sampled river segments reflects the existence of sediment patches within an otherwise bedrock channel, where high w:d ratios represent sediment patch locations. This effect was seen where wide channels, including bifurcated channel threads, were situated directly upstream of headcutting knickpoints. In modeled contexts, wider channels have been shown to increase slope in order to generate the shear stress required to transport bedload (Yanites and Tucker 2010). Accordingly, our study channels appeared to widen in association with bifurcated channel reaches, which were often truncated by knickpoints. It is important to note that knickpoint locations on longitudinal segment profiles (Fig. 11), extracted from a regional 10m DEM, are likely out of sync with field data given the apparent rapid knickpoint migration rate based on observations between field seasons and discrepancies between 2001 aerial images and the current channel configuration. Observed changes in the channel morphology of bifurcated channels indicate that one channel thread appears to gather more flow and incise, driving a positive feedback loop and leading to the abandonment of the other, presumably until the widening cycle repeats.

Yanites and Tucker (2010) explored the relationship among channel width, slope, and incision rate between detachment-limited bedrock channels with and without a veneer of bedload alluvium. They showed that the variability in channel width and slope for natural systems experiencing a range of sediment input and erosion rates was generally resolved when sediment mantles were integrated into a model of bedrock channel evolution, and a tendency toward minimum-slope geometry emerged. Minimum-slope geometry is achieved when any subsequent changes in channel width or depth effectively reduce *average* bed shear stress. In other words, the minimum slope that can transport sediment delivered to the system under the existing flow regime defines equilibrium channel geometry. However, Yanites and Tucker's (2010) results demonstrated that where substantial base level lowering influences a bedrock channel covered by a sediment mantle, channel geometry shifts to a wider, shallower, and steeper equilibrium channel in sync with the base level lowering rate in order to sustain transport of the delivered sediment load. Bedrock incision alone requires a lower shear stress relative to channels with a bed sediment mantle that must transport bedload in addition to incising bedrock to keep up with base level lowering. Therefore, sediment transport requirements control channel geometry and maintain equilibrium in systems with rates of base level dropping low enough to allow sediment patches to persist along sections of the channel bed. In contrast, faster rates of base level fall tend toward detachment-limited systems that adjust incision rates to match base level drop through a combination of steeper slopes and narrower channels while transporting all supplied sediment (Yanites and Tucker 2010).

Resolving the morphological w:d pattern in the three studied rivers hinges on deciphering the mechanisms of patch creation and migration. Interpreting process from form assumes that the snapshot in time recorded by our field measurements accurately portrays the multiple temporal expressions of process captured spatially by the high-resolution sampling. Figure 12 illustrates the repeating pattern of narrow, bedrock-lined reaches bound upstream and downstream by wide, sediment-loaded, often braided reaches. The simulation of a reference discharge through the Atirro segment revealed that deep narrow channels tended to produce the greatest total shear stress. The shear stress values positively correlate with d_{84} and roughness, (Fig. 9, Fig 10), and negatively correlate with w:d in non-bedrock channels, particularly along reaches AT2 to AT14 (Fig. 9). Reaches with smaller d_{84} values represent the sediment patches with greater w:d. Where shear stress was greatest, larger grains lined a deep, narrower channel bed relative to sediment patch locations where total shear stress was spread across the wider bed, effectively decreasing competence and promoting deposition of the smaller sediment grains. This pattern disappeared in bedrock channels (e.g. AT21 & AT24), as only lag deposits existed. The regularity and agreement among the repeated trends suggests a self-organized expression of balanced forces in these systems.

Land Use and Alternative Equilibrium

Deforestation in the study watersheds may have amplified stream power and the capacity for channel scour. The delivery of water and sediment from a catchment to its stream network is altered by land cover conversion (Spaans et al. 1989, Germer et al. 2010, Hanson et al. 2004, Toohey 2012, Chapter 2), and the reduction of large wood in channels following deforestation has been shown to increase the distribution of bedrock versus alluvial channel reaches (Montgomery et al. 1996). Large wood plays a lesser role in forcing such geomorphic shifts in the humid tropics relative to temperate mountain basins however; high discharge per unit area and rapid decomposition rates restrict long-term morphological features that support alluvial reaches seen in small temperate mountain streams (Montgomery et al. 1996, Cadol et al. 2009, Wohl et al. 2012). Yet, Pike et al. (2010) show that a shift from colluvial to alluvial channels occurs when drainage area reaches 10km^2 in mountain watersheds of northeast Puerto Rico, similar to the threshold in large-wood-dominated coastal temperate streams of the Pacific Northwest (Brummer and Montgomery 2003). Our 25-35km^2 study watersheds also support alluvial channels, and if the described equilibrium condition of these end-member fluvial environments is accurate, effects of deforestation can be predicted and identified. For example, increasing stream power or decreasing sediment supply can generate heightened channel scour and expose previously mantled bedrock reaches. Given the high shear stress and sediment transport capacity of these systems, the balance between sediment load and fluvial transport likely manifests as the proportion of exposed bedrock reaches to sediment-mantled reaches (*sensu* Chatanantavet and Parker 2008).

The prevalence of bedrock reaches in Platanillo relative to Atirro and Gato may represent the geomorphic response to widespread deforestation. The Platanillo catchment was characterized by 41% land cover conversion, including sugar cane and pasture extending up steep slopes and along the channel banks, in contrast to the primarily forested Atirro and Gato basins (Fig. 1). Variability was inherent among all three river systems, but comparison across the three basins with different land use intensities revealed variation in the prevalence of bedrock and alluvial reaches. The 16 of 24 reaches that displayed bedrock along the 2.5km Platanillo segment contrast to five in Atirro and two in Gato. The discrepancy is consistent with simulations of the hydrological effects of land cover conversion in the basin using a physically-based distributed hydrological model (see Chapter 2) – greater peak flows generated greater stream power. Given unaltered or reduced sediment supply, the increase in stream power can maximize transport capacity, leading to a greater proportion of bedrock channels (Chatanantavet and Parker 2008). Essentially, the balance tips toward sediment transport, making sediment patches less common as they migrate out of the system.

We affirm that river systems defined in terms of equilibrium, including explanation of the mechanisms driving morphological variability, provide a foundation for informed management decisions. Acknowledging self-organizing equilibrium conditions and the temporal scale at which geomorphic responses to changes in hydraulic forcing and sediment supply manifest can provide a baseline for effective watershed management. For instance, where downstream sediment flux impacts hydroelectric power generation, the upslope impacts of land cover conversion can be foreseen and potentially avoided if areas of high sensitivity are identified and protected. Modeling watershed hydrology can simulate changes in water delivery to channels in order to anticipate effects that may transition areas of in-channel sediment storage to mobile sources of downstream deposition. Coupling knowledge of hillslope hydrology with an awareness of geomorphic process balance can reveal the resilience of a watershed to climate and vegetation changes.

Conclusions

Along the three studied river segments wherein strong hydraulic forces prevail, a lack of a consistent bankfull discharge or well-developed DHG initially suggested morphological disequilibrium. High spatial resolution sampling, however, demonstrated evidence of equilibrium defined by rapid, but predicable geomorphic change. Analysis of the fine scale variations in DHG revealed a nested pattern of w:d in the three end-member systems characterized by high precipitation amount and intensity, steep terrain, active base level lowering, and high chemical weathering and vegetation growth rates. Complex in terms of precise links between mechanism and morphology, the alternating trend in w:d ratio in all three rivers suggests a distinct geomorphic process. The pattern of sediment patches, including the proportion of wide sediment-covered reaches to bedrock or otherwise narrow, deep reaches, appears to represent a morphological balance with the strong hydraulic driving forces acting on these systems. Well-developed w:d ratios suggest that the system has reached a dynamic equilibrium in which a high rate of sediment transport is sustained as base level continues to drop. Implications of our findings are important for identifying equilibrium conditions in mountain river systems and predicting changes in channel morphology and sediment flux as land cover conversion and climate change intensify. Future work should address the mechanisms of patch development, including whether patches are migrating. Realizing spatially continuous measures of channel width, depth and slope will more precisely depict process-producing patterns, and lead to stronger models of river channel evolution.

Tables

Table 1. Watershed Characteristics

Watershed	Drainage Area	Elevation Range	Max Slope	Median Slope	Percent Altered Land Cover
Gato	3340ha	755-2355m	58^o	31^o	<0.1%
Atirro	3249ha	780-1980m	60^o	26^o	2.5%
Platanillo	2595ha	700-1940m	56^o	24^o	41%

Table 2. Precipitation Averages within Study Region (2002-2012)

WATERSHED	GATO				ATIRRO		PLATANILLO
STATION	ALTO GATO	TABANO	TAUS	ORIENTE	CUENCAS	LA ESPERANZA	PLATANILLO
Precipitation Average (mm)	7067.1	6865.0	5220.2	3974.3	5288.0	4623.5	3678.8
Station Elevation (m)	1700	1443	945	740	1835	873	889
Number of years in record	6	6	9	7	8	8	6

Table 3. Stream Power, Transport Capacity and Bed Shear Stress for Mid-Segment Transects

SITE ID	STREAM POWER AT BANKFULL ($W\ m^{-1}$)	Ω/d84 ($W\ m^{-1}m^{-1}$)	BANKFULL TRANSPORT CAPACITY (kg/s)	BANKFULL SHEAR STRESS (Nm^{-2})	d84 CRITICAL SHEAR STRESS	d50 CRITICAL SHEAR STRESS	CRITICAL DEPTH (m)	d84 CRITICAL DEPTH (m)	MEAN BF DEPTH (m)	MAX BF DEPTH (m)
AT14	21,375	**42,887**	**199,270**	988	484	39	0.19	0.85	1.8	2.5
PL14	22,718	**57,718**	**42,154**	573	382	64	0.29	0.84	1.3	2.1
EG14	47,763	**390,728**	**28,425**	345	119	36	0.26	0.53	1.6	2.3

AT=Atirro; PL=Platanillo; EG=Gato – 14th transect is the middle reach from each river segment

Table 4. Downstream Hydraulic Geometry

	range of upstream area		*r2 > 0.50 for 2 or more response variables = well-developed DHG*			*>10,000 = well-developed DHG*	
RIVER BASIN	**AREA (km2)**	**DISCHARGE (m3/s) (SndDev)**	**r2 for Q vs. w (DHG exp)**	**r2 for Q vs. d (DHG exp)**	**r2 for Q vs. v (DHG exp)**	**Ω/D84 MEAN**	**Ω/D84 STD DEV**
ATIRRO	19.3 - 32.5	20 - 147 (34)	0.10 (0.24)	0.07 (0.14)	0.03 (0.17)	115,102	119,589
PLATANILLO	20.8 - 26.0	13 - 202 (44)	0.29 (0.22)	0.10 (0.16)	0.02 (0.07)	149,672	201,654
GATO	27.9 - 33.4	16 - 349 (77)	0.10 (0.15)	0.19 (0.19)	0.06 (0.11)	231,930	174,950

Figures

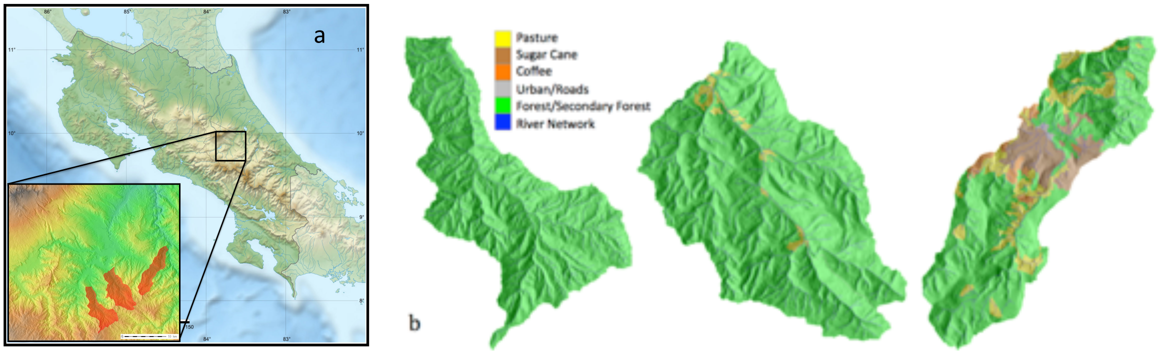


Figure 1. (a) Location of the three study watersheds in the Talamanca Mountains of central Costa Rica. (b) Land use distribution in the three study watersheds.

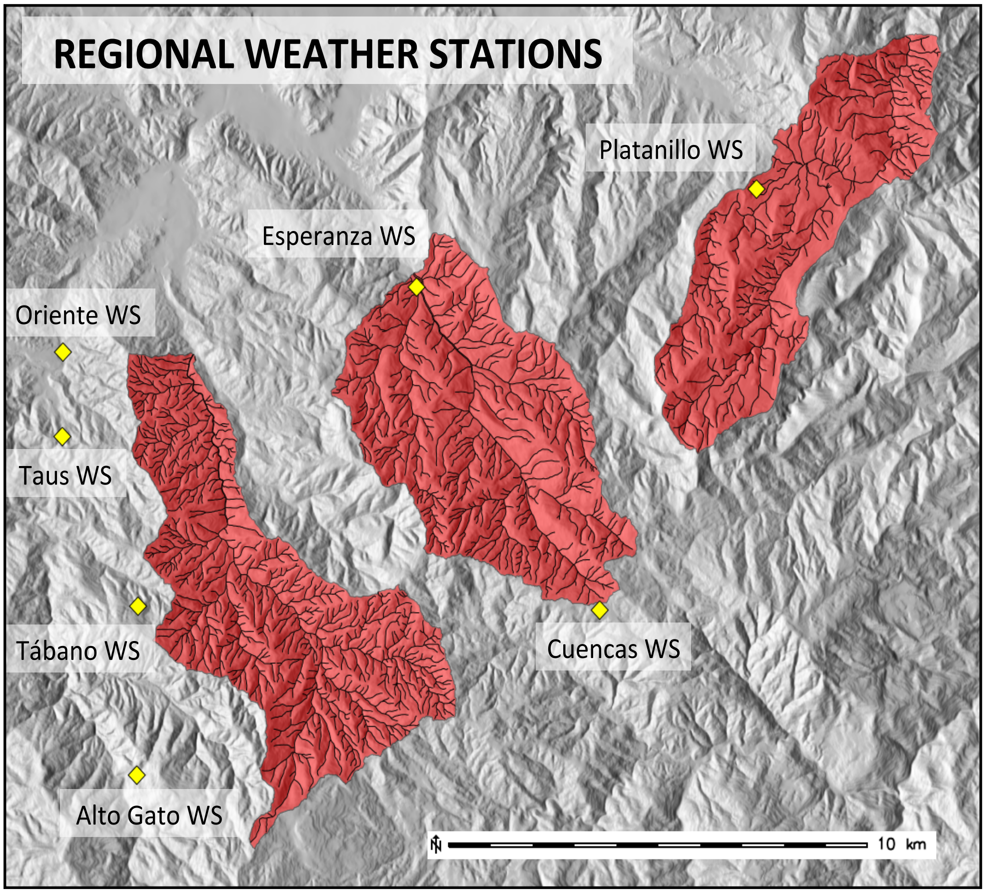


Figure 2. Location of meteorological stations in study region. Red borders delineate the three study watersheds with inset river networks.

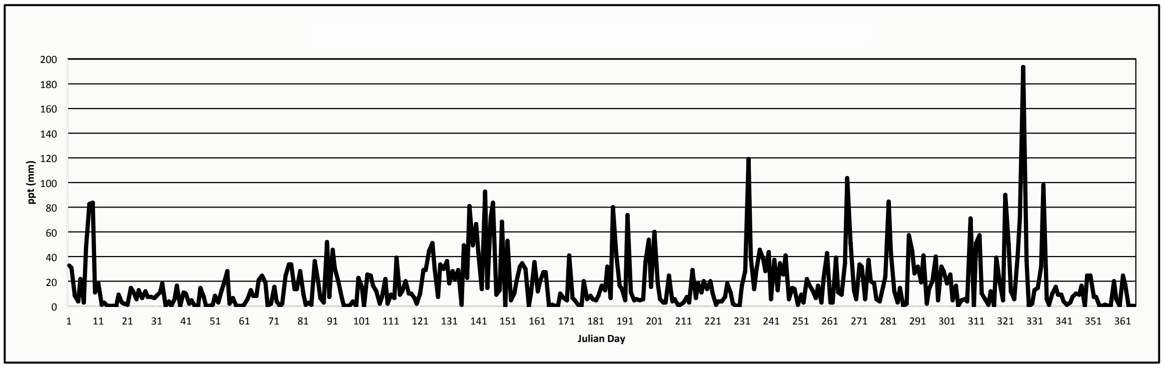
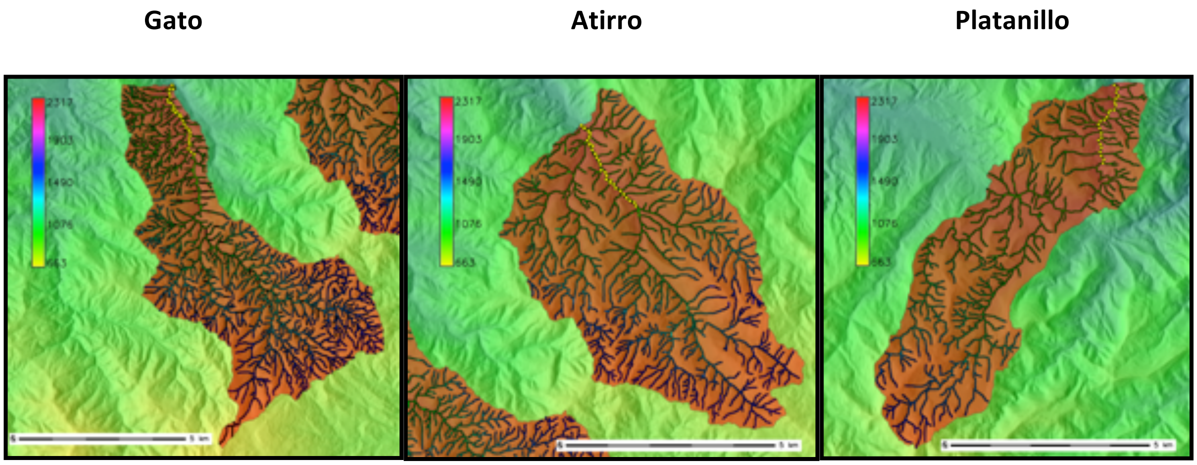


Figure 3. Sample annual rainfall record for Alto Gato for 2002 displaying the seasonal trend.


Gato

Atirro

Platanillo

Figure 4. Drainage network with channel transects. Color gradient represents elevation. Channel transects represented by yellow points along 2.5km of river channel at the downstream end of each watershed.

Figure 5. Images depicting morphological change that occurred between field seasons. Circles indicate the same location or boulder before and after. Images a-f are from Atirro site AT13; a-b are oriented downstream and c-f are oriented upstream. Images c and e are magnified views of the left edge of images d and f. Image g highlights active bedrock incision at AT12 (Fig. 7).

Figure 6. Images illustrating Platanillo channel dynamics. Images a and b (PL3a) were taken one year apart and depict active channel widening. Images c and d (PL3b) were also taken one year apart, and illustrate adjacent channel abandonment. Circled areas in images highlight the same location one year apart. Image e (PL14), representative of scoured bedrock channel reaches in Platanillo, was taken downstream of images a-d.

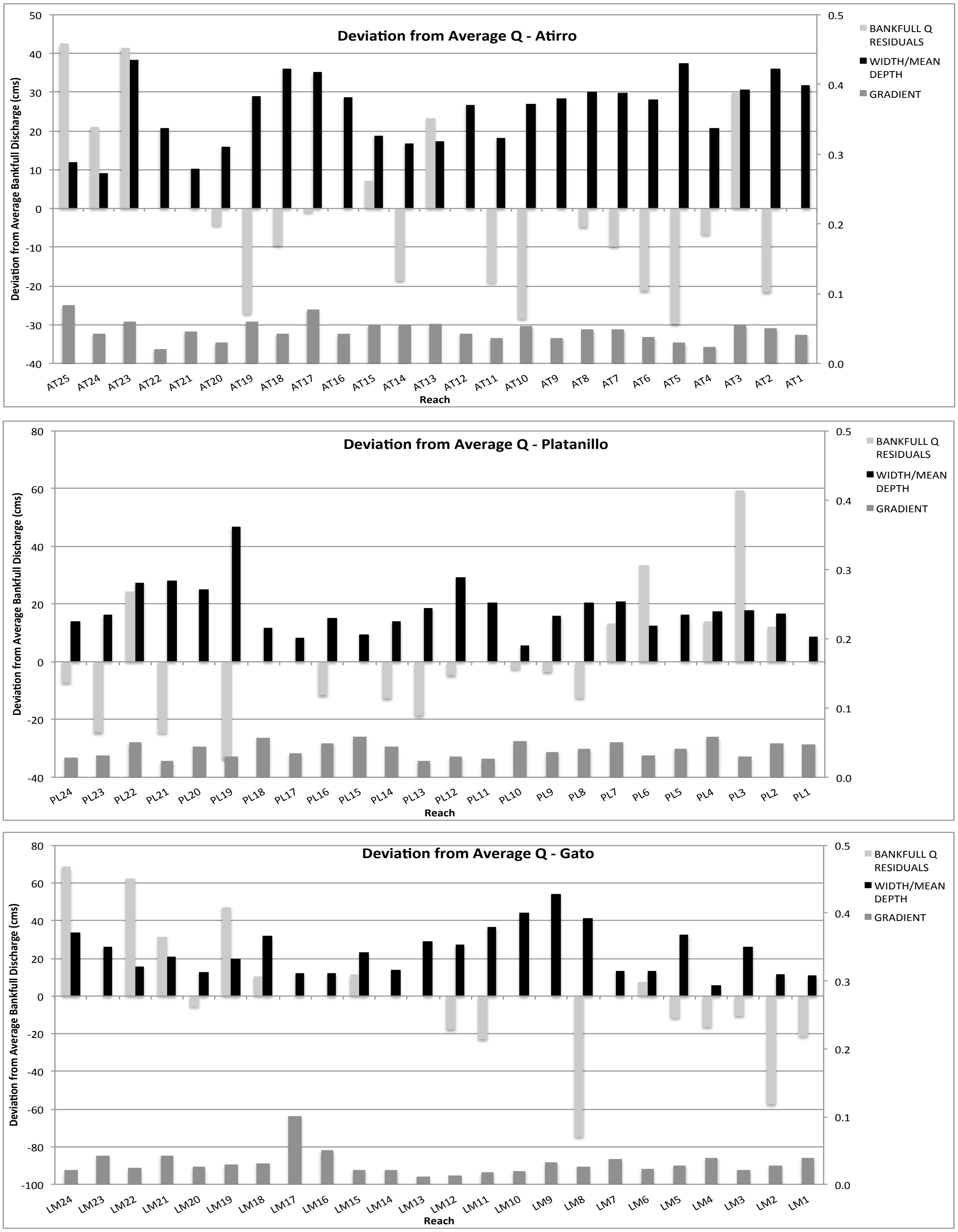


Figure 7. Deviations from average bankfull discharge (cms) relative to w:d ratios and reach gradient along each sampled river segment. A graduated alternating pattern of w:d ratios along each river segment may directly depict sediment patches. Where the ratio is high, the channel is wide and shallow due to a sediment patch and vice versa. The smooth trend represents a process acting on all three channels. Gradient also follows an alternating pattern.

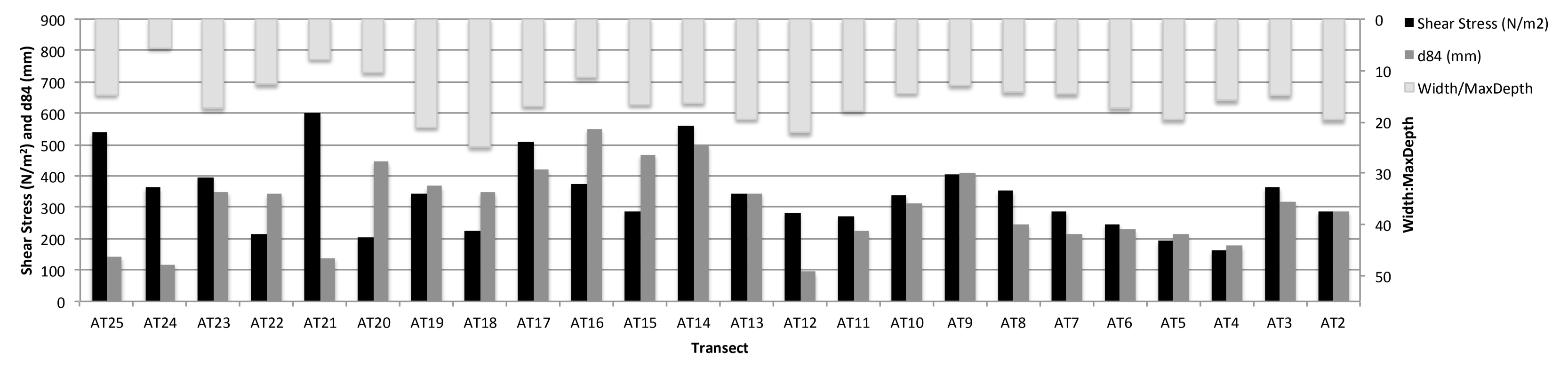


Figure 8. Relationship between the total bed shear stress derived with HEC-RAS using a reference discharge of 20cms and field-measured d84 at each Atirro transect.

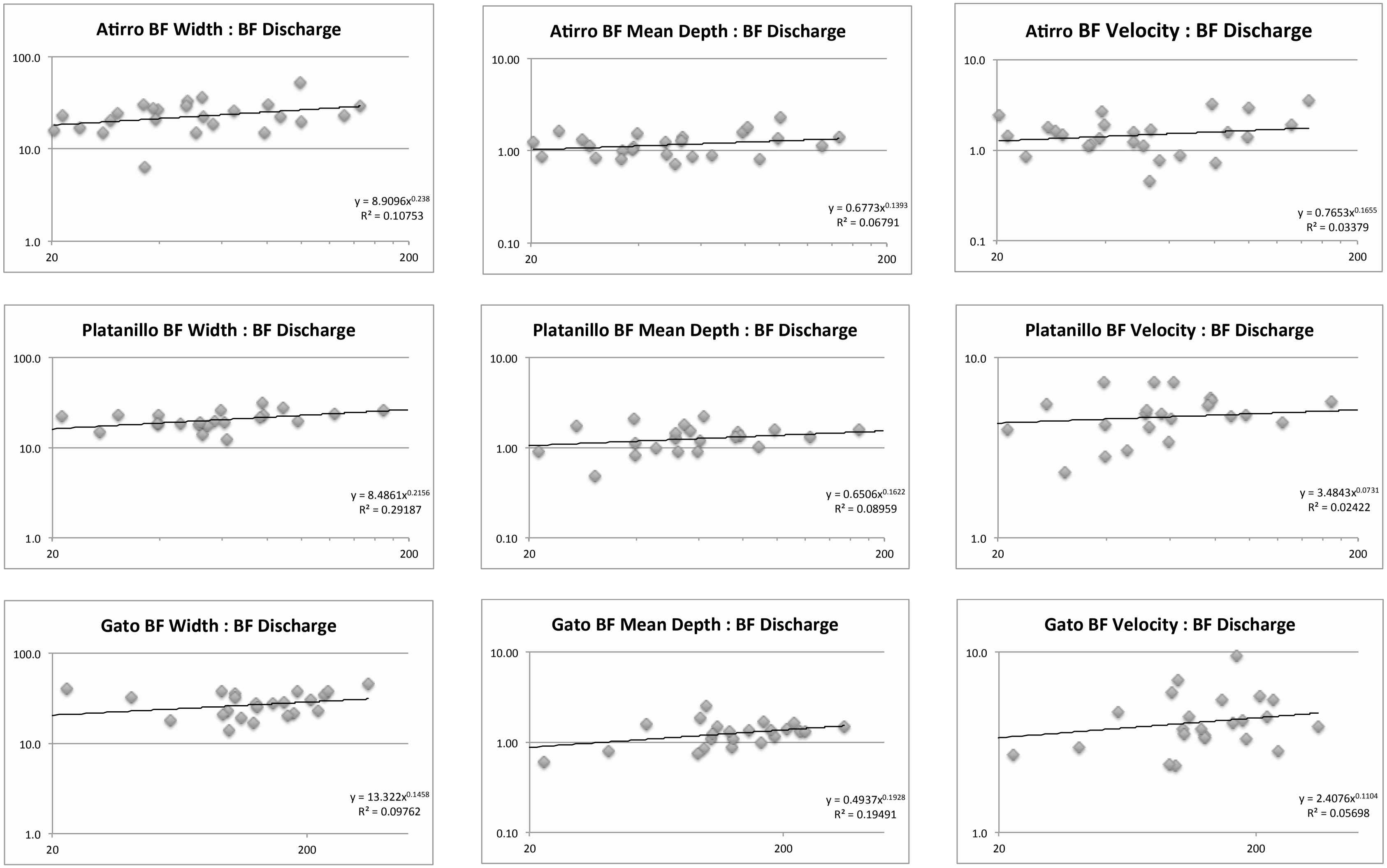


Figure 9. Downstream hydraulic geometry represented by least-squares log-linear regression between bankfull channel geometry measurements.

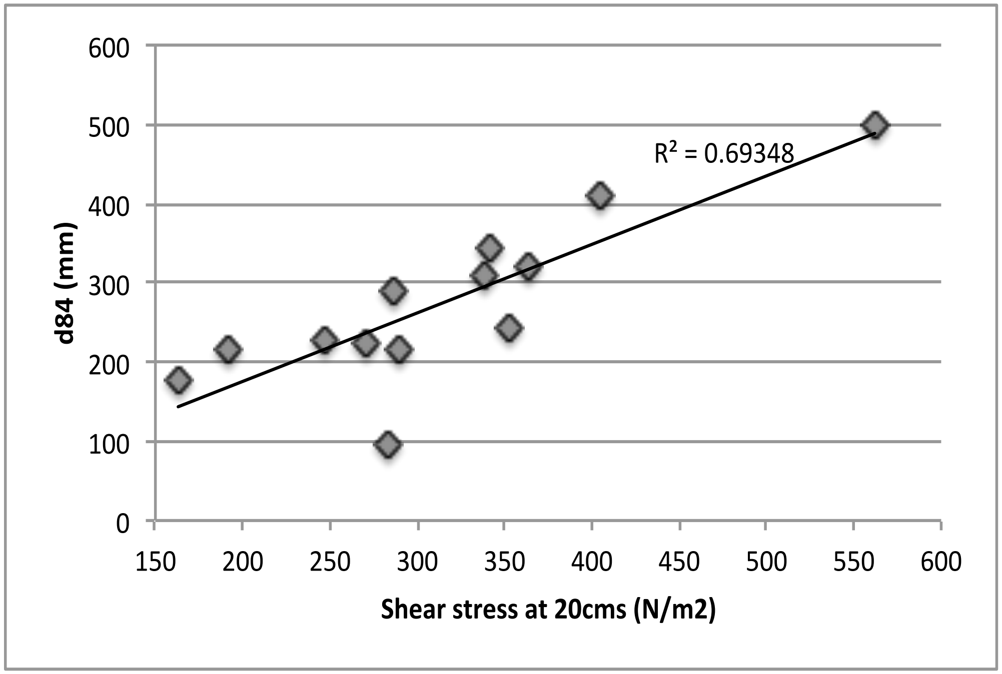


Figure 10. Relationship between total bed shear stress and d84 in Atirro at a reference discharge of 20cms for transects AT14-AT2.

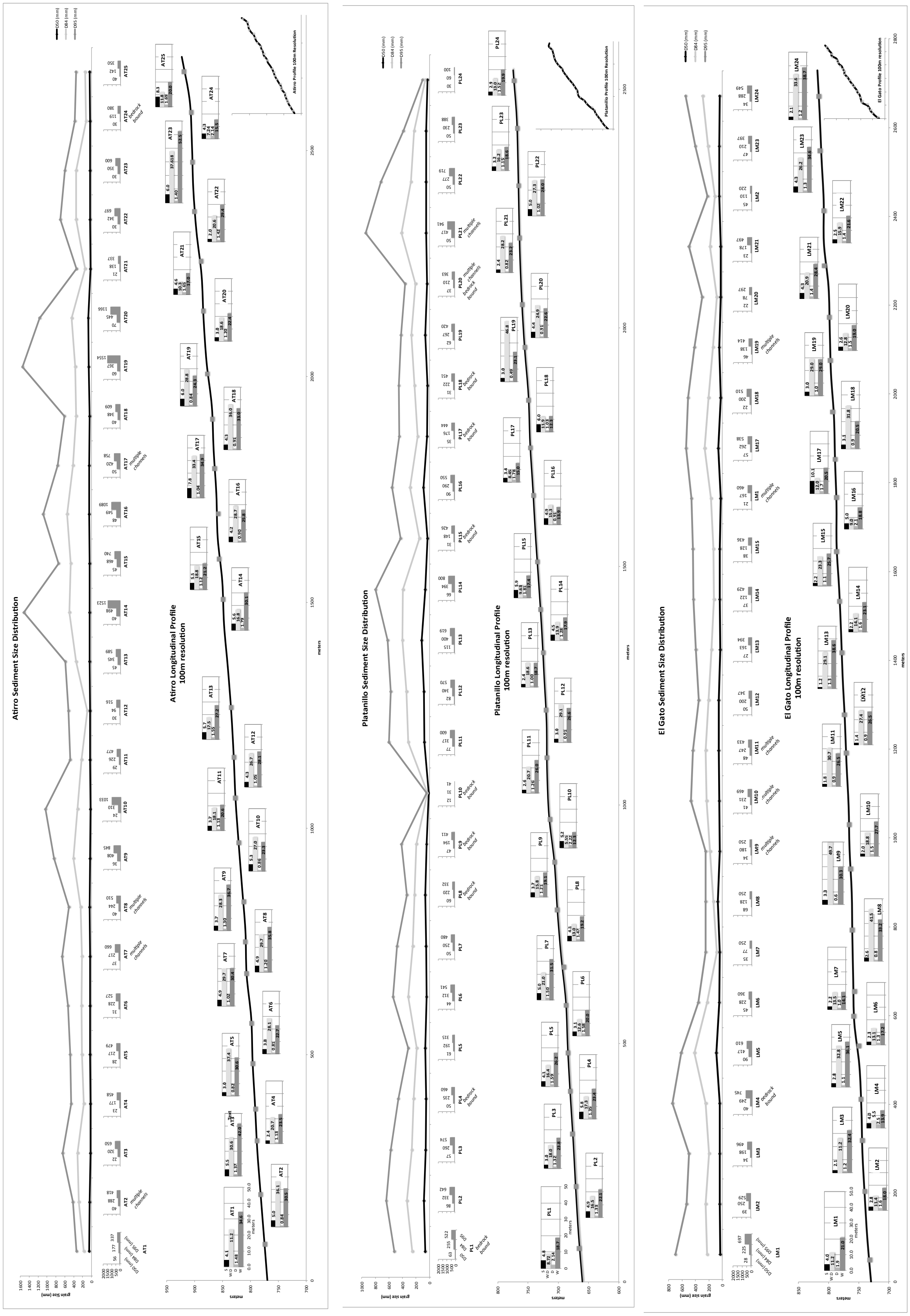


Figure 11. Longitudinal profiles, sediment size distribution and channel geometry.

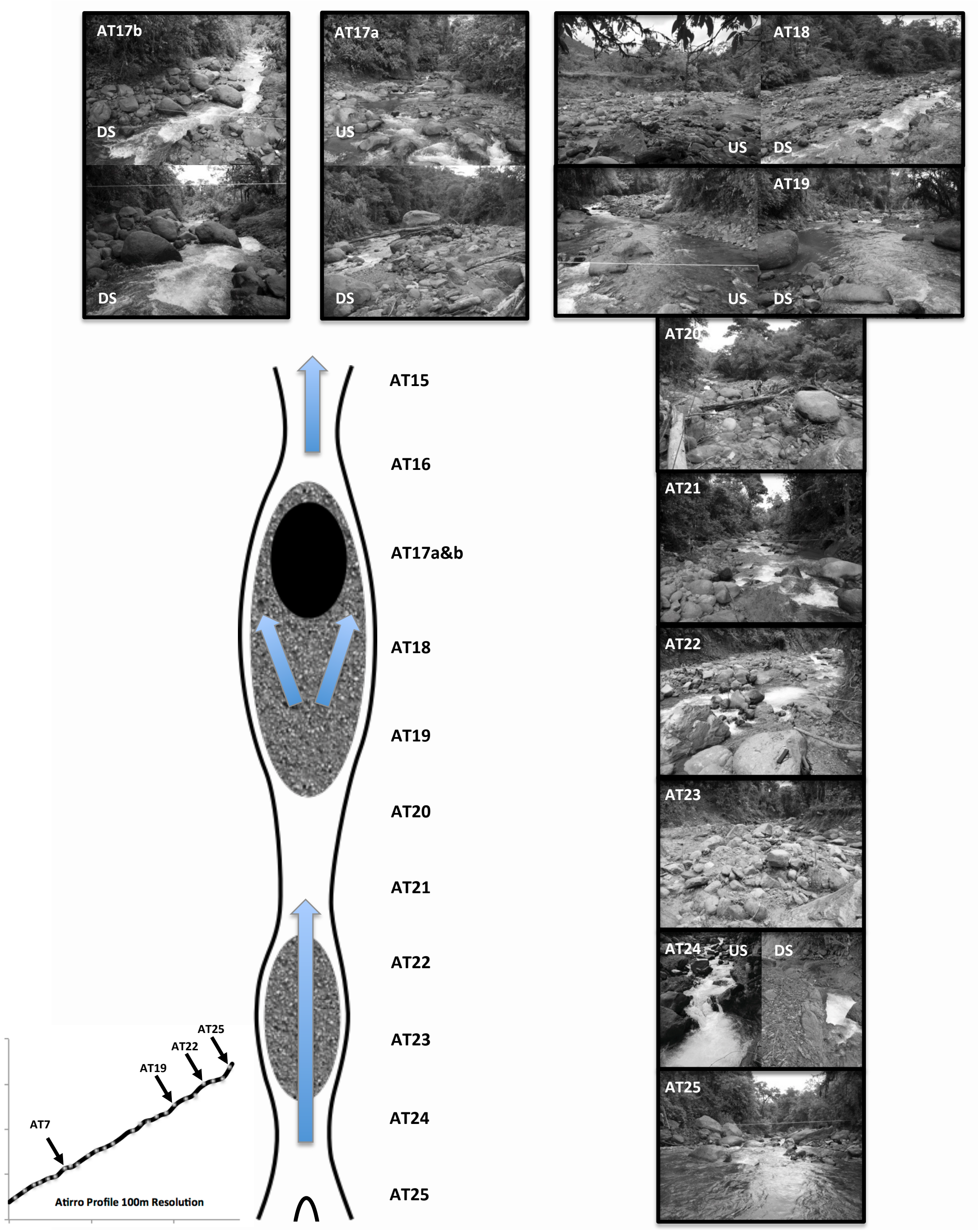


Figure 12. Representation of uppermost reaches in Atirro. Arrows indicate flow direction. Sediment patch locations (gray ovals) are based on w:d ratios (Fig. 9). Note locations of channel bifurcation upstream of AT25 and AT17 (black oval is a vegetated medial bar), and knickpoint locations on longitudinal profile derived from a 10m DEM at AT7, AT19, AT22 and AT25. Knickpoints are often associated with sediment patches in all three studied river segments. Photos show the wide sediment-laden zones where w:d is high relative to narrow, bedrock-lined channels with low w:d. US = upstream view, DS = downstream view.

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CHAPTER 2

Land use and climate change impacts on mountain watershed hydrology in data-poor humid tropics

Abstract

The tropical low latitudes, characterized by extensive multi-use landscapes that support rural livelihoods, are experiencing climate shifts more significantly than elsewhere on the planet. In these regions, land use induced changes to soil matrix and macropore hydraulic conductivity strongly affect the processes of percolation, lateral flow, and overland flow generation. This leads to highly altered watershed and stream hydrology. To interpret the influence of climate conditions and variable land use on stream hydrology, we used a distributed physical hydrology model to describe and predict watershed and stream hydrology under variable land use and climate conditions in mountainous terrain of the humid tropics. The model simulates the hydrological response of a watershed for a specified land use configuration where coarse-scale precipitation and soil data are available. We simulated the rate that precipitation travels through the catchment to the channel network and explore how resilient that travel time is to changing conditions such as climatic fluctuations, altered soil and vegetation characteristics due to land use, and the location and extent of land use within a watershed. Within three study watersheds in the central highlands of Costa Rica, abrupt changes in simulated stream hydrology result from modeled land use conversion and increases in precipitation intensity. Our findings suggest that decreased soil storage capacity associated with deforestation leads to increased overland flow and peak flow magnitude, reducing the hydrologic resilience of watersheds to predicted increases in precipitation intensity.

Introduction

Departure from long-term climate averages has occurred more rapidly and is more significant in the tropics than anywhere on the planet (Mora et al. 2013). Scientists predict departures to reach unprecedented conditions as early as 2020 (Mora et al. 2013). Moreover, low latitudes harbor the majority of developing nations with limited capital available for monitoring water resources and climate change (Revkin 2007). Resilience of coupled human and natural systems to disturbances, such as climate change or land cover conversion, is a desirable but difficult system characteristic to define (Walker and Salt 2006). In particular, system resilience is difficult to estimate prior to disturbance in systems experiencing unprecedented trajectories. There is an acute need to understand watershed resilience based on how disturbance alters interactions among system components. As climate change intensifies, the interaction between changing precipitation regimes and modified vegetation and soil conditions associated with expanding agricultural and pastoral land use may reduce the intrinsic resilience of watersheds to maintain services to the ecosystems and societies they support.

Watershed hydrology strongly influences river flow and sediment regimes. Changes in land use can impact the amount and timing of water moving through a watershed, but the mechanisms remain unclear (Allan 2004). This gap in knowledge is particularly significant in the humid tropics where modified landscapes often extend into the headwater basins of steep mountain terrain characterized by relatively greater drainage densities and sediment fluxes (Horton 1945, Wohl 2006). In the tropics, conversion from forest to agricultural and pastoral land use has been shown to alter land cover and soil properties considerably, affecting vadose zone hydrology, reducing the pervious nature of forest soils, and lowering storage capacities, infiltration rates and lateral flow (Spaans et al. 1989, Bruijnzeel 1991, Bruijnzeel 2004, Hanson et al. 2004, Germer et al. 2010, Toohey 2012, Niemeyer et al. 2014). In Costa Rican soils altered by pastoral land use, Spaans et al. (1989) found a twentyfold drop in saturated hydraulic conductivity. Accordingly, Toohey (2012) and Hanson et al. (2004) measured the soil properties (see Table 4) that explain why overland flow is more prevalent in pasture than in forest. Such shifts in watershed hydrology associated with deforestation can alter streamflow. For example, Germer et al. (2009) documented a doubling in runoff event frequency in pasture relative to forest accompanied by a 17-fold increase in streamflow magnitude through pasture in southwestern Amazonia. Similarly, Costa et al. (2003) found that mean annual discharge and peak flow increased in response to dramatic changes in land cover in southern Amazonia.

Humid tropical climates coupled with mountain topography may amplify the effects of altered watershed hydrology. Relative to temperate and arid regions, the precipitation regime in the humid tropics is marked by subtle seasonality and frequent high magnitude and intensity events, often flashier on an annual scale with lower interannual hydrological variability (Wohl 2006). However, recent climate change predictions for the tropics forecast increased interannual variability (Mora et al. 2013), potentially intensifying the hydrological effects of land use, which in mountain watersheds of the humid tropics is growing faster with less regulation than mountains in temperate and semi-arid regions (Wohl 2006). The expected departure from historic climate extremes includes more intense precipitation events and droughts (IPCC 2007, Mora et al. 2013). With these looming changes, watershed scale hydrology models can help inform how increasingly intense precipitation events and the prevalence of altered land cover might alter hydrology in the mountainous humid tropics.

According to Bruijnzeel (2004), a lack of long-term high quality monitoring data in the tropics has complicated hydrological analyses aimed at evaluating the influence of land use on river flow regimes. In the absence of long-term streamflow data, physically based hydrology modeling can help define dynamic system properties, and explain how disturbances impact a system, informing managers in data-limited complex systems that are increasingly characterized by non-stationarity. Due to the deep hydrologically connected soils in the humid tropics, a model that simulates surface and subsurface flow at a watershed scale is preferred. Where subsurface flow is considered a “complexity” and soils are shallow, surface runoff models such as HEC-HMS have been used to simulate watershed hydrology (e.g., Adams & Spotila 2005). The Soil Moisture Routing (SMR) model (Boll et al. 1998, Frankenberger et al. 1999, Brooks et al. 2007), however, is a GIS-based spatially distributed hydrologic model appropriate for both deep and shallow tropical soils and limited environmental data found in humid tropics because it accounts for subsurface flow parameters and requires limited data.

In Costa Rica, population growth and rapid land development between the 1940s and 1980s resulted in an 83% reduction of forest cover (Sader & Joyce 1988, Bonell et al. 2010). The trend continued from 1986 to 1991 as deforestation rates surged higher than anywhere on the planet (Sanchez-Azofeifa et al. 2002). In addition to intense land development, a climate regime characterized by frequent intense precipitation events (UNESCO 2007, MINAE 2008) and deep well-developed soils make the central Costa Rican highlands an ideal site for hydrological studies, especially in contrast to temperate and semi-arid regions. Moreover, the relatively stable climate regime of the tropics is expected to deviate from its long-term average range sooner than any other ecoregion (Mora et al. 2013). Similar to other developing counties, Costa Rica does not have an extensive environmental monitoring infrastructure, particularly for water resources. Consequently, limited long-term data coupled with impending climate change and pervasive losses of hydrological functions associated with land use preclude informed management strategies.

Ongoing land cover and climatic shifts across the humid tropics present a challenge for land managers responsible for regions lacking long-term monitoring. The main objective of this paper is to determine hydrologic dynamics at the catchment scale in data-poor regions of the humid tropics. We apply first-order physical process controls within a spatially distributed hydrology model to avoid reliance on calibration, a need expressed by McDonnel et al. (2005). We upscale plot-scale hydrology to understand the influence of land cover and precipitation magnitude and intensity on streamflow in HUC level 3 (10,000 acre) steep mountain basins (river gradient >0.002) of central Costa Rica. Our efforts provide a rapid and inexpensive procedure for deciphering the effects of land use and changes in precipitation regime on watershed hydrology in steep terrain of the humid tropics without need for long-term or spatially exhaustive datasets (*sensu* Ticehurst et al. 2007; and Wohl 2010).

Methods

Study Sites

We selected three mountain watersheds in Costa Rica to study the effects of climate change and land use on humid tropical watersheds: Gato, Atirro, and Platanillo. These watersheds (HUC level 3 – 3,000ha) are located in the Talamanca Mountains in central Costa Rica draining to the Atlantic Ocean. The watersheds have similar area, shape, elevation gradient, average channel slope, climate, geology and proximity to one another (Table 1). Two of the watersheds, Gato and Atirro, lie within the Reventazón Watershed, and the third, Platanillo, is part of the Pacuare Watershed (Fig. 1a). The watersheds represent a gradient of land use, allowing analysis of land use effects on watershed hydrology. Located within a forest reserve, Gato is 99.9% primary and secondary forest with no known roads. Atirro has 2.5% non-forest land cover, with deforestation including roads within or adjacent to the riparian zone. Plantanillo is intensely modified with 41% of the watershed experiencing modified land cover including agriculture, pasture, and urban uses (Peréz 2009) (Fig. 1b). The land use in all three watersheds has been consistent for decades.

The region encompassing the three watersheds has an annual rainfall average of 5.25m, over the study period from 2002-2012 (Instituto Costarricense de Electricidad (ICE)). A precipitation gradient, evident in records from meteorological stations in and near Gato and Atirro watersheds (Fig. 2), ranges from 7.07m at 1700m elevation to 4.62m at 873m elevation (Table 2). Although rain falls almost daily at higher elevations in the study region, a drier season reduces precipitation during the months of February through April (Fig. 3). A weaker gradient from west to east is also evident from the decline in precipitation between stations at similar elevation including the Alto Gato and Cuencas stations and La Esperanza and Platanillo stations (Table 2).

Soils in the region are mapped as Typic Haplohumults and Typic Dystrudepts depending on proximity to lowland alluvial valleys where Inceptisols are most common (Winowiecki et al. 2007). In the study watersheds, Haplohumults dominate, although soil depth varies depending on slope (Table 3). Jansson (2002) summarized soil descriptions from Torres (1952), Bergoeing and Malavassi (1982), and Mora (1987) for the Pejibaye watershed that includes the Gato watershed. Clay-rich Ultisols dominate the Gato watershed. Geology and native land cover is similar for both the Atirro and Platanillo watersheds.

Evaluation of Hydrologic Response Variability

The hydrologic routing of precipitation to channel outflow was simulated using the physically based spatially distributed SMR model (Boll et al. 1998, Frankenberger et al. 1999, Brooks et al. 2007). The soil parameter inputs (Table 4) are based on plot-scale measurements of soil parameters from

Hanson et al. (2004), (Toohey 2012), field-measured soil properties from the three study watersheds, and local meteorological station data (Tropical Agricultural Research and Higher Education Center (CATIE), ICE). Spaans et al. (1989), Hanson et al. (2004) and Toohey (2012) adopted the soil hydrology parameters from plot-scale soil hydrological analyses of land use effects under topographic, soil and climate conditions similar to the study watersheds. The soil description from Hanson et al. (2004) most closely agree with the soil type identified in the three basins and was used in the model. Although Toohey's (2012) sites are near to the study basins, significant soil age and parent material differences between the two regions can explain much of the difference in the adopted soil hydrology values from Hanson et al. (2004) compared to Toohey's (2004) values.

We ran the SMR model in the open source Geographic Information System (GIS) software GRASS (Geographic Resource Analysis Support System, http://grass.osgeo.org/). The model runs in a GIS environment allowing it to route precipitation through soil and runoff pathways in a simulated contiguously gridded landscape. Each grid or cell is given a value based on its layer theme, and each layer represents one model input parameter (Table 4). Layering themes representing soil parameters in the GIS environment allows the model to calculate the input and output amount and flow path at each cell for a given time step (Figs. 4, 5 & 6). Modeling the timing and magnitude of flow at basin outlets generated hydrographs at the resolution of the input time step.

In order to validate the SMR results for the two ungauged study watersheds where direct comparison to actual stream discharge values was not possible, we modeled output discharge for the Atirro watershed where a gauge exists. We determined the proportion of flow contributed by the Gato watershed to a downstream gauge in order to compare simulated discharge values with the gauge record. For Atirro, we determined base flow through post-processing a groundwater recession equation to explain the draw down rate and pattern for the gauge data. Observed data show that the basins respond as non-linear reservoirs, so they were simulated using the equation:

$$Q_b = \left(\frac{P_c}{a}\right)^{(1/b)}$$

where $Q_b$is base flow, P_c is the cumulative percolation at each time step, a and b are recession constants.

Using a 10m grid resolution, we simulated streamflow at the outlet of each of the three watersheds for scenarios defined by input soil parameters associated with a range of land use configurations and precipitation intensities associated with climate predictions (Figs. 5 & 6, Tables 5 & 6). The analysis of streamflow patterns includes comparison of peak flow events and low flow periods simulated using existing and high-intensity precipitation regimes (Table 5) and land use configurations representing existing, forested, and pasture converted land cover.

We modeled maximum rainfall intensity ranging from of 19.4 to 116.6 mm 2hr^{-1}. The rainfall intensity was adopted from rainfall totals at the nearby Aquiares Farm (Roupsard, personal communication) (Table 5) and the CATIE campus outside of Turrialba. The Aquiares rainfall totals are an order of magnitude less than Atirro totals, and the recorded maximum two-hour rate (35.5mm) is roughly twice the maximum intensity used in the model runs for existing conditions (19.4mm). The precipitation intensity classified as "existing" was derived by taking the gauged daily precipitation total and distributing it over 24 hours with a 16 hour period of evenly-distributed precipitation bound by four hours at half the intensity before and after the 16 hour period. The maximum rainfall intensity rate was ramped up by reducing the time of daily rainfall distribution to six hours with the central two-hours receiving the highest intensity. We simulated watershed hydrology in the study watersheds using soil parameters associated with existing, forested and intense land use, under both actual and high precipitation intensity (Table 6).

SMR Model additions

We adjusted the SMR model (Brooks et al. 2007) by developing algorithms for overland flow, elevation-adjusted rainfall, and multiple land use types within soil parameters classes. Overland flow routing provides a way to evaluate re-infiltration of overland flow as runoff travels downslope from one land cover and soil type to another. During every time step, each cell's incoming and outgoing runoff was calculated, and, based on soil storage capacity, either infiltrates into the downslope cell or was added to the cell's runoff total. All overland runoff was processed for all cells in the simulated watershed until it either infiltrated or reached a channel. Due to the significantly extended run time of the model with overland flow routing (days versus hours), we only used it for simulations of the existing land use configuration in Platanillo since it represents a mixed land use matrix. If desired, the runtime can be reduced by decreasing cell size and by simulating smaller basins.

The model can process two-hour time steps in order to capture more precise peak flow events given the observed flashy nature of mountain watersheds. Again, this addition to the model extended the run time considerably. For our existing rainfall intensity runs, we assumed a distribution of daily rainfall totals in which 5% of the daily total fell in each of the two first and last two-hour intervals of each day and 10% of the daily rainfall total fell during each of the remaining two-hour intervals spanning 4am-8pm.

We also added an algorithm to generate a gradient for both soil depth based on slope and precipitation based on elevation. We extracted the range of soil depth reported in Jansson et al.

(2002) to create the boundaries of the soil depth gradient, modeled as a linear relationship with slope angle. The precipitation gradient was extrapolated from known gauge records where more than one weather station was present in the modeled basin (Fig. 2). This was done for Gato and Atirro, but the sole weather station in Platanillo restricted generation of a precipitation gradient.

Model accuracy assessment

Of available data, the 2002 records provided the most comprehensive precipitation and gauge data for both Atirro and Gato basins. For Gato, the observed discharge data were only available for one full year (2002) at the Victoria Gauge three river kilometers downstream of the confluence of the Gato and Marta rivers. The simulation was performed within the Gato basin directly upstream of this confluence using nonlinear base flow recession constants equivalent to the Atirro simulations when calculating the contribution of percolation storage to runoff at each time step. The average proportion of the observed gauge discharge simulated in Gato was used to determine the overall contribution of Gato basin to the observed flow downstream.

The model accuracy was assessed using the Nash-Sutcliffe efficiency parameter Ns (Nash and Sutcliffe 1970). The equation used to calculate the Ns parameter is as follows:

$$Ns = \frac{v_o - \sum_{i=1}^{N}(x_i - y_i)^2}{v_o N} = \frac{\sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

where v_o is the variance of observed values, N is the total number of data points, x_i is the observed value, y_i is the corresponding simulated value, and $\bar{x}$ is the average observed for the study period. Results were evaluated where observed gauge data were available.

Results

Stream flow simulations

The SMR model accurately simulated the 2002 stream gauge data available from Atirro and Gato basins. A Ns parameter of 0.67 was calculated for Atirro (Fig. 7). A Ns parameter of 0.64 was calculated using simulated Gato discharge and 56% of the Victoria Gauge record, the average proportion of Gato contribution at the Victoria Gauge (Fig. 8). These results were achieved without calibrating the model. No gauge data exist for Platanillo, and thus the results are assumed accurate based on the success of the model simulations from neighboring Atirro and Gato.

Mass balance

SMR simulations for the Atirro Watershed under existing and pasture-conversion scenarios illustrate the relative contributions from each component of the 2002 water budget (Table 7). Most significantly, differences in the contributions of percolation and overland runoff to streamflow between the two land use configurations were the fundamental hydrological differences between the simulated scenarios. The percolation contribution to streamflow represents 74.2% of total basin output in the existing land use configuration whereas overland runoff accounted for only 7.5% of the annual output. Simulated conversion to pasture caused a marked increase in runoff at the expense of percolation. Simulation of the existing land use configuration in Atirro indicates a 4.8% storage coefficient relative to 1.6% storage in the pasture conversion. Storage includes water occupying soil pore space (percent saturation), active lateral flow, and precipitation intercepted by the canopy at the end of the simulated year. In both simulations, the final balance was slightly negative in the subsurface reservoir indicating a net loss from the initial percolation storage amount – 7.9cm from the existing modeled watershed and 11.4cm from the pasture converted watershed. Simulated evapotranspiration amounts were similar for both land cover configurations at approximately 70cm total lost per year across the basin, accounting for 14% of the water budget.

Cumulative plots of each water balance component illustrate the percolation and overland runoff contributions to streamflow associated with forest conversion to pasture (Fig. 9). Seasonality is also evident. The dry season ends near day 125 followed by a gradual response in the forested watershed relative to the nearly mirrored response to increased precipitation by discharge and runoff in the pasture configuration. Base flow only slightly increases after the onset of the wet season in the pasture configuration, whereas the rise in discharge in the existing, forested configuration is clearly due to a parallel, albeit steady increase in base flow. The rate of percolation contribution to base flow in the pasture configuration appears to remain relatively constant throughout the year. We were unable to accurately maintain the greater observed base flow level in our model during the dry season for Atirro.

Runoff coefficients calculated from observed precipitation and discharge gauge records in Atirro indicate a delay in the basin response to wetter periods (Fig. 10). In addition, there is a balance between the annual precipitation input and discharge output, however the monthly runoff coefficients reveal the lag in discharge increase following wetter months. A lag in discharge response occurs at the transition from the dry to wet seasons, indicating storage filling (Fig. 10: Apr-June 2002 & 2003). Likewise, a slower discharge decline occurs at the shift to the dry season (Fig. 10: Nov-Dec 2002). Evapotranspiration loss is not represented due to the apparent balance of annual precipitation and discharge. This relationship is also evident to a lesser degree in the larger Pejibaye Basin; there is a larger precipitation gradient between the upper and lower elevation weather stations relative to Atirro making an annual input-output balance less apparent.

Land cover effects

After conversion from forest to pasture, peak flow increased and event duration before reaching base flow decreased dramatically in all three basins (Figs. 8, 11 & 12). Although no river gauge has ever monitored flow in Platanillo, the existing mixed land use matrix was unique relative to the other two basins. Besides the existing land use scenario, simulations in Platanillo also represented the basin as completely forested and as dominantly pasture with existing urban areas and road network. The results of the three simulated land use configurations demonstrate similar trends of high flow spikes and subsequent rapid drops below the forested base flow stage (Fig. 12).

When using the two-hour time step for the pasture-dominated land use, peak flows fluctuated more than in the simulated daily hydrographs. The two-hour time step simulation under the extreme pasture-dominated land use scenario for Atirro is shown in Figure 13. This greater fluctuation in the shorter time step simulation reveals the importance of the response time to changes in precipitation magnitude and intensity during a single day. In the two-hour simulation, the discharge closely follows the dynamics of the input precipitation rather than moderating the flow regime.

Precipitation intensity

Increasing precipitation intensity did not significantly alter average daily discharge in simulations of forested basins, although when rainfall intensity was increased in the pasture conversion scenarios, daily peak flows generally increased (Figs. 14 & 15). It is important to recognize that daily averages do not capture the shorter duration peak flows that move through the system. From the daily resolution of the precipitation record, intensity can only be estimated, and daily discharge averages tend to smooth the rapidly responsive flow peaks and troughs observed in the field. Applying rainfall intensity over a two-hour frequency simulated more extreme differences in flow peak magnitude between the existing and pasture scenarios (Fig. 16). The flashy nature of the hydrograph is exacerbated by the greater runoff potential of pasture relative to forest. The two-hour time step simulations improve resolution of the fluctuations in flow from pasture, closely reflecting the variation in precipitation intensity (Fig. 13). To more accurately simulate the peaks in flow associated with changes in land cover and rainfall intensity, a two-hour time step is recommended at the expense of a longer run time.

Runoff routing

We found that routing saturation-excess overland flow was most beneficial in watersheds characterized by a mixed matrix of land use. Particularly when a land cover associated with significant subsurface storage is situated downslope of land cover that frequently generates surface runoff, re-infiltration can occur. The conventional method of subtracting all saturation-excess runoff at each time step fails to account for re-infiltration. This effect is evident in the Platanillo simulation results, in which the watershed is characterized by 41% deforestation and land cover conversion (Fig. 1 & 17). Figure 17 shows the drop in peak flows due to inclusion of the overland flow algorithm; peaks are somewhat lower in simulations incorporating the routing script as a result of downslope re-inflitration.

Discussion

Land cover and rainfall intensity

Land cover most strongly influences the delivery of precipitation to the channel network in simulations of the three watersheds. Changes in stream hydrology driven by precipitation intensity, while significant, appear of a lesser magnitude. The influence of land cover, caused by the associated changes in soil conditions, is most pronounced in the conversion of forest to pasture. In pasture, discharge closely follows the dynamics of the input precipitation as opposed to the moderated flow regime produced by the forested watershed. Soil storage and percolation contribute to the buffered flow regime in the forest relative to pasture or sugar cane dominated watersheds in which lateral flow, flow convergence and saturation-excess runoff constitute the majority of streamflow. It is no surprise then that forest conversion to intensive land use leads to greater peak flows followed by rapid returns to lower than forested base flow levels. One implication of greater peak flows is greater stream power capable of transporting more and larger sediment from channel bed and banks. Channel widening and/or channel incision can result from such hydraulic shifts.

Beyond the effects of agricultural and pastoral land development, simulations of greater rainfall intensity falling on existing land cover, complete forest cover, and complete pasture in all three basins reveal the filtering effect of vegetation and associated soil conditions (Figs. 14, 15 & 16). Where forest soils dominate, high vertical hydraulic conductivities direct the majority of non-intercepted infiltration water into storage. Percolation from this storage to the stream channel contributes the majority of discharge in forested basins (Table 7 & Fig. 9). Although stream hydrographs are still flashy, the storage buffers this major flow path and thereby moderates the influx of water to channels, maintaining a more consistent flow regime relative to pasture-dominated watersheds (Fig. 11). Given the inherent flashy nature of these systems, daily flow averages serve to minimize flow peaks that pass through the channel in response to intense rainfall. Figure 13 more precisely illustrates the flow peaks produced in a pasture-dominated watershed compared to the same watershed with forest cover. Above all, the simulations show that these systems rely heavily on groundwater storage and pasture conversion effectively reduces the connectivity with deep storage. Thus, increased rainfall intensity as predicted for the tropics (IPCC 2007) can be expected to generate a relatively greater effect on pasture and sugar cane dominated watersheds in the mountainous humid tropics than forested or agro-forested basins (Fig. 14, 15 & 16). The shift to pasture and other hydraulically restricting land uses sets up a positive feedback loop in that both climate change and altered watershed hydrology reinforce each other toward greater runoff peaks separated by deeper base flow troughs.

Cutting off subsurface storage reservoirs and amplifying surface and near surface flow paths shortens the watershed response time during precipitation events, and consequently the resilience of these systems to climate change. In fact, the state of these systems is fundamentally altered after conversion from a forest. It is possible that reforestation can return the hydrology of these systems to their prior state if enough time is given for soils to reestablish their porous quality with the aid of deep and dense rooting (Niemeyer et al. 2014). The rapid vegetation growth rate in the humid tropics should support a return, but success depends on the time frame for redevelopment and reconnection of deep soil structure capable of storage and water transmission.

Even if long-term monitoring data exist, unprecedented climate conditions expected in the tropics (Mora et al. 2013) will impact landscapes undergoing intensifying land use, rendering past trends effectively irrelevant. These effects ripple into river channel hydrology, sediment transport and associated channel morphology, spreading impacts downstream. Tools to predict the effects of climate change on diverse landscapes under a variety of land cover scenarios can aid land managers planning for non-stationary future conditions. Furthermore, there is a growing need to replace models that require calibration with models that rely on the fundamental physical processes driving the transport of precipitation through watersheds (McDonnell et al. 2005, Wohl 2010).

Watershed Hydrology Dynamics

Simulations of water flow through the Atirro Watershed highlight the effects of land cover conversion on base flow and overland runoff generation. Soil matrix and macropore saturated hydraulic conductivity and subsurface hydraulic conductivity most strongly influence groundwater transmission through the watershed, but in conjunction with soil depth and horizonation, also control a saturation-excess fill-and-spill mechanism of runoff generation. Toohey (2012) observed fill and spill runoff events in pasture plots on the western slope of Turrialba Volcano associated with high intensity, short duration rainfall events, and described the unique fill-and-spill mechanism at the plot-scale in the tropical Andisol. Antecedent soil moisture values below field capacity combined with reduced percolation rates and lateral flow convergence, characteristic of the compacted soils in sugar cane fields and pasture, contributed to saturation-excess overland flow generation. Although soils in our modeled watersheds are Ultisols, our use of soil parameters derived from an analogous environment in Honduras (Hanson et al. 2004) produced similar soil hydrology dynamics. Our simulations demonstrated dominant overland flow in pasture whereas rapid vertical percolation overwhelmed the capacity for significant lateral flow or saturation-excess runoff to develop in the forested watershed.

Hanson et al. (2004) measured no lateral flow in the Honduran forest soil, only vertical. In contrast, Schellekens et al. (2004) observed rapid lateral flow reaching adjacent channels quickly due to decreasing K_{sat} with depth that set up a perched water table and drove lateral flow through macropores in a forested Ultisol of the Luquillo rain forest of Puerto Rico. Both historic land clearing in Puerto Rico (Clark and Wilcock 2000) and impacts of frequent hurricanes may have influenced the decrease in K_{sat} with depth. The Atirro Watershed has not experienced large-scale land clearing above the modeled basin outlet. In fact, during intense rainfall events in the adjacent forested Gato

Watershed, we observed multiple piping features contributing flow along steep hillslopes adjacent to the river channel. Macropore hydraulic conductivity likely drives much of the subsurface delivery of water at the watershed scale in the study basins.

Runoff coefficients derived from stream and precipitation gauges in Atirro reveal that precipitation input and discharge output appear balanced (Table 8 & Fig. 10). Evapotranspiration seems to be missing from the gauged mass balance. Model simulations of both the pasture and forested scenarios for Atirro produced near identical ET losses, roughly 70cm annually basin wide (Table 7). Toohey (2012) also noted similar ET losses among SMR-modeled watersheds in the region with both forest and mixed land use. Toohey (2012) attributed the annual balance between pasture and forest ET losses to lower ET rates year round in pasture versus more seasonally polarized yet greater ET rates from forests. Brauman et al. (2012) measured lower PET rates in forests relative to grass pastures on coastal mountain slopes of Kona, Hawai'i, claiming that ET is not an important mechanism driving impacts on water resources after land cover conversion.

Deep percolation may be contributing water from beyond the Atirro Watershed boundary. Direct ET measurements from the CATIE campus approximately 8km from the outlet of the Atirro Watershed range from 82cm to 142cm for years 1968 to 2013 (Roupsard, personal communication). The proportion of precipitation calculated as ET in the years 2010-2012 at the CATIE weather station was 36%, 39%, and 43%, respectively. Our simulated ET losses accounted for an average of 14% of the annual precipitation input between the two land cover scenarios for Atirro, and are likely underestimated. A regional strike-slip fault parallels the valley axis through Atirro (Montero et al. 2013), and could be funneling water into the basin from the southeast, potentially accounting for the greater observed base flow level in our model during the dry season for Atirro.

Given the strong influence of matrix and macropore K_{sat} and soil horizonation due to plowing and compaction, the deep influx of groundwater and ET were not as critical in our model designed to elucidate responses in watershed hydrology to land cover and climate change. The effects of land use changes predominantly influence K_{sat} and thereby the hydrologic dynamics associated with infiltration, lateral flow and percolation. Niedzialek and Ogden (2005) explored runoff mechanisms within the Río Chagres Watershed of Panama using the Sacramento Soil Moisture Accounting Model, *SAC-SMA* (Burnash et al. 1973) rather than a fully distributed physical model. Root mean square errors for their simulation ranged from 26.0% to 31.1%, struggling most with shifts in wet season base flow levels. Two stream gauges in their study basin allowed identification of different base flow responses, possibly representing regional groundwater circulation within the basin described as headwater infiltration reaching the river channel, bypassing the upper of the two gauges. Gauge data from the Río Chagres Watershed also revealed a similar discharge response at the transition from dry to wet seasons (Fig. 10). Greater runoff coefficients during the wet season were attributed to storage capacity filling after the initial filling stage during the transition from dry to wet seasons indicated by lower runoff coefficients. It should be noted that Niedzialek and Ogden (2005) calculated much lower runoff coefficients (6-77% monthly) than expressed in the gauge data from Atirro. In contrast to the Atirro gauge data, they identified high runoff coefficients immediately at the transition from the dry to wet seasons, attributed to decreased infiltration capacity due to dry season soil hydrophobicity. We did not notice a significant lag in base flow or runoff response following the onset of the wet season.

Conclusions

Our results demonstrate that physically based spatially distributed hydrologic modeling can provide a rapid and inexpensive procedure for interpreting the effects of land cover and climate change on watershed and stream hydrology. Through modeling of hydrological processes in a region with minimal soil and stream hydrology data, we demonstrate simulated watershed response and stream hydrology for spatially explicit land use conversion scenarios within a chosen range of precipitation intensities without the need for calibration. We show that land development coupled with intensifying precipitation events will amplify the hydrological extremes in steep mountain watersheds of central Costa Rica through alterations to first-order hydrologic hillslope processes. Significant decreases in soil storage associated with deforestation lead to increased peak flow magnitude while flow duration and base flow decreases. Given the flashy nature of these fluvial systems, sub-daily time steps can better reproduce peak flow events at the cost of longer model run times. Simulations of mixed land use matrices can benefit from routing overland flow; however for simulations of one dominant land cover and soil type, routing overland flow is unnecessary. Future work should incorporate feedback mechanisms driven by watershed hydrology such as channel morphology, sediment transport, vegetation growth and groundwater availability, into a more comprehensive model of watershed sensitivity.

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Tables

Table 1. Watershed Characteristics

Watershed	Drainage Area	Elevation Range	Max Slope	Median Slope	Percent Altered Land Cover
Gato	3340ha	755-2355m	58^o	31^o	<0.1%
Atirro	3249ha	780-1980m	60^o	26^o	2.5%
Platanillo	2595ha	700-1940m	56^o	24^o	41.0%

Table 2. Precipitation Averages within Study Region (2002-2012)

WATERSHED	GATO				ATIRRO		PLATANILLO
STATION	**ALTO GATO**	**TABANO**	**TAUS**	**ORIENTE**	**CUENCAS**	**LA ESPERANZA**	**PLATANILLO**
Precipitation Average (mm)	7067.1	6865.0	5220.2	3974.3	5288.0	4623.5	3678.8
Station Elevation (m)	1700	1443	945	740	1835	873	889
Number of years in record	6	6	9	7	8	8	6

Table 3. Land Use and Soil Texture at Meteorological Stations and Field Sites

Station	Land Use	%Clay	%Silt	%Sand	Texture	Source
Alto Gato	Primary Forest	56	33	11	Fine (clay)	Mora (1987)
Tabano	Primary Forest	45	34	21	Fine (clay)	Mora (1987)
Oriente	Pasture	20	26	54	Medium (sandy clayey loam)	Mora (1987)
Site	**Land Use**	**%Clay**	**%Silt**	**%Sand**	**Texture**	**Source**
Gato A	Secondary Forest	23.4	39.5	37.1	Loam	Bulk sample
Gato B	Secondary Forest	23.5	34.4	42.1	Loam	Bulk sample
Atirro A	Fallow Pasture	10.9	14.5	74.6	Sandy loam	Bulk sample
Atirro B	Fallow Pasture	20.9	34.5	44.6	Loam	Bulk sample
Atirro (Río Oro) A	Pasture	26.0	16.9	57.1	Sandy clay loam	Bulk sample
Atirro (Río Oro) B	Pasture	30.9	14.5	54.6	Sandy clay loam	Bulk sample
Platanillo A	Pasture	36.0	34.4	29.6	Clay loam	Bulk sample
Platanillo B	Pasture	36.0	34.4	29.6	Clay loam	Bulk sample

Table 4. Input Parameters for Soil Moisture Routing Model

SMR Input Parameter	Source	SMR Input Parameter	Source
Precipitation	Meteorological station data (ICE), Climate models (IPCC 2007)	Initial Canopy Storage Amount	Toohey 2012
Soil Depth	Field sampled and corrected for slope	Saturated Moisture Content	Spaans et al. (1989), Toohey 2012
Slope	DEM	Recession Content	Spaans et al. (1989), Toohey 2012
K_{sat} Matrix	Hanson et al. (2004)	Rock Content	Field sampled
K_{sat} Macropore	Hanson et al. (2004)	Wilting Point Moisture Content	Hanson et al. (2004) Spaans et al. (1989), Toohey 2012
Field Capacity Moisture Content	Spaans et al. (1989), Toohey 2012	Subsurface Hydraulic Conductivity	Spaans et al. (1989), Hanson et al. (2004), Estimated
Porosity	Spaans et al. (1989), Toohey 2012	Road Area	Aerial photos
Residual Moisture Content	Spaans et al. (1989), Toohey 2012	Road Runoff Coefficient	Estimated
Max Capacity Storage Amount	Spaans et al. (1989), Toohey 2012		

Table 5. 2013 1/2hour Precipitation Intensities from Aquiares

when rain recorded, average rate =	0.83	mm/half hour
when rain recorded, median rate =	0.20	mm/half hour
when rain recorded, max rate =	48.55	mm/half hour
when rain recorded, max 2hr rate =	35.5	mm/2hr
when rain recorded, max 1hr rate =	58.4	mm/hr

Table 6. Simulation scenario matrix

	Land Use	Rainfall Intensity	Land Use and Intense Rainfall
Atirro	○ All pasture ○ Existing	○ High range ○ Existing range	○ High range, all pasture ○ High range, existing
Gato	○ All pasture ○ Existing	○ High range ○ Existing range	
Platanillo	○ All forested ○ Existing	○ High range ○ Existing range	

Table 7. Atirro Mass Balance

Atirro Existing

MASS BALANCE:		**DEFICIT:**
basin depth		**basin depth**
ppt input (cm/basin)	***output (cm/basin)***	***ppt - output***
503.524	479.500	24.023

Water Balance Term	**%**	**cm**
Precipitation	100.0%	503.52
Evapotranspiration	13.5%	68.10
Percolation to runoff	74.2%	373.43
Runoff	7.5%	37.96
Storage	4.8%	24.02

Atirro Pasture Conversion

MASS BALANCE:		**DEFICIT:**
basin depth		**basin depth**
ppt input (cm/basin)	***output (cm/basin)***	***ppt - output***
503.524	495.316	8.207

Water Balance Term	**%**	**cm**
Precipitation	100.0%	503.52
Evapotranspiration	14.5%	73.26
Percolation to runoff	38.6%	194.49
Runoff	45.2%	227.56
Storage	1.6%	8.21

Table 8. Runoff Coefficients for Atirro Basin

	Total (cm)	**Runoff Coefficient**
Esperanza (gauge)	691.46	Avg: 92.7%
Esperanza (low elev)	728.73	94.9%
Cuencas (high elev)	763.04	90.6%

Figures

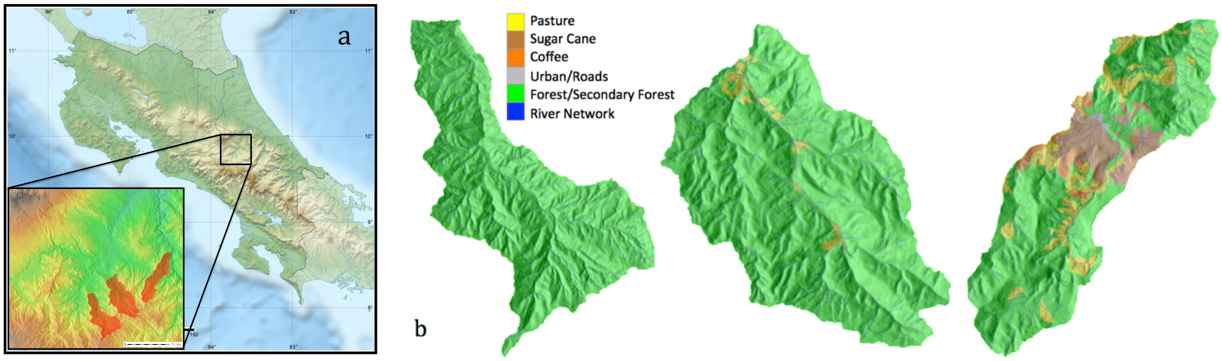

Figure 1. (a) Location of the three study watersheds in the Talamanca Mountains of central Costa Rica. (b) Land use distribution in the three study watersheds.

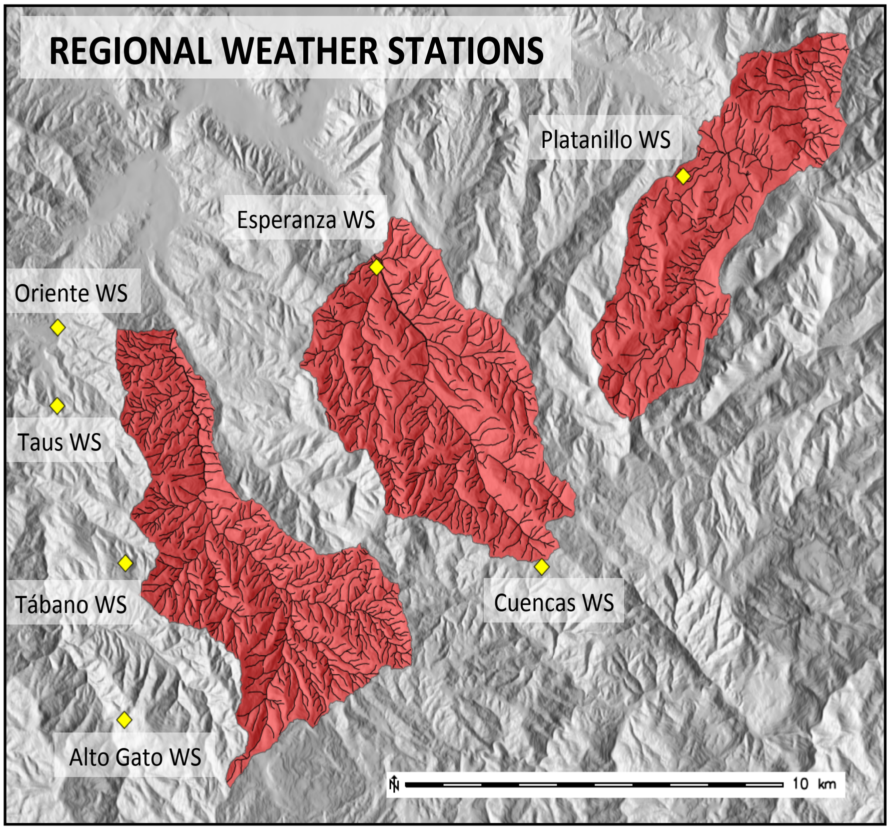

Figure 2. Location of meteorological stations in study region relative to the study watersheds.

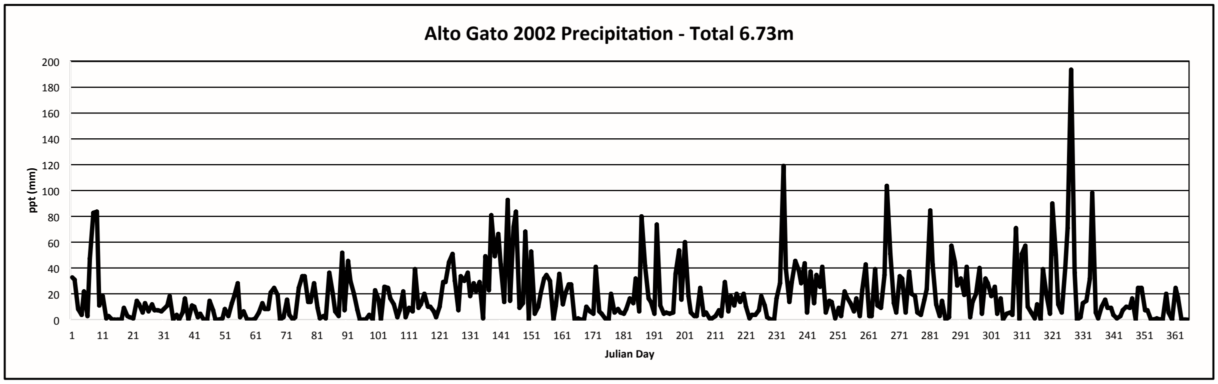

Figure 3. Sample annual rainfall record displaying a seasonal trend from the Esperanza Weather Station located near the outlet of the Atrirro Watershed (Fig. 3).

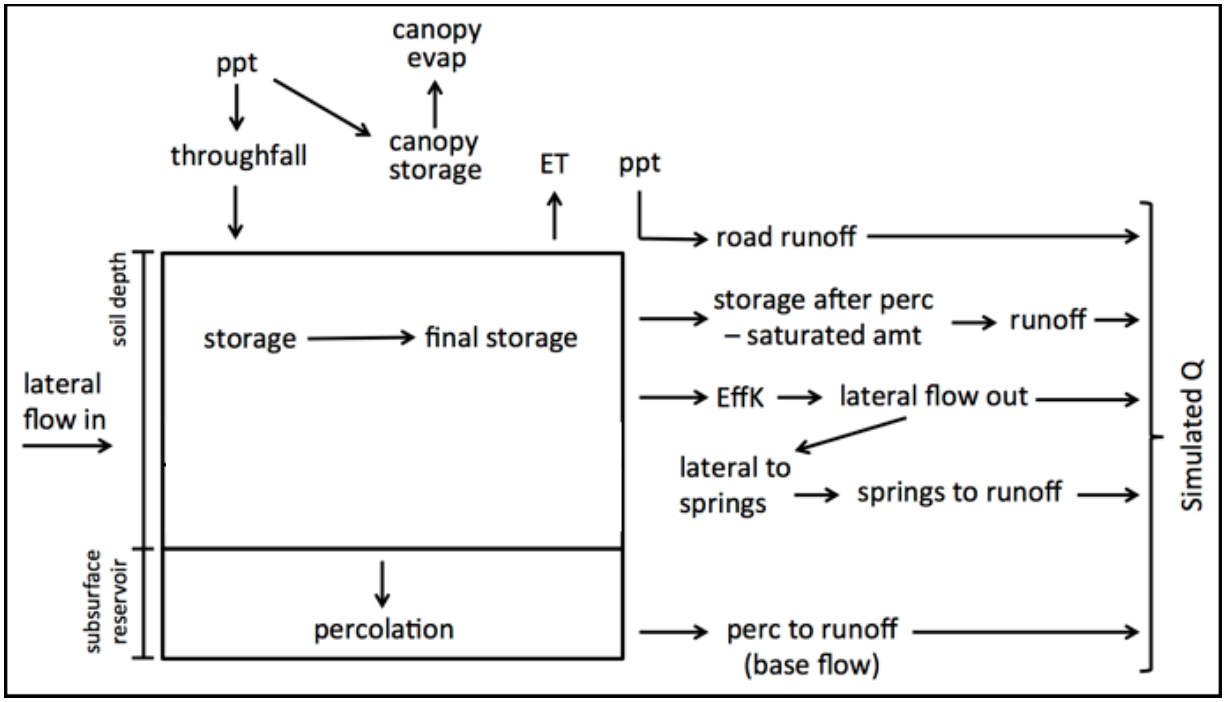

Figure 4. Primary inputs, outputs and component interaction for each cell in the SMR model.

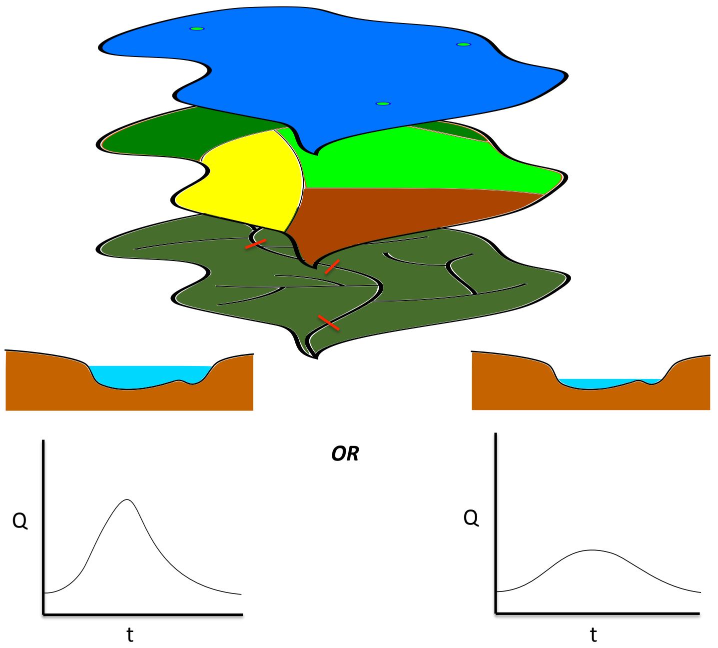

Figure 5. Hypothetical hydrographic responses to a specified precipitation regime under a specified land use configuration. A response will be simulated at specific transect locations illustrated by red bars.

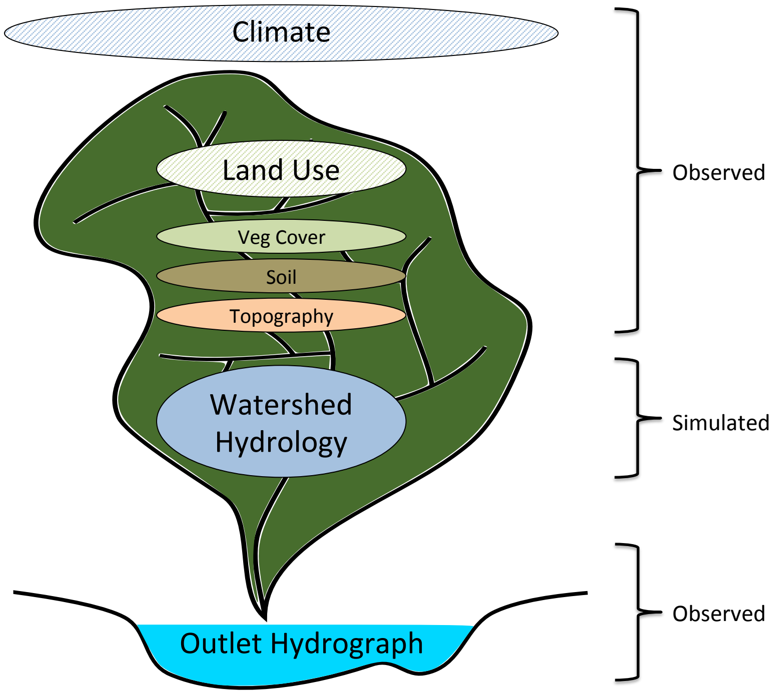

Figure 6. Major components of SMR watershed hydrology model. Land use affects vegetation cover and soil conditions.

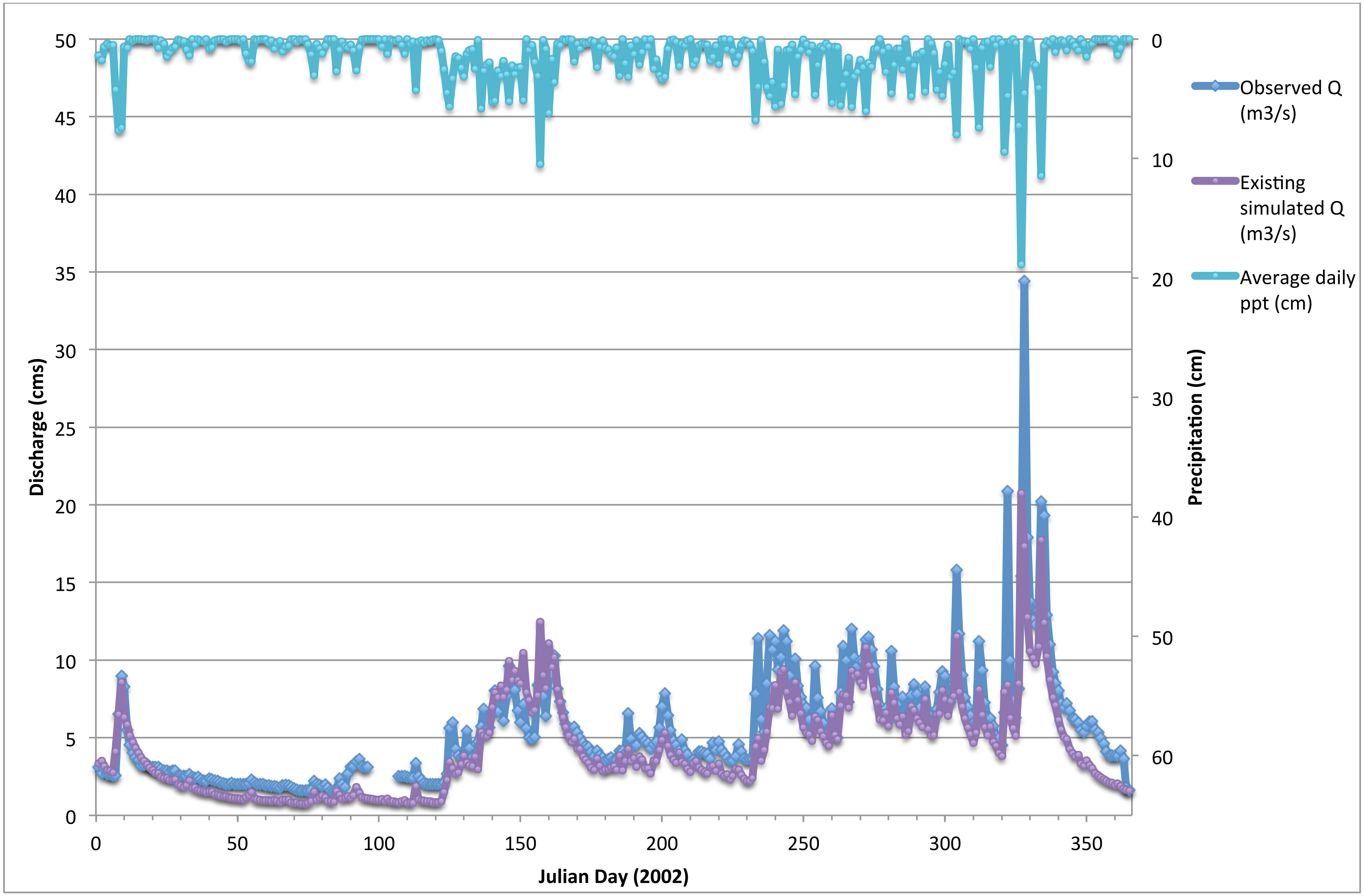

Figure 7. Atirro observed and simulated daily discharge for the existing land use scenario.

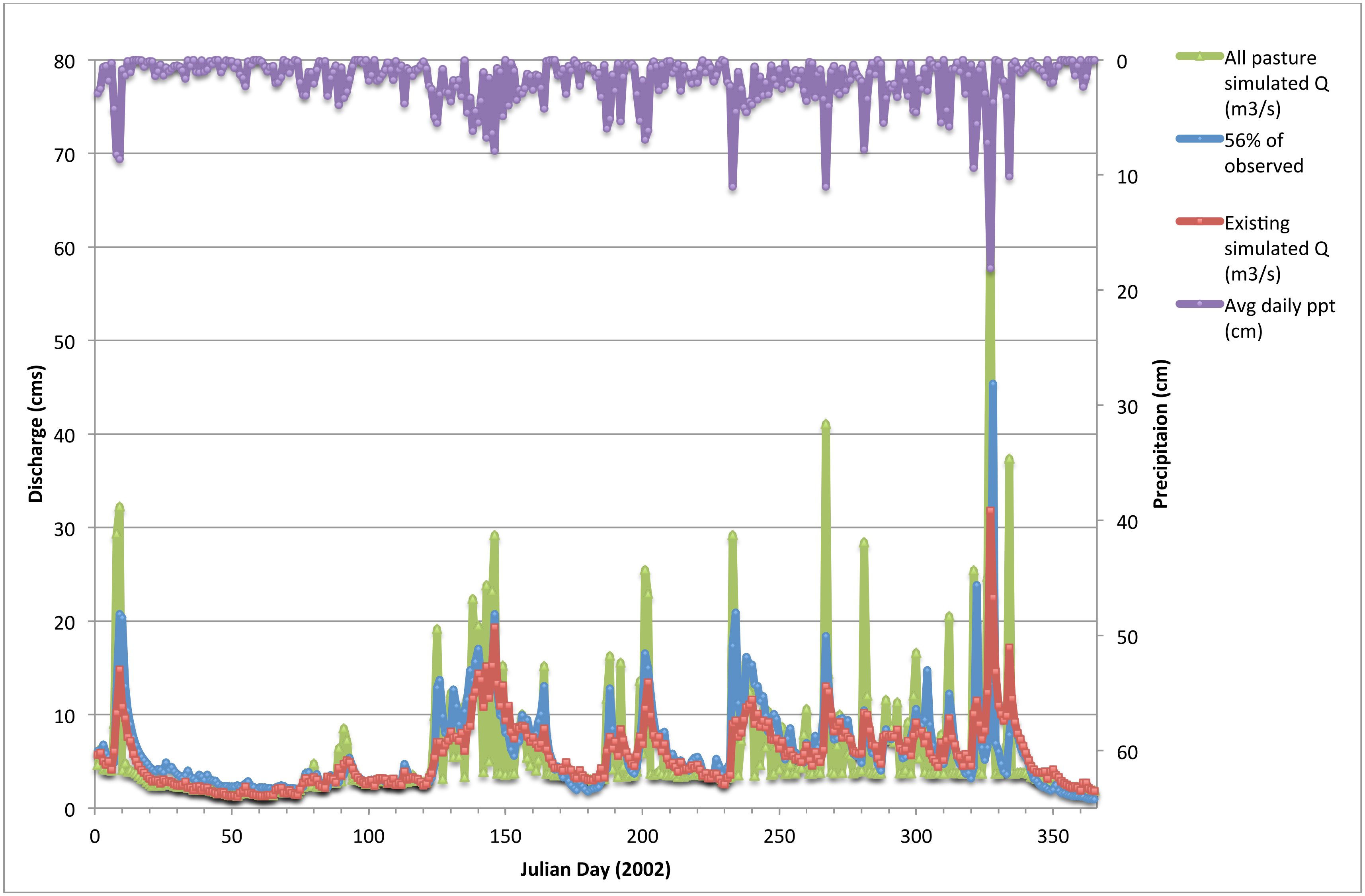

Figure 8. Gato observed (56% of downstream gauged discharge) and simulated daily discharge for existing and all-pasture land use scenarios.

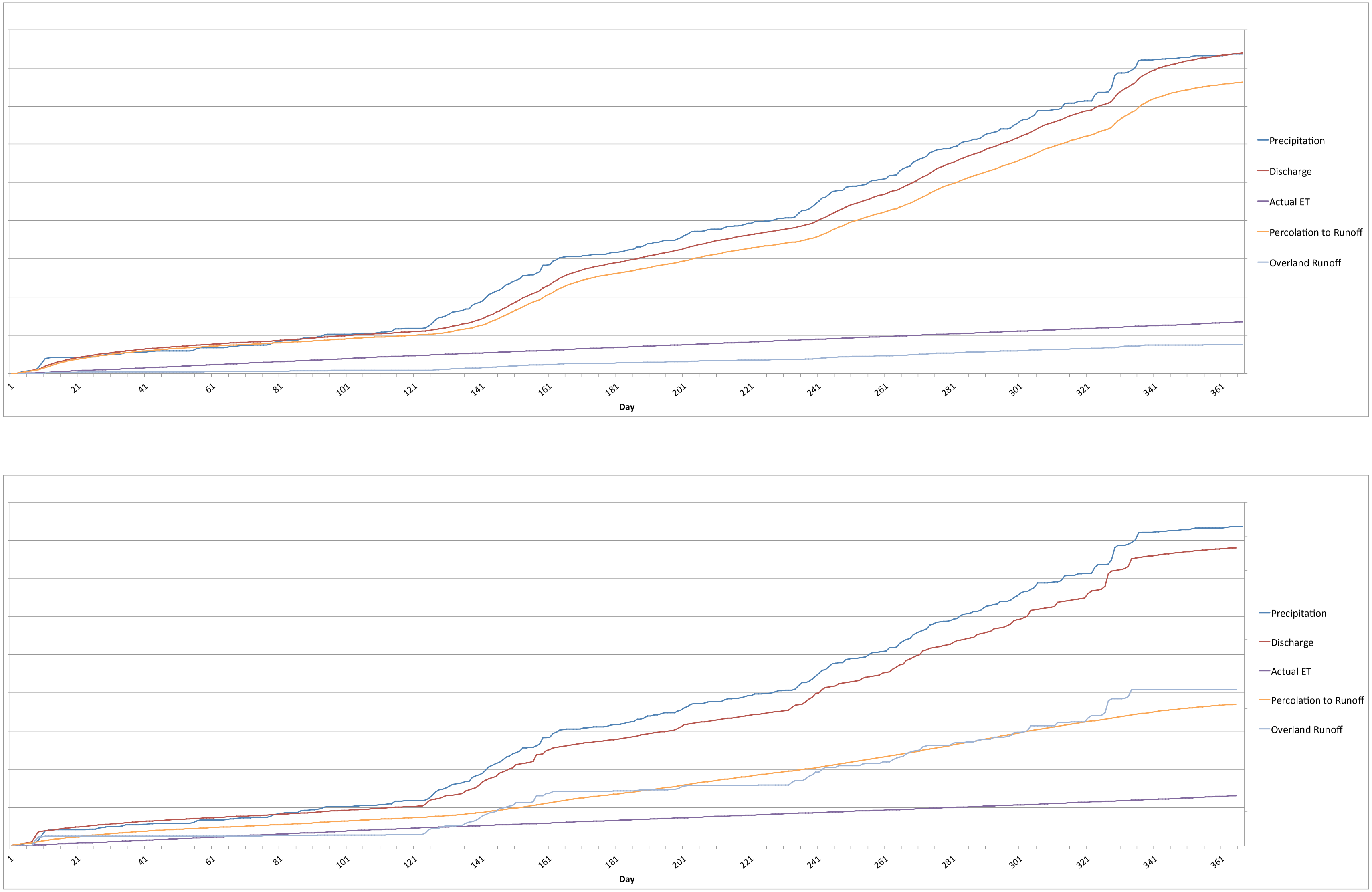

Figure 9. Cumulative values of annual precipitation, discharge, actual ET, base flow and overland flow for 2002 simulations of Atirro under existing and pasture-converted land cover scenarios.

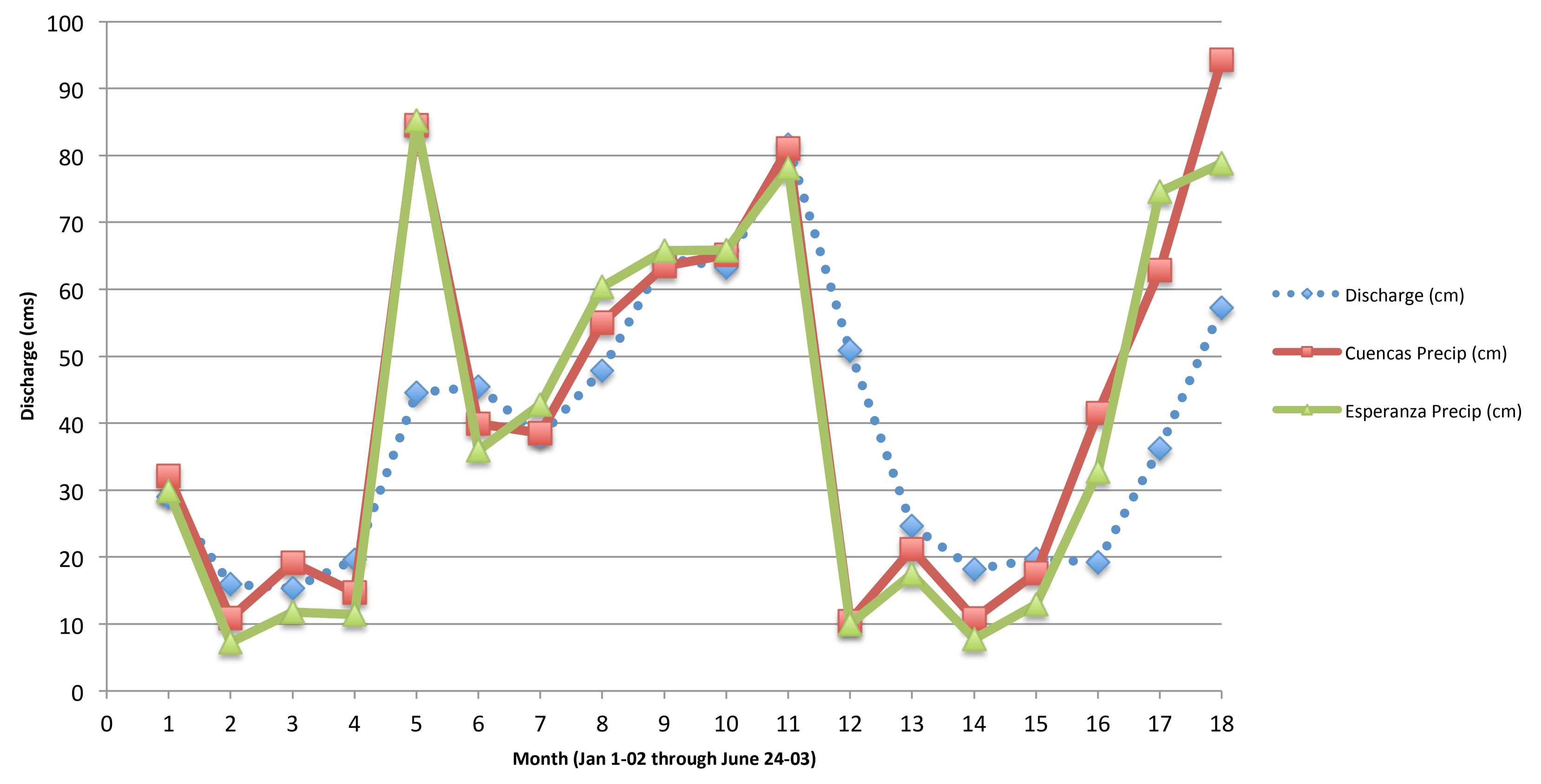

Figure 10. Atirro Precipitation and Discharge 2002-2003. Runoff relative to precipitation over 18 month period from 2002-2003. Precipitation recorded at two weather stations, one at the head of the watershed (Cuencas) and another near the stream gauge station (Esperanza)

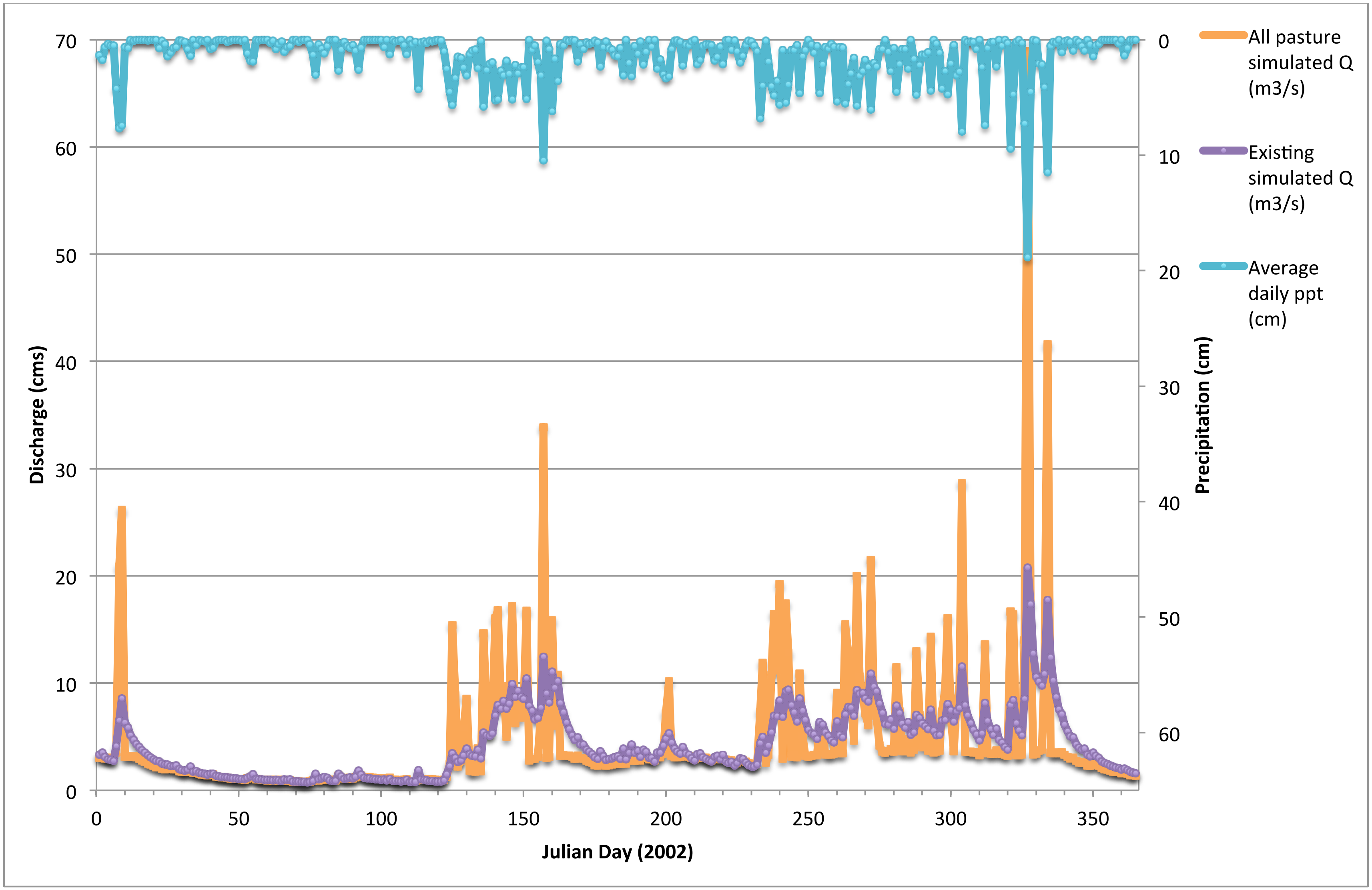

Figure 11. Atirro simulated daily discharge for the existing and all-pasture land use scenarios.

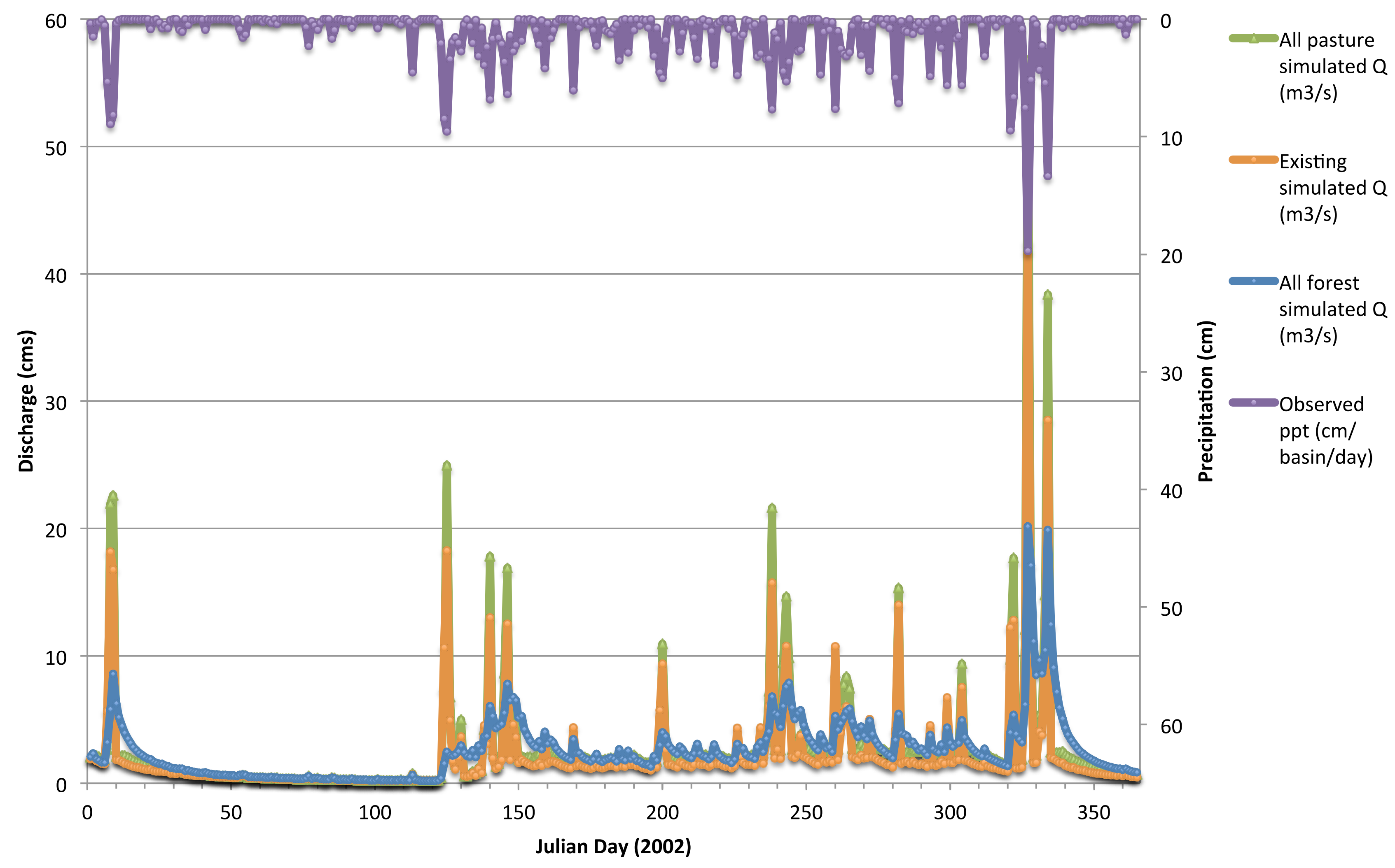

Figure 12. Platanillo simulated daily discharge for existing, all-forest and all-pasture land use scenarios.

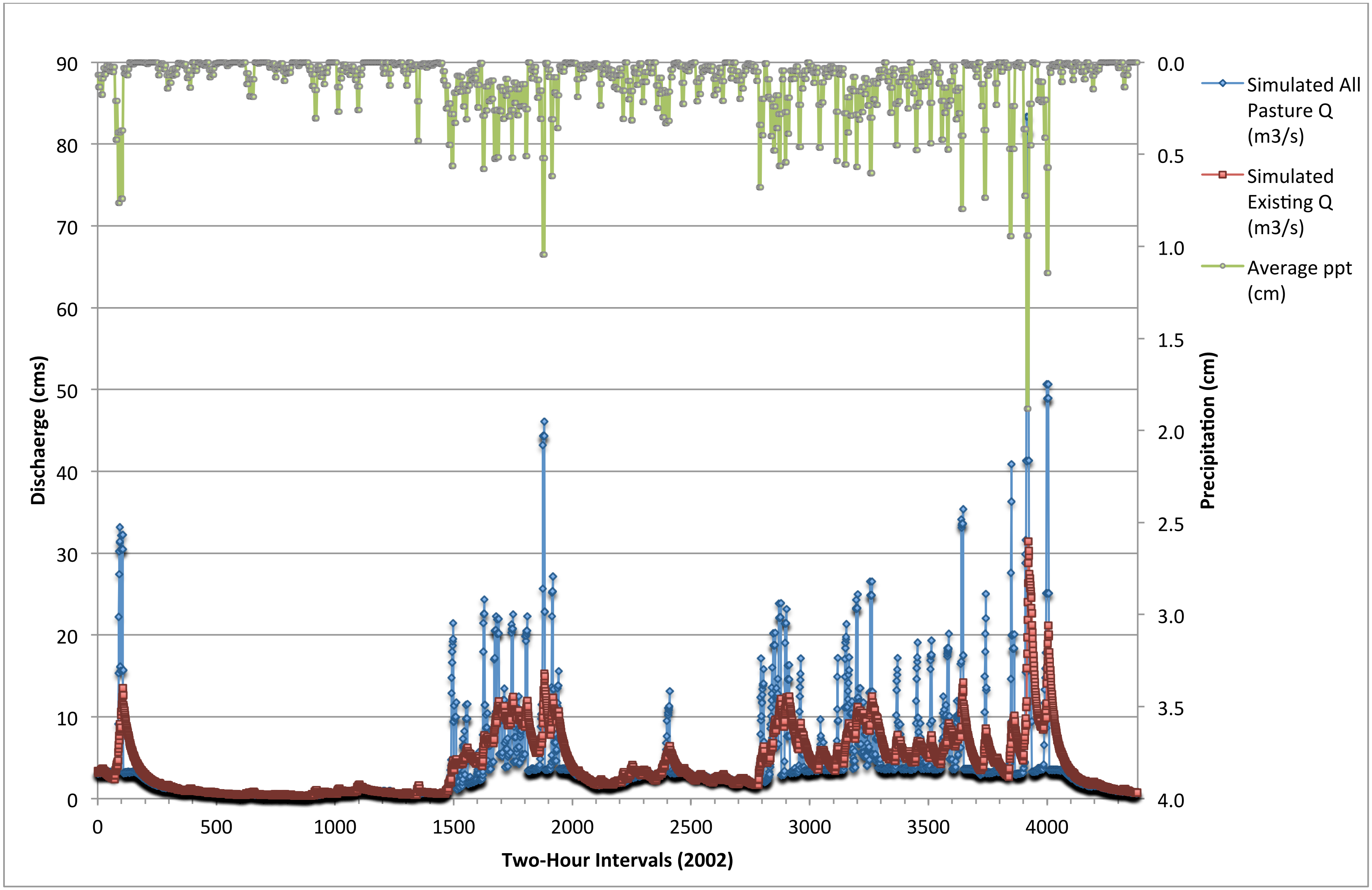

Figure 13. Atirro simulated discharge for the existing and all-pasture land use scenarios at a two-hour interval.

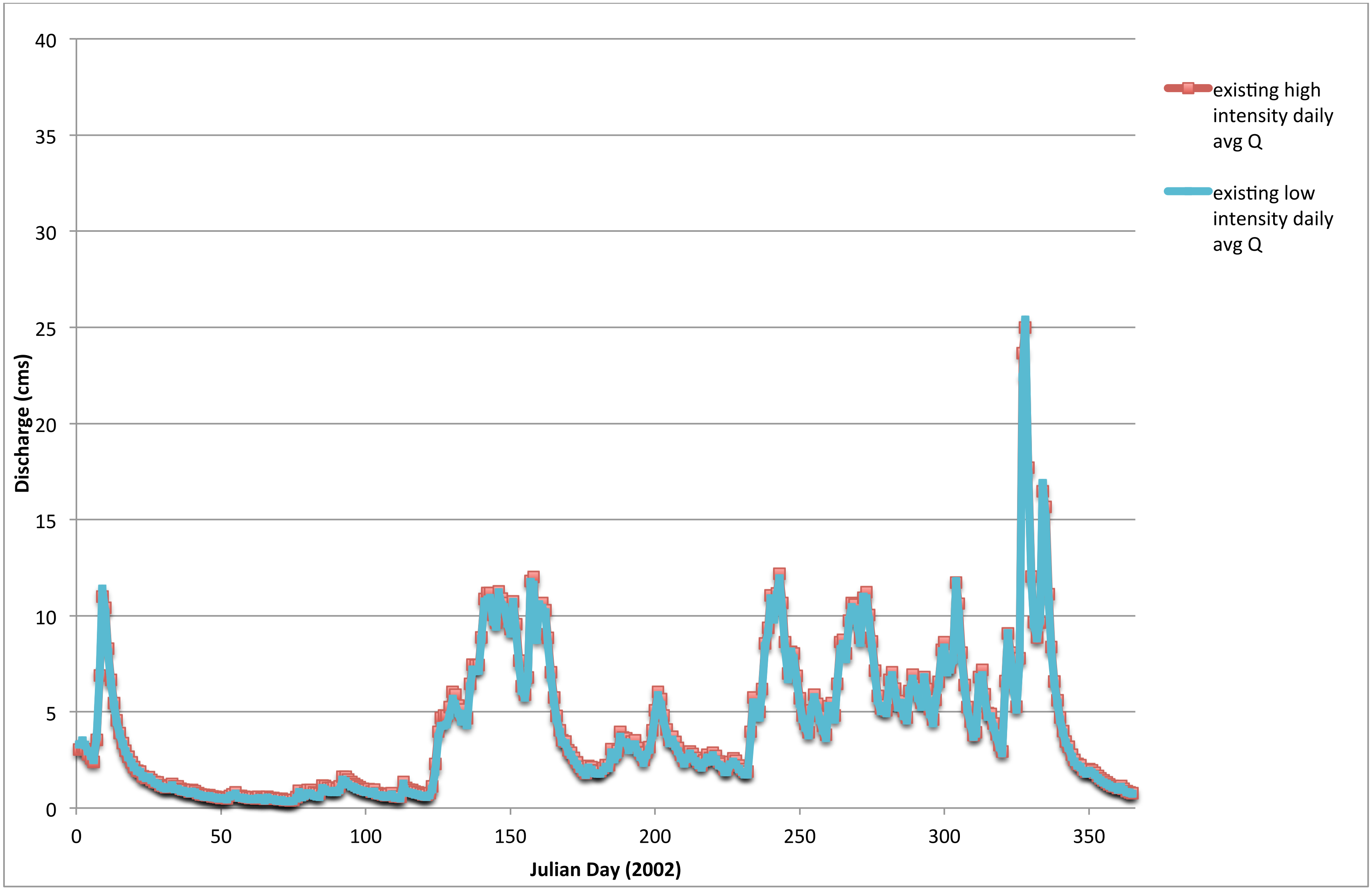

Figure 14. The preciptation intensity effect using a daily time step in Atirro for the existing land cover scenario.

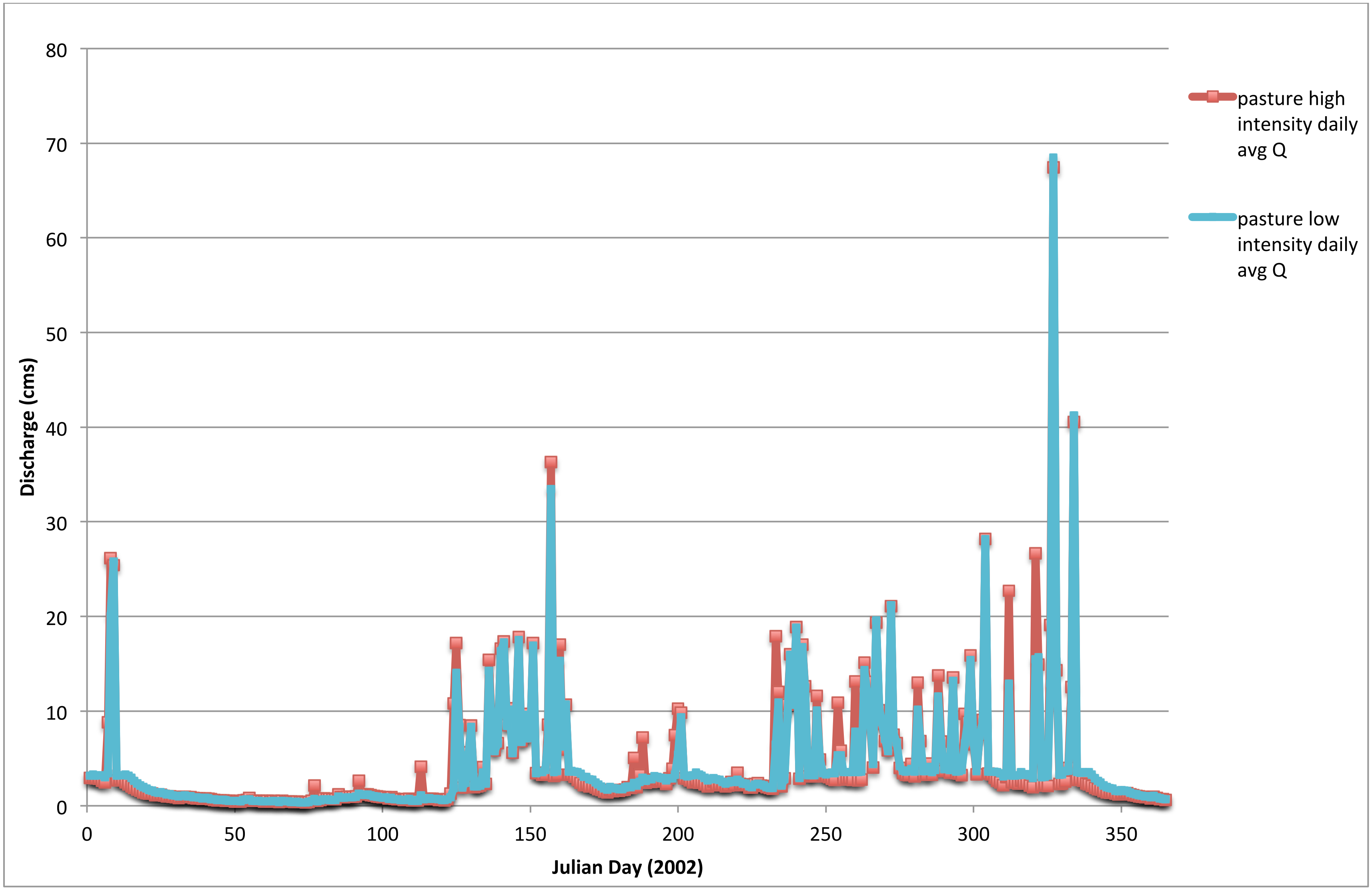

Figure 15. The preciptation intensity effect using a daily time step in Atirro for the all-pasture land cover scenario.

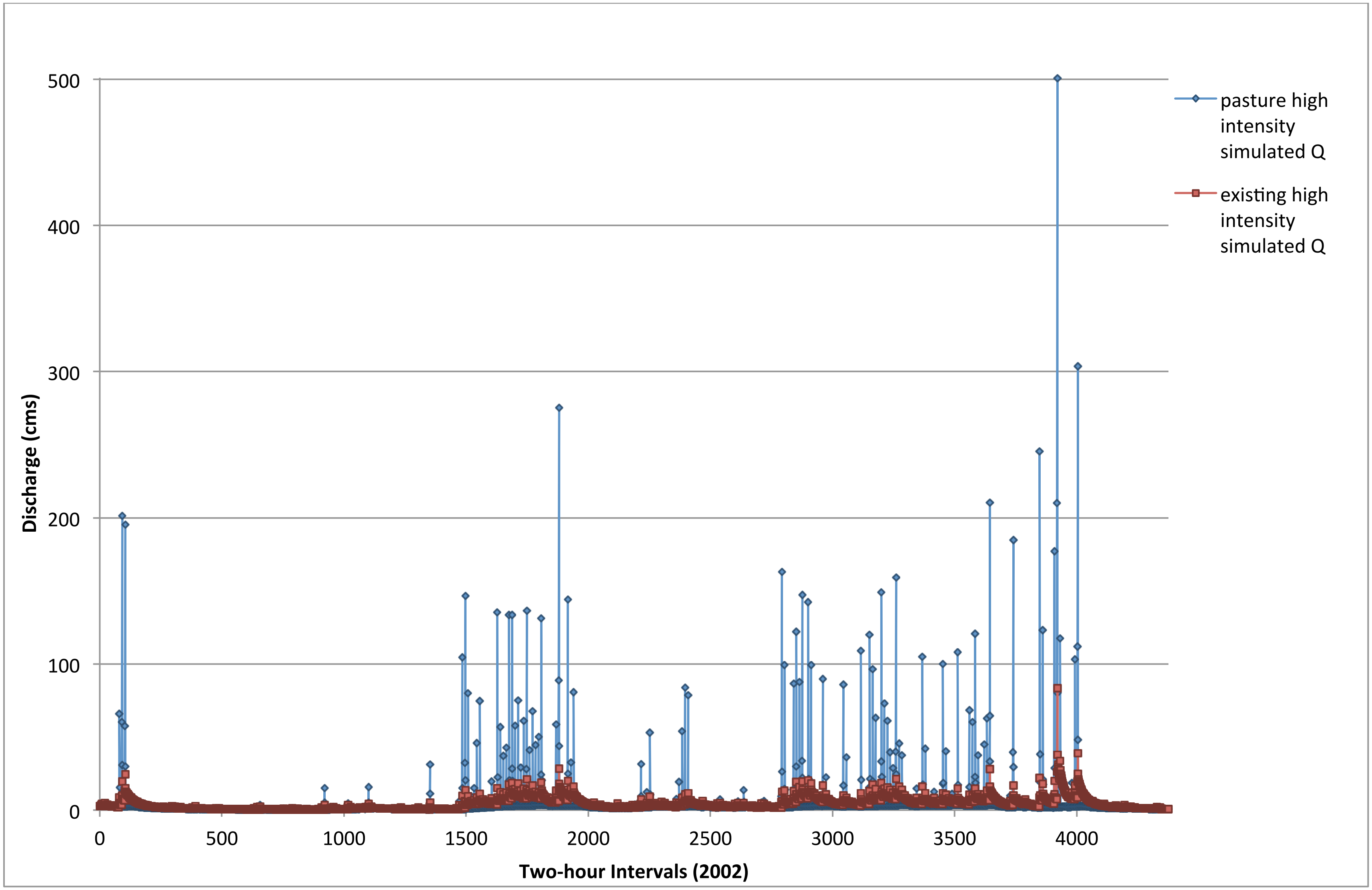

Figure 16. The preciptation intensity effect for a two-hour time step in Atirro for the existing and all-pasture land cover scenarios.

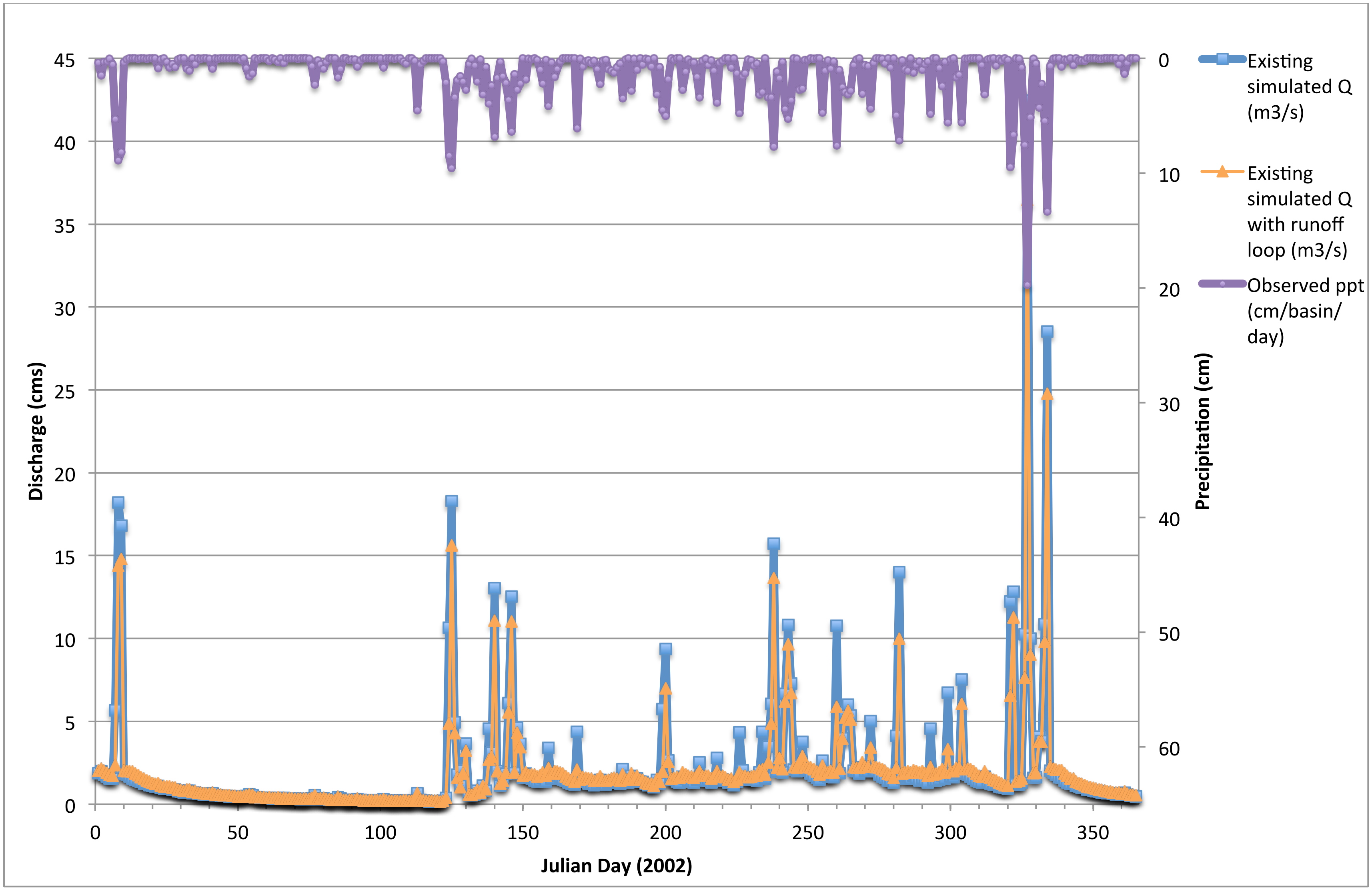

Figure 17. Platanillo simulated daily discharge for the existing land use scenario showing the difference resulting from routing runoff.

CHAPTER 3

Reconciling resource management with the landscape: An approach to identify scale mis-fit in social-ecological systems

Abstract

Scale mis-fit occurs when natural resources are not managed at the spatial or temporal scale at which they are provisioned. Issues of scale mis-fit abound in social-ecological systems. They can hinder efforts to effectively manage resources and threaten resilience of the larger ecosystem, thus affecting societal well-being and livelihoods. Here, we present an approach to identify issues of scale mis-fit. Our approach can be used to define a specific natural resource problem, determine the scales at which relevant biophysical processes and management actions occur, assess spatial and temporal scale mis-fits, and identify potential solutions. We provide two case studies of drinking water resource management in Costa Rica and the Pacific Northwest United States as applications of our approach to natural resource management. While our case studies focus on a subset of water resources, the approach we present is broadly applicable to an array of social-ecological systems.

Introduction

Humans rely on natural resource provision for many facets of life, including sustenance, energy, livelihoods, recreation, and shelter. Effective management of natural resources is crucial to ensure their sustained use. Natural resource provision results from complex ecosystem interactions occurring across spatial and temporal scales, but resource use by society often occurs without understanding of the multi-scale biophysical processes that produce the resource or the complex response to management (Levin 1992). As a result, this lack of understanding is often exacerbated when management of natural resources occurs at different scales than those at which natural resources are provisioned and has been recognized within a variety of social-ecological systems (SES) and governance approaches (Ludwig and Smith 2005, Cumming et al. 2006, Dore and Lebel 2010, Termeer et al. 2010, Carmona-Torres et al. 2011, Apostolopoulou and Paloniemi 2012, Johnson et al. 2012, Paloniemi et al. 2012, Vervoort et al. 2012, Cumming et al. 2013).

Failing to manage natural resources at the appropriate scales can compromise both the long-term availability of the resource and the functioning of the larger SES (Lee 1993, Cumming et al. 2006, Wilson 2006, Dore and Lebel 2010, Moss and Newig 2010, Johnson et al. 2012, Fremier et al. 2013). Therefore, effective management of natural resources requires reconciling complex biophysical and social interactions that occur across different temporal and spatial scales within an SES (Gunderson and Holling 2002, Cash et al. 2006, Cumming et al. 2006) to fit management actions to the scales at which biophysical processes are provisioning the natural resource.

The SES perspective to natural resource management has emerged from the recognition that: (i) interactions and feedbacks between the biophysical processes that provision resources and actions related to their management commonly occur, (ii) unexpected changes in natural resource availability are common (e.g., due to natural and social system dynamics), and (iii) management actions aimed at adapting to changes in natural resource flows, rather than maintaining constancy, are necessary to sustain natural resource availability (Folke 2006). Thus, the SES framework requires holistic approaches to management that integrate system components (social and ecological) and their interactions to analyze and elucidate problems of natural resource sustainability (Liu et al. 2007, Ostrom 2009). Interdisciplinary SES approaches provide a unique opportunity to analyze complex environmental problems from varying perspectives and to investigate a problem more thoroughly (Newell 2001).

Scale mis-fit commonly exists and has been recognized within SES; however, systematic approaches to identify scale mis-fit are lacking. Therefore, we present an integrated approach to analyze natural resource problems using a scale mis-fit lens that deconstructs components of an SES while enhancing understanding of complex interactions within the system. Users of this approach determine the scales at which relevant biophysical and governance processes occur to identify spatial and temporal scale mis-fit and propose potential solutions to a natural resource problem in an effort to align management actions to the relevant biophysical scales.

We suggest that framing complex natural resource issues explicitly in terms of spatial and temporal scales may allow for new insights to identify, analyze, and resolve natural resource problems in SES. By defining a system based on the scales of biophysical processes that sustain natural resources and the scales of management actions that influence these processes, the complex interactions between the biophysical and human components of the SES can be reduced to fundamental elements underlying a specific natural resource problem. This clarity may reveal critical mis-fits in the scales of biophysical processes and management actions, highlighting possible improvements for natural resource problems. For example, natural cycles of forest loss and regeneration take much longer than historical management practices of wildfire suppression allowed. Recognizing this as a temporal scale mis-fit places more focus on defining management actions that allow forests to burn at a recurrence interval that better aligns with natural forest regeneration processes.

Our approach is designed for researchers, managers, and other practitioners to become aware of spatial and temporal scale mis-fits within various SES and identify solutions to address problems arising from them. The overall goal of this approach is to advance management by understanding the integrated biophysical and governance context of natural resource problems and applying that understanding to management actions. Systematically identifying sources of scale mis-fit and outlining solution options will assist users in achieving this goal. We recognize that no simple or single solution exists for resolving scale mis-fit complexity. However, this approach can be useful across a wide variety of SES to identify scale mis-fits and possible solutions without suggesting panaceas (Bovens and Hart 1996, Brunner et al. 2005, Ostrom et al. 2007).

Scale mis-fit definitions

Scale is a fundamental aspect of social, physical, and biological systems and is considered a unifying concept between different academic traditions (Silver 2008). Scale has previously been studied and defined in the literature (see Gibson et al. 2000, Young 2002, Cash et al. 2006, Cumming et al. 2006), and we adopt the definition “dimensions used to measure and study any phenomenon” (Gibson et al. 2000, p. 218) However, both within scientific literature and colloquially, scale is also used as an overarching term to refer to points along a spatial or temporal scale. We adopt this common terminology. For example, the terms “national scale” and “local scale” (i.e., jurisdictional boundaries) and the term “watershed scale” refer to different geographically defined areas on a spatial scale; different time frames (e.g., decades or minutes) refer to different points along a temporal scale. Box 1 presents several key definitions related to scale that we have adopted for this approach.

Box 1. Key definitions and explanation related to scale mis-fit

Scale: "The spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon." (Gibson et al. 2000, p. 218)

Spatial scale: The geographically-defined area where biophysical, management, or governance processes occur in a system.

Temporal scale: The amount of time it takes for biophysical, management, or governance processes to occur in a system.

Scale mis-fit: When adequate management actions do not occur at the spatial scales (i.e., geographic areas) or temporal scales (i.e., amount of time) most relevant to the biophysical processes provisioning the resource.

Here, biophysical processes are the interactions between two or more components of a natural system that contribute to the provisioning of a resource. We use the term biophysical explicitly to include both biological and physical components of an SES. The term management specifically refers to the actions of overseeing resource provision and usage. Management actions are the implementation of rules and regulations that are determined by governance processes, which occur through the larger social system (Parkes et al. 2010). Governance processes extend beyond formal government and include the actions of all individuals and institutions involved in making decisions and establishing rules and norms that influence a natural resource (Richards and Smith 2002, Graham et al. 2003, Armitage and Plummer 2010).

We define scale mis-fit as a discrepancy between the scales of biophysical processes and management actions (Box 1). Spatial and temporal scale mis-fits exist when adequate management actions do not occur at the spatial scales (i.e., geographic areas) or temporal scales (i.e., amount of time) most relevant to the biophysical processes provisioning the resource. Although governance processes occur at multiple scales, resolving scale mis-fit problems necessitates adequate management actions at the spatial and temporal scales most relevant for the biophysical processes specific to the natural resource problem of concern.

Sources and consequences of scale mis-fit

Scale mis-fit in SES may arise from a variety of causes. Note that the terms "mis-fit" and "mismatch" are often used synonymously; we prefer the term "mis-fit" because it does not imply the existence or feasibility of an exact match between scales and/or processes. Cumming et al. (2006) categorize sources of scale mis-fit (referred to by the authors as "scale mismatch") as mainly social, ecological, or coupled social-ecological, clarifying that mis-fit can be caused by environmental factors, the organizations responsible for management, or interactions between them. These authors provide examples of environmental sources of scale mis-fit including natural cycles within ecological communities (e.g., due to disease outbreaks or predator-prey interactions) or unexpected environmental responses to management. They also describe social drivers of scale mis-fit as changes in land tenure, technology, human population growth, markets, infrastructure, and values. Others have further described the sources of scale mis-fit as rooted specifically in the governance system, such as imperfect knowledge about the biophysical system being managed (Hessl 2002, Apostolopoulou and Paloniemi 2012), constraints within the institutions charged with management (Paloniemi et al. 2012), short-term economic returns overshadowing environmental processes in policy development (Ludwig and Smith 2005, Dore and Lebel 2010, Ahlborg and Nightingale 2012, Paloniemi et al. 2012), and difficulty in adapting legislation and agency practices to meet environmental needs (Gibson et al. 2000, Young 2002). In our view, the primary source of scale mis-fit is a failure to fully understand and consider the scales of biophysical processes provisioning a resource and to subsequently align management actions and governance processes accordingly.

A lack of understanding or recognition of the most relevant scales at which biophysical processes provision a resource can hinder efforts to align resource management with these processes (Cash et al. 2006). For instance, Johnson et al. (2012) explored potential causes of sea urchin declines in Maine, USA in the late twentieth century. They concluded that the small-scale biophysical processes most important for maintaining sustainable sea urchin fishery levels (local migration of sea urchins to areas in which they were easily harvested) were not adequately incorporated into state-scale fishery co-management policies, resulting in persistent sea urchin decline. In another example in the western United States, management actions designed with a temporal understanding discordant with cross-scale ecological dynamics, including forest dynamics, grazer population dynamics, and fire regime, have also have been blamed for decline of forests (Holling 1986, Hessl 2002). Furthermore, since natural systems rarely follow socio-political boundaries, consequences of management actions in one region can have transboundary effects. For example, upstream river degradation can influence downstream water quality, flood occurrence, and fisheries (Fremier et al. 2013). While it is increasingly evident that effective resource management necessitates that social processes are consistent with the scales of related biophysical processes (Cleveland et al. 1996), scale mis-fit continues to exist within many SES and contribute to many environmental problems (Young 2002).

Toward an approach to identify and address scale mis-fit

Many examples of natural resource problems resulting from scale mis-fit in SES exist in the literature (Wilson 2006, Dore and Lebel 2010, Ahlborg and Nightingale 2012, Apostolopoulou and Paloniemi 2012, Johnson et al. 2012, Kane 2012, Vervoort et al. 2012). However, systematic identification and analysis of scale mis-fit is lacking. Moreover, identifying problems related to mis-fit prior to natural resource decline or system collapse is more effective to prevent and mitigate problems than retrospective analysis. Cumming et al. (2006) concluded that once identified, resolving scale mis-fit first requires an awareness of how scale contributes to problems within an SES, followed by the development of a range of potential solutions. We build on this conclusion by proposing that systematic problem definition should be the first step towards diagnosing and potentially resolving issues of scale mis-fit and presenting a process for identifying scale mis-fit.

Our approach to identify and analyze scale mis-fit integrates concepts from existing theoretical frameworks, mainly the policy sciences (Lasswell 1968, Clark 2002) and social-ecological resilience (Cumming et al. 2005, Walker and Salt 2006, Walker and Salt 2012). Both frameworks have been used to map biophysical and social processes within SES (Walker et al. 2002, Rutherford et al. 2009, Wilshusen 2009, Brunner and Lynch 2010, Walker and Salt 2012), and our approach incorporates insights from specific aspects of each of them. The policy sciences framework offers a problem definition process as a starting point for natural resource managers to guide their analysis and resolution of complex problems (Clark 2002, Lynch et al. 2013, Hammer 2013). Resilience theory, with its origins in describing non-linear behaviors in biophysical systems (Holling 1973), offers tools to assess complex dynamics in coupled SES (Walker and Salt 2006). These frameworks help define a system based on available knowledge and we propose applying this knowledge specifically to identify issues of scale mis-fit and potential ways of improving alignment of management actions to the relevant scales of resource-sustaining biophysical processes. In our approach, we reiterate the emphasis that both of these frameworks place on promoting participatory processes to engage multiple stakeholders in research and practical applications of analyzing these dynamics in SES (Clark 2002, Walker et al. 2002, Walker and Salt 2012).

Much of the published literature related to scale mis-fit in SES focuses primarily on the effects of scale mis-fit in natural resource provisioning (Gunderson and Holling 2002, Cumming et al. 2006, Moss & Newig 2010, Carmona-Torres et al. 2011, Ahlborg and Nightingale 2012, Johnson et al. 2012, Vatn and Vedeld 2012, Vervoort et al. 2012). Identifying effective solutions to problems within SES often requires addressing scale mis-fit, although tools to identify and analyze scale mis-fit are lacking. The only approach that we have found in the literature to identify scale mis-fit is presented by Ludwig and Smith (2005) based on Walker et al. (2002). Their four-step approach to address scale mis-fit uses resilience analysis in Australian rangelands. The steps include: (i) mapping the scales at which key processes and components of the SES occur, (ii) evaluating potential trajectories of the SES, (iii) assessing the effects of scale mis-fits driving uncertainty in trajectory predictions, and (iv) gauging how different methods for correcting scale mis-fits may affect management actions. We expand on this approach by beginning with focused problem orientation, followed by a systematic appraisal of the relevant scales for both the biophysical processes that provision a natural resource and the management actions pertinent to the stated problem.

An Approach To Identify Scale Mis-Fit

Our stepwise approach to identify and address scale mis-fit in SES is presented in Box 2 as a series of six steps, where each step builds on understanding gained in previous steps. The approach is designed to focus on one specific natural resource problem, although many problems may exist within an SES. We see great value in using professionally facilitated, interactive processes engaging multiple stakeholders to complete these steps.

Box 2. A six-step approach to identify, analyze and address scale mis-fit

Step 1. Define the problem related to the natural resource of concern.

a) What is the natural resource of concern in the system?

b) What is the specific problem related to this resource?

Step 2. Describe biophysical processes that provision the resource.

a) What biophysical processes are relevant for providing the resource?

b) Where do these processes occur on the landscape? (spatial scales)

c) How much time does it take for these processes to occur? (temporal scales)

d) What are the spatial and temporal scales most relevant to address the specified problem?

Step 3. Describe how humans influence biophysical processes contributing to the resource.

How do human activities influence the biophysical processes at the most relevant spatial and temporal scales (from Step 2d)?

Step 4. Describe management actions and governance processes that influence the resource.

a) What institutions (governmental and non-governmental) play a role in managing these human activities, and what management actions do they take?

b) What governance processes determine these management actions?

c) Where geographically are management actions focused? (spatial scale)

d) What time frames do management actions address? (temporal scale)

Step 5. Assess spatial and temporal scale mis-fits.

a) Do adequate management actions (Step 4) occur at the biophysically relevant spatial and temporal scales (Step 2)?

b) What spatial and/or temporal scale mis-fits exist?

Step 6. Identify potential solutions to address scale mis-fits.

a) What management actions are needed at the relevant spatial and/or temporal scales to address the scale mis-fits identified?

b) What governance processes are needed to achieve these management actions?

c) What barriers exist under current laws and policies and what process would be necessary to overcome these barriers?

d) What potential solutions could be implemented over short-, medium-, and long-terms?

Scale Mis-Fit In Water Resource Management

We found our approach useful for examining case studies in water resource management, where scale mis-fit exists prominently (Cash et al. 2006, Dore and Lebel 2010, Moss and Newig 2010) but has not been resolved effectively (Poff et al. 2003). As with other natural resources, the biophysical processes that influence water resources occur at multiple spatial scales ranging from small-scale molecular processes (e.g., interactions between chemical pollutants) to large-scale basin, continental, or global-level processes (e.g., groundwater flow and climate, flood, and drought regimes). Management actions often are not aligned with the scales of these biophysical processes. For example, political boundaries generally do not follow watershed boundaries, making watershed management more complex when crossing multiple jurisdictions. Moreover, defaulting to a focus at the watershed scale could ignore or fail to prioritize biophysical processes that occur at different scales, such as climate regimes or groundwater recharge, which do not generally adhere to topographic watershed boundaries (*sensu* Vatn and Vedeld 2012).

One example of an effort to address issues of scale in water resource management problems is Integrated Water Resource Management (IWRM). IWRM promotes both a watershed vision for management actions (Agarwal et al. 2000) and integration of governmental authority over various activities that impact the water resource (Cosens and Stow 2014). However, water resource problems are often very unique and cannot utilize one standard solution (Biswas 2004). While IWRM is an attempt to address water issues at the most appropriate biophysical spatial scale (i.e., the watershed), some point out that the watershed is not always the most appropriate scale of addressing governance processes (Cohen and Davidson 2011). In addition, despite the prevalence of scale issues in water resource systems, IWRM principles do not specifically address the issue of scale mis-fit. IWRM is designed to address fragmentation in management of human activities that affect the same connected water resource. While this may at times address scale issues, they are not the focus. Ultimately, given the multiple spatial and temporal scales that are involved in water resources, water management must address scale mis-fit issues to be effective and to produce long-term results. In addition, participatory methods that engage multiple stakeholders have been particularly effective in establishing opportunities to overcome scale mis-fit (Dore and Lebel 2010) and in enabling vertical integration, linking the levels of water governance (Knuppe and Pahl-Wostl 2011). We demonstrate how our approach promotes integration and multi-scale considerations in two water resource management case studies.

Case studies: Water resource management in Costa Rica and the Pacific Northwest USA

We present two case studies focused on drinking water management to demonstrate the utility of our approach in analyzing SES problems. By presenting these case studies, we aim to contribute to the continuing development of heuristic approaches to identify, understand, and resolve scale mis-fit. The first case is based in Costa Rica and was developed through interdisciplinary teamwork of four doctoral students in the Joint Doctoral Program between the Tropical Agricultural Research and Higher Education Center (CATIE) and the University of Idaho (UI). The second case is based in the western United States and draws from long-term involvement of the University of Idaho in scientific studies on regional water resources, as well as interdisciplinary studies by faculty and students in the

UI Waters of the West Program. With both case studies, we present relevant background information before using our scale mis-fit approach to analyze the SES.

Costa Rica case study background

The Costa Rica case study focuses on drinking water quality in rural communities in the Cartago Province of central Costa Rica. This case study draws from findings from interviews with community organizations and government agencies involved in drinking water management and a survey and workshop with community drinking water organizations in the study region. Drinking water quality remains largely unknown, although potentially hazardous contaminants, such as agrochemicals, are used within the watershed and are likely entering community water sources. Throughout the country, local community-based drinking water organizations (CBDWOs, or ASADAs and CAAR in Spanish) are responsible for overseeing the management and provision of drinking water in rural communities. In this region, drinking water is piped directly from springs and most CBDWOs use chlorine treatments to reduce the risk of bacterial contamination. Water quality testing is conducted once every six months to two years, if at all. In addition, common land uses within the contributing area include agriculture and pasture, and contaminants from these practices threaten water quality. The Water Law (Costa Rica Government 1942) and the Environmental Law (Costa Rica Government 1995) mandate forested protection zones of 200 m and 100 m radii, respectively, around the spring. Most citizens are uncertain about which radius to use, and enforcement of the two laws is minimal. Moreover, these protection zones are not based on scientific evidence. The upstream area contributing to a spring (springshed) lies largely unprotected, while the majority of the protected area lies downstream of the spring in areas that do not contribute groundwater to the spring flow (Figure 1). Therefore, much of the springshed is not protected under the two laws. We use the term springshed to refer to the area of land in which water infiltrates into the ground and exits at a common spring source. We differentiate springshed from watershed, which is typically determined by topography, since springs mainly rely on only groundwater sources that may not follow topographic relief.

As a result of the discrepancy between the protection areas and the boundaries of the springsheds, CBDWOs often are not aware of the influence that the springshed has on water quality and do not monitor activities that occur in these regions. Due to limited or non-existent water quality testing, CBDWOs and users lack information about the quality of their drinking water sources. Potential threats that exist in the springshed interfere with the ability of CBDWOs to provide potable drinking water for local communities. In some cases these threats may pose hazardous to community members' health. Limited financial and human resources prevent communities and government agencies from conducting studies to identify where groundwater recharge occurs, to determine whether water contamination is occurring within the springshed, and to establish effective management plans.

Six-step approach applied to the Costa Rica case

Using the six-step approach presented in Box 2, we analyze the SES related to drinking water in the Cartago province of Costa Rica.

Step 1: Drinking water quality is a significant concern within rural communities of Costa Rica. Water quality monitoring is infrequent, and understanding of groundwater recharge zones for the springs is limited, preventing CBDWOs from identifying both potential contaminants and the human actions that are responsible for contamination. This uncertainty about water quality jeopardizes human health.

Step 2: Many biophysical processes influence the provision of clean drinking water, including climate processes (precipitation) and hydrogeologic processes (infiltration, groundwater flow, and spring water discharge). Precipitation occurs at a regional scale, while the interactions between infiltrated water, groundwater, and spring water occur at the scale of the springshed. Precipitation occurs on the order of minutes to hours, while infiltration and shallow groundwater flow to springs occur on the order of hours to months, depending on springshed size, soil parameters, and precipitation intensity and magnitude. In order to address the problem of focus, the relevant spatial scale is the springshed, while the relevant temporal scale is in the range of hours to days.

Step 3: Human activities primarily influence water quality through land use management practices. Within the springsheds, which are not protected by the Water Law (1942) or Environmental Law (1996), many concerning land uses occur, such as intensive agriculture and cattle grazing. Agrochemicals applied to crops and fecal coliforms from cattle manure can enter soils and flow to the spring on the temporal scale of hours to days.

Step 4: Several institutions are responsible for management actions and governance processes in this region. The National Institute for Water and Sewage (ICAA, or AyA in Spanish) is responsible for providing CBDWO administrative support; they also provide occasional training and limited financial resources. The Ministry of Energy and the Environment (MINAE) developed and enforces the Environmental Law (Costa Rica Government 1995) that stipulates the 100 m radius protection area around drinking water sources. The Water Law (Costa Rica Government 1942) stipulates the 200 m radius (Fig. 1). The CBDWOs act on the local community scale to develop spring sources, maintain infrastructure for water delivery, collect fees, and finance maintenance of the system. Spatially, management actions are limited to areas directly around the springs, although very few springs are fully protected by the mandated 100 and 200 m radius zones. Temporally, the relevant management actions, water quality tests, generally occur on a scale from once every six months (most frequent) to once every two years (least frequent), or sometimes not at all.

Step 5: The relevant biophysical spatial scale is the springshed, where recharge contributes to spring flow. Land use within the springshed, including agriculture and cattle grazing, threatens water quality, but management actions to regulate these practices, when undertaken, usually only occur within the 100 to 200 m surrounding the springs. Of the limited management practices undertaken to mitigate the effects of land use on water quality, many are targeted in locations outside of the springshed, downslope of the spring in the area that does not contribute to spring flow. Therefore, there is a spatial scale mis-fit between the scale of drinking water management with the scale of the biophysical processes that provision the resource. Management actions also do not occur at the temporal scales most relevant for drinking water provisioning. Water quality tests are conducted infrequently, but potential threats to water quality (e.g., agrochemicals and fecal coliforms) are possibly occurring in the springshed, ranging on the order of minutes to days (Fig. 2). Therefore, the limited testing that is conducted has a high probability of not identifying any acute contaminants that pass through the system; this results in a temporal scale mis-fit.

Step 6: To address these scale mis-fits, management actions are needed at the springshed scale, and governance processes should focus on establishing the springshed as the protection area for management focus. Delineation of springshed boundaries requires significant resources given the difficulty of determining the extent of groundwater contribution to springs. However, the watershed, based on topographic boundaries, may be initially considered, given the likelihood of significant overlap with the springshed. Also, the watershed is a more feasible and cost-effective scale to begin protecting. More frequent water quality monitoring aligned with the temporal scale of infiltration and shallow groundwater flow rates is also needed to identify potential rapid changes on the landscape that lead to contamination of drinking water supplies.

Potential short-term solutions include delineating watershed boundaries for all springs and conducting targeted sampling after rainfall events when occurrence of contaminants might be greatest. Two medium-term solutions could include 1) developing a monitoring plan to capture the appropriate spatial extent and temporal variability of the biophysical processes to sustain consistent, clean drinking water for the communities, and 2) forming regional bridging organizations (i.e., a watershed management group) among CBDWO water managers to promote water quality training, shared knowledge, communication, and collective garnering of financial resources. Two potential long-term solutions are to 1) modify existing laws and enforcement mechanisms to establish appropriate upslope spring protection areas and focus management actions at the watershed scale and 2) determine groundwater contributions to the springs for management at the springshed scale.

Overview of the six-step approach in Costa Rica

Applying the six-step approach to this SES in Costa Rica reveals a predominant issue of spatial scale mis-fit involved in drinking water management, as management actions do not exist at springshed levels. The spatial scale of biophysical processes responsible for water provisioning (i.e., the springshed) is not sufficiently considered in the design of Costa Rican drinking water management policy. Use of this approach indicates that several potential options exist for community members to address water quality in this region, including short-term efforts that can provide insight into the problem while longer-term solutions are refined and implemented. Results of our approach also emphasize the importance of monitoring water resource dynamics at the appropriate temporal scale.

The strategy of focusing water protection efforts at the springshed scale, monitoring spring water quality more frequently, and sharing this information throughout a local CBDWO network would establish community knowledge to inform short-term actions in lieu of long-term policy that will require significant time to reform. Therefore, a change in the spatial and temporal scale of management actions would more closely align the governance actions with the biophysical processes for water provision in this particular case as well as in other cases facing similar issues.

Palouse Basin case study background

The Palouse Basin case study focuses on groundwater availability in the Palouse Basin located in the Inland Northwest of the United Sates (Fig. 3). The majority of water from the basin is pumped from the Grande Ronde, a deep fractured basalt aquifer that provides groundwater for domestic and industrial users located in the Idaho and Washington states. Significant concern exists over aquifer levels, which have been declining at a rate of 20-45 cm per year for the past 60 years (see Figure 4; Beall et al. 2011, Moran 2011) with no direct evidence of aquifer recharge (Belknap 1999). Water allocation occurs at the state level in the United States (California Oregon Power Co. v. Beaver Portland Cement Co. 1935, Tarlock 2011), but the Washington/Idaho state line divides the Grande Ronde Aquifer. Idaho state law prohibits aquifer mining, defined as water pumping rates that exceed the rate of natural groundwater recharge (Idaho Statutes 42-237a(g)). Therefore, the occurrence of aquifer mining as defined by law cannot be determined without knowing the recharge rate, which has not been determined in this case. Washington state law is less specific but prohibits pumping beyond the source’s yield capacity (RCW 90.44.070), which has not yet been scientifically determined for this aquifer. Continued need for a scientific answer to the questions of the exact size and recharge rate of the aquifer has diverted attention from developing plans to reduce pumping rates, reinforcing the spatial and temporal mis-fits.

With approval of Congress, federal law allows the creation of an interstate authority that crosses state lines and allows the region to control management of their water system as one unit. However, studies show that decision makers in the region have rejected this approach based on fear that federal approval will complicate management (Richartz 2011). The Palouse Basin Aquifer Committee (PBAC) was established in 1967 as a voluntary entity bridging the state divide and has been instrumental in facilitating voluntary conservation measures. However, PBAC lacks management and enforcement authority for conservation goals in the region.

Six-step approach applied to the Palouse Basin case

Using the six-step approach presented in Box 2, we analyze the SES related to the Palouse Basin.

Step 1: The resource of concern is groundwater from the Grande Ronde Aquifer. The water level of the aquifer has been declining significantly for the last 60 years. However, uncertainties remain over whether the aquifer is recharging and if the basin will experience a water shortage, since the recharge rate has not been scientifically determined. Existing local policies encourage voluntary conservation measures. State law requirements for curtailment of pumping on a "mined" aquifer have not been met in either state in which the aquifer occurs. Political will to develop alternative drinking water sources is lacking, as any viable surface water sources are shared by the two states.

Step 2: The biophysical processes that influence the aquifer include climate processes (precipitation) and hydrogeologic processes (primarily infiltration and aquifer recharge). Precipitation occurs at a regional scale, whereas infiltration and recharge occur on the aquifer scale. A shallow aquifer provides water to portions of one city and its recharge occurs on a scale of hours to months. The occurrence of recharge to the primary deep aquifer is unknown, but movement of recharge, if any, into production zones is clearly not occurring in a timeframe to prevent aquifer decline. In order to address the problem of focus, the relevant spatial scale is the aquifer, while the relevant temporal scale is unknown, but longer than the current period of record (60 years).

Step 3: Municipal groundwater pumping accounts for the most significant use of water from the aquifer and pumping rates increase with population growth. Groundwater pumping is likely occurring at a rate greater than recharge to the production zone given declines in the level of the aquifer over the last 60 years.

Step 4: The aquifer extends across the Washington-Idaho border and, as a result, is managed independently by the two states, invoking jurisdictional complexity. The PBAC, composed of representatives of the communities reliant on the aquifers and representatives of each state in an advisory capacity, was established to bridge efforts at the aquifer scale. The PBAC promotes information sharing and establishment of joint conservation goals, including the 1993 Groundwater Management Plan (GWMP). Although suggested management actions such as the GWMP are not legally binding, generally communities have complied. Although the rate of aquifer decline has slowed since implementation of the GWMP, aquifer levels continue to decline (Fig. 4). In the state of Idaho, Statute 42-237a(g) prohibits aquifer mining exceeding the groundwater recharge rate (a standard that cannot be met if recharge is unknown), while Washington law (RCW 90.44.080) prohibits pumping an aquifer beyond its “safe yield.” The relevant spatial scale of management actions includes the four cities that pump water from the aquifer and the state scale at which management is dictated. The temporal scale of management actions ranges from daily (pumping) to years (for development of city and university plans) to decades (for development and implementation of legislation).

Step 5: Currently there is no legally binding governance or management at the aquifer scale, which is the scale at which groundwater resources are provisioned, resulting in a spatial scale mis-fit. However, PBAC forms a bridging organization between the states of Idaho and Washington at this scale. The rate of aquifer recharge has not been determined and steady decline of the aquifer level over time suggests that the rate of extraction is greater than the rate of recharge at least to the production zone of municipal wells, indicating that a temporal mis-fit is occurring. The limited scientific investigations of recharge rate preclude imposing legal restrictions on pumping rates. The high cost associated with such research has inhibited the necessary scientific studies. Stakeholder attention primarily focuses on the state-defined spatial mis-fit and the need for further scientific study. However, application of this approach indicates that the temporal scale is far more important.

Step 6: Strategies to overcome scale mis-fit in the Palouse Basin must address the problem of declining groundwater reserves at the aquifer scale and at a temporal scale that matches the discrepancy between the recharge rate to the production zone and rate of groundwater decline. Adequate investment to develop new water sources is paramount. Continued effort to determine recharge rates is warranted, although they have proved unsuccessful to date. The basin may be better served by determining the maximum depth of production through test wells and consideration of the economics of pumping from that depth. Based on maximum depth of pumping, the timeframe for aquifer decline to this point (assuming current rate of decline) and thus the need for supplemental resources may be determined.

One potential short-term strategy to address these issues is the establishment of a facilitated forum where scientists and decision makers can discuss relevant issues and identify the roles of science and policy in addressing existing problems. Over several years, a medium-term strategy to incorporate university-based research to determine maximum economic pump depth and possibly aquifer recharge rates could provide student training and valuable knowledge to the regional groundwater problem. Efforts to identify alternative water sources and design, permit, and develop compliance measures for new water sources could move forward. Potential long-term strategies include determining a more robust means for communities to work together across the state line, potentially through empowering PBAC, and coordinating appropriate pumping levels of the aquifer based on scientific evidence.

Overview of the six-step approach in the Palouse Basin

Applying the six-step approach in the Palouse Basin reveals a spatial scale mis-fit in this SES. Given that a state line divides the Grande Ronde Aquifer, management occurs within jurisdictional boundaries that do not overlap with the most appropriate spatial scale, the aquifer scale, for regional groundwater resources. While the scale at which PBAC is focused aligns well with the biophysical scale at which water is provisioned in the Palouse Basin, the organization has no enforcement authority. However, this spatial scale mis-fit overshadows and tends to mask the temporal scale mis-fit, which lies at the heart of the problem. The main source of the water resource problems in this region is that the withdrawal rate exceeds the timeframe in which aquifer recharge occurs within the production zone. Since legislation in both states requires scientific determination of the general recharge rate in order to legally limit pumping, costly and lengthy studies are needed before adequate water conservation practices will be implemented. Using our approach in this case study helps users identify the temporal scale mis-fit occurring and place more focus on potential short-term solutions to mitigate the effects of waiting for necessary long-term solutions.

Applicability of the six-step approach for the case studies

The case studies demonstrate a useful approach to identify, further understand problems associated with, and discuss alternative solutions for scale mis-fit. In the Costa Rica case, by framing the management problem in terms of spatial and temporal scales, potential avenues for improving resource governance and defining management actions emerged. Our approach revealed feasible means to address water quality issues in drinking water. CBDWOs are spending human and financial resources to manage protection areas that do not contribute to the quality of spring water in the region. Resources would be more effectively used to protect those areas that have the most influence on drinking water quality. Delineating watersheds in lieu of springsheds provides an essential and feasible starting point for aligning the spatial scale of management actions with the spatial scale most relevant (and practical) for water resource provisioning. Ultimately, identifying the scale mis-fit between management actions and biophysical processes of an SES exposes potential vulnerability that may threaten the ability of an SES to provision an adequate supply of resources. Addressing this weakness could strengthen the SES to address ongoing large-scale issues including increasingly common problems associated with climate change and population growth.

Restatement of the Palouse Basin aquifer issue from a scale mis-fit perspective distilled the complex problem to an awareness of specific spatial and temporal mis-fit in water resource governance. Focusing on both spatial and temporal scales clarified the multi-scale nature of the problem and highlights the need for cross-scale collaborations. Using our approach revealed that a critical temporal mis-fit issue is likely masked by the obvious spatial mis-fit created by the political border dividing the aquifer. Significant attention is being placed on the political boundaries rather than focusing on the likely decline of the aquifer, precluding more appropriate sustainable management of groundwater resources. Our approach identified that more knowledge of the system could potentially improve mismanagement. The lack of management actions at the basin scale and the lack of a long-term, legally binding conservation plan contribute to uncertainty about the future availability of drinking water in the Palouse region.

These two cases provide examples of how our approach is useful for identifying and understanding issues of scale mis-fit within SES. The steps in our approach provide a process for navigating environmental problems by first focusing on a specific natural resource problem and then framing the problem explicitly in terms of the scales of both biophysical and governance processes, thereby making the problem more manageable to tackle without ignoring system complexity. When addressing complex problems with an interdisciplinary systems approach, it is often difficult to strike a balance between holistically understanding a problem that involves multiple interactions and feedbacks and deconstructing the problem into individual components. With this approach we intend to provide an entry point for breaking a problem down into manageable components through an analysis that acknowledges system complexity while identifying specific vulnerabilities. This approach is applicable to other contexts, both in water resource management and with other natural resource problems where spatial and temporal scales are of particular relevance and will be useful to researchers, managers, and other practitioners involved in natural resource management.

Discussion

This six-step approach to analyzing scale mis-fit has several unique aspects. First, a focus on scale facilitates mutual understanding among researchers and stakeholders with different disciplinary orientations. This focus is of particular importance given the need for interdisciplinary approaches to SES (Redman et al. 2004, Lang et al. 2012) that can be hampered by the inherent difficulty of interdisciplinary collaboration (Eigenbrode et al. 2007, Morse et al. 2007). Second, specifically emphasizing the scales of resource provision and management offers an opportunity to identify "critical causes," when they are related to scale, of natural resource problems that are not always intuitive or obvious in SES. Third, this approach explicitly places a concurrent emphasis on both spatial and temporal scales, as well as biophysical and governance systems, which are critical for effective natural resource management. Lastly, our approach encourages users to identify a range of possible solutions over different time frames rather than focusing on a single solution to resolve problems of scale mis-fit.

We also recognize the need to address potential weaknesses of this approach. For example, solutions to address scale mis-fit are often complex and not straightforward. After identifying an existing scale mis-fit, one cannot simply "align the scales" to "fix" the problem. For example, where a problem is identified in an SES, creating or changing legislation might better protect resources and prove to be necessary to address the scale mis-fit. However, as new legislation requires a long-term vision, waiting for changes in legislation without additional short-term actions to address problems could allow them to worsen. More importantly, uncertainty requires a more nimble approach than legislative action in a governance structure that fits the scale of today's problem but may prove inadequate in the future. Therefore, short- and medium-term mitigation strategies that address certain aspects of a problem could be explored concurrently with comprehensive long-term approaches. We propose that considering multiple solutions for different time frames will avoid issues that occur when focusing on one solution for a specific time frame.

Potential solutions and governance approaches need to be tailored for each resource and unique SES (Vatn and Vedeld 2012). Therefore, we envision that this approach will require in-depth, participatory discussions involving multiple stakeholders relevant for a specific case. Given that identifying solutions to scale mis-fit is complex, we would like to highlight that Step 6 is intended to encourage users of this approach to consider potential solutions to specifically address identified scale mis-fits. However, further work would be needed to identify a range of potential options that would satisfy multiple stakeholders' interests and to analyze the benefits and drawbacks of each solution. In addition, some factors influencing natural resource use, such as culture, history, religion, or economics, may not be explicitly addressed in this approach and may need further consideration in some cases. We encourage users to apply other relevant conceptual models, frameworks or analytical tools in conjunction with this approach specific to scale mis-fit.

Conclusions

Issues of scale mis-fit, when natural resources are not managed or governed at the scale at which they are provisioned, exist in a wide variety of SES. Lack of understanding the scales at which biophysical processes influence natural resource provisioning can lead to misalignment of management actions influencing resources. Identifying effective solutions to problems within SES often requires addressing scale mis-fit, although limited tools to identify and analyze scale mis-fit have been developed. We propose a systematic, approach for identifying, analyzing, and addressing scale mis-fit in environmental problems, based upon the premise that many natural resource problems are ultimately caused by a misalignment of the scales of management to the scales of resource provisioning.

The two case studies presented, from Costa Rica and the Inland Northwest region of the United States, highlight the applicability of our approach in two different social-ecological contexts related to water resource management. However, this approach for interdisciplinary investigation of spatial-temporal phenomena will be useful to analyze natural resource problems across a variety of SES contexts. We encourage others to test and refine this scale mis-fit approach for a range of natural resources issues, such as species, forest, and marine management, in various SES contexts to aid in its development and practical application. While identification of scale mis-fit is an imperative step towards reconciling natural resource management with biophysical processes occurring on the landscape, additional work is particularly necessary to identify and implement solutions to address scale mis-fit problems.

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Figures

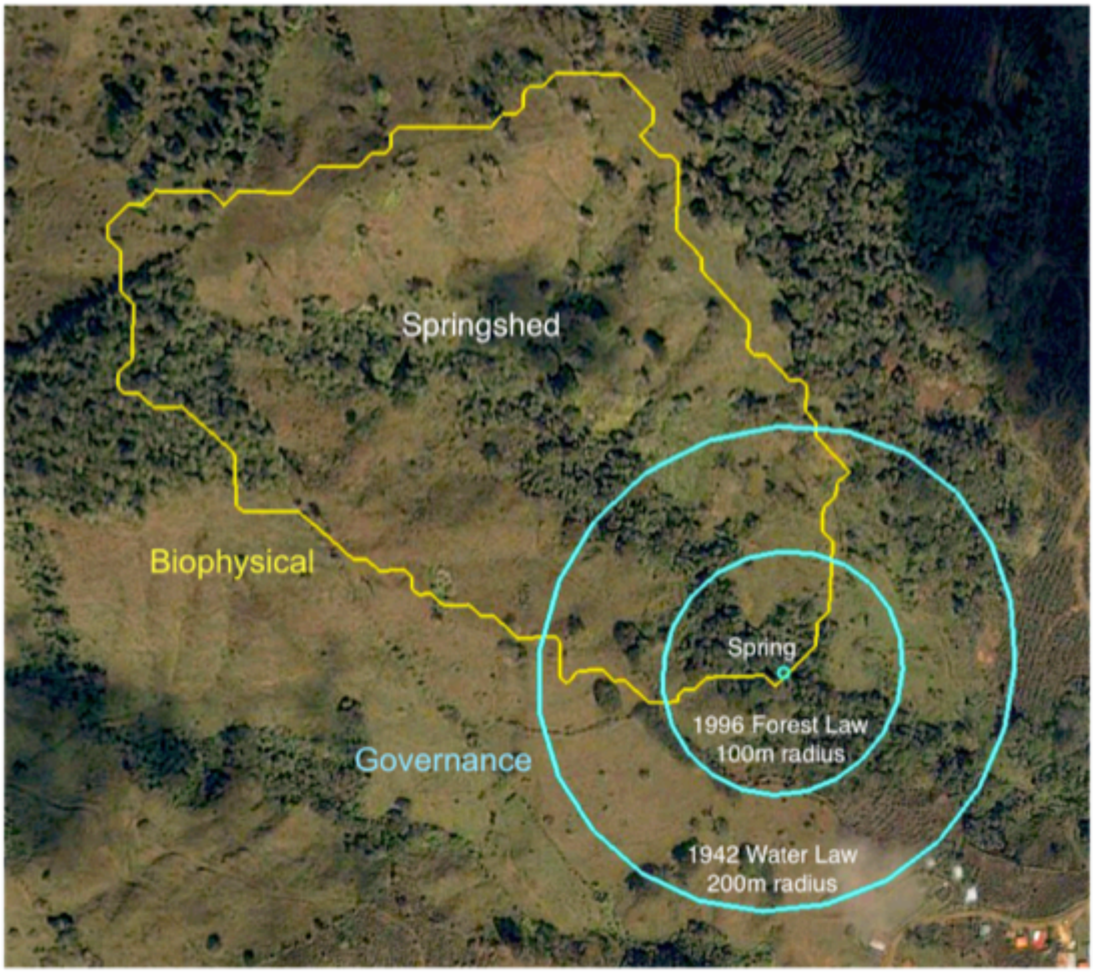

Figure 1. Illustration of a spatial scale mis-fit between the upstream area contributing to spring discharge (the potential springshed, yellow polygon) and the mandated protection buffers surrounding the spring (blue polygons) managed by a CBDWO in the Cartago Province of Costa Rica. Management actions primarily occur within the protection buffers, which do not fit the spatial scale of the biophysical processes that provision the drinking water (i.e., within the springshed) (Map data ©2013 Google, Digital Globe).

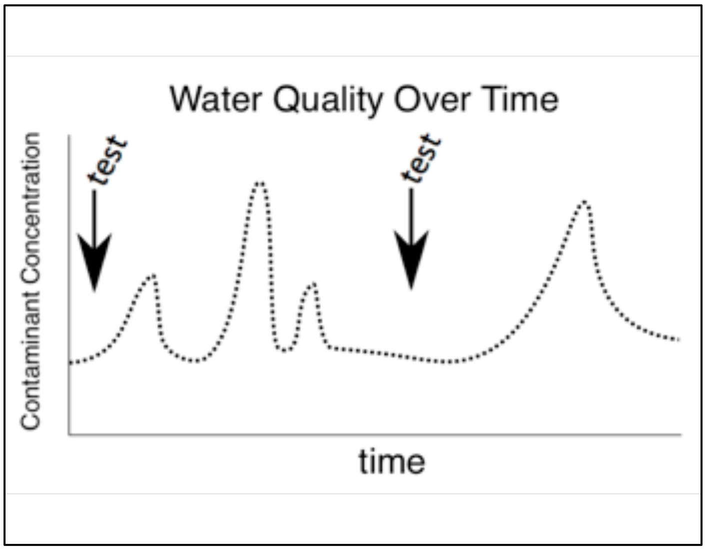

Figure 2. Conceptual illustration of a temporal scale mis-fit between the frequency of water quality testing and the probable changes in water contaminant concentration over time. CBDWOs in Costa Rica typically sample water for contaminants less than twice per year, and thus the tests are not likely revealing the suitability of the water for drinking.

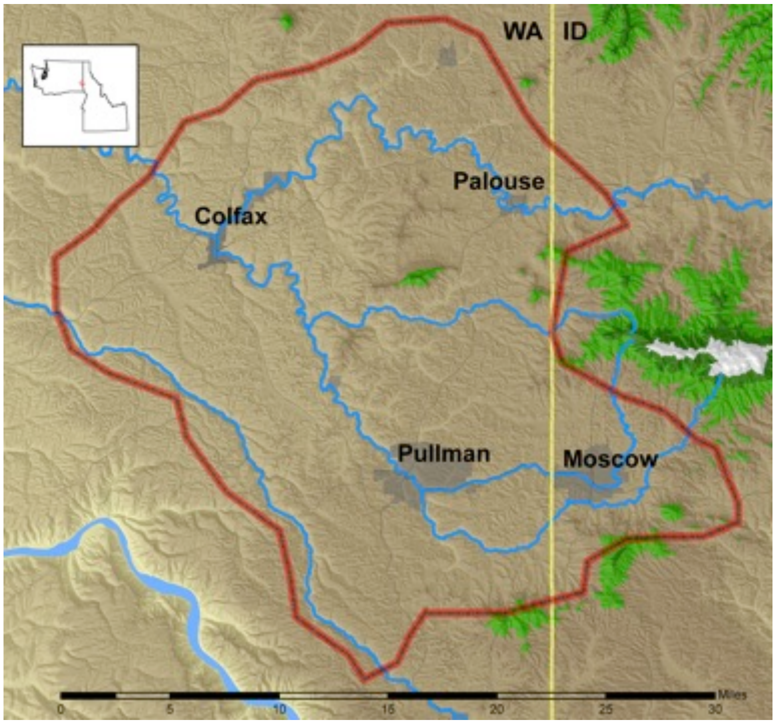

Figure 3. Palouse Basin showing boundary between Idaho and Washington (yellow line) and the approximate boundary of the Grande Ronde aquifer (red line) located within both states. The inset shows where the aquifer is located within both states.

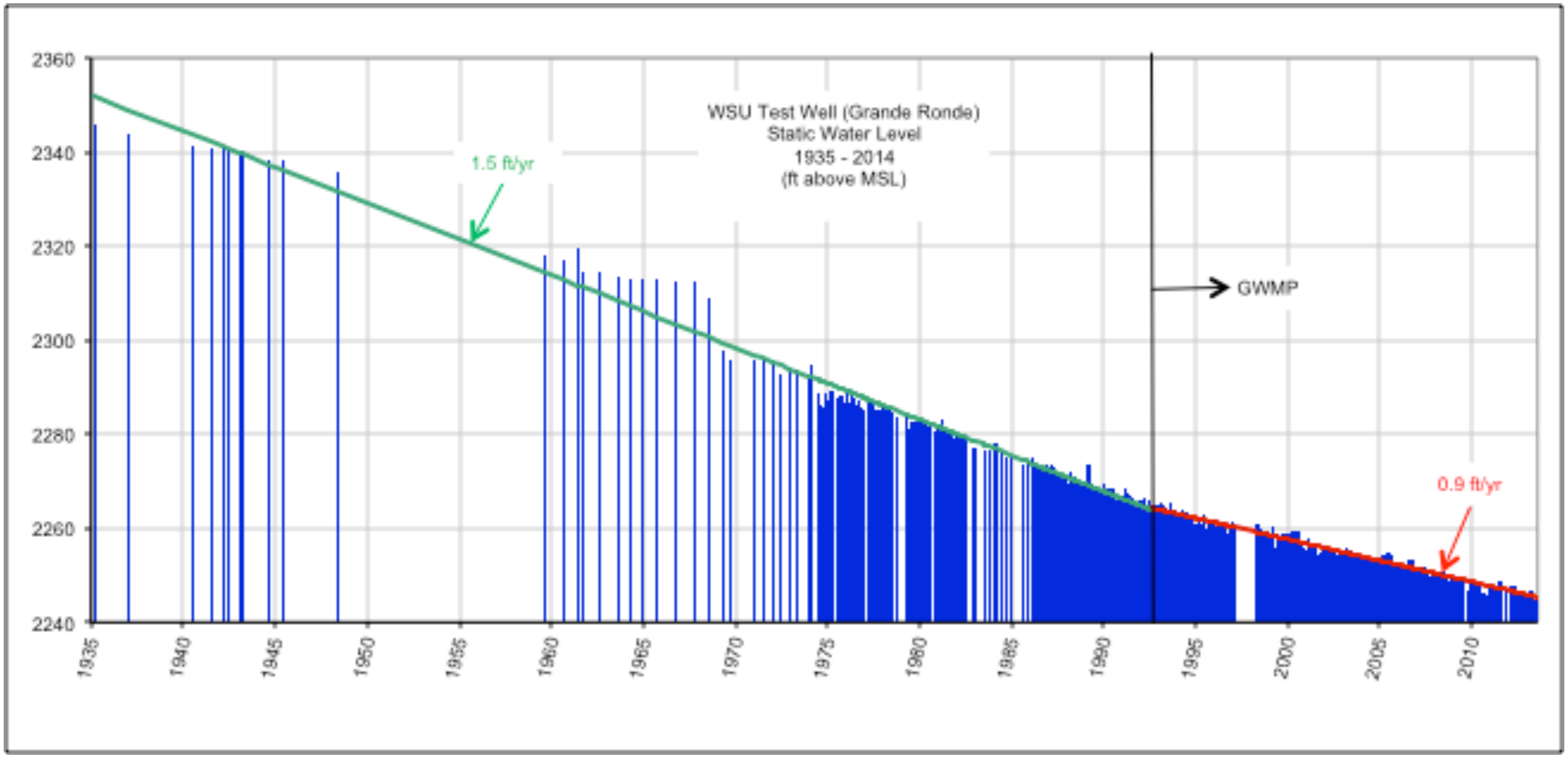

Figure 4. Static water levels in the WSU Test Well. Green and red regression lines show decrease of levels prior to and after 1993, respectively, when the Groundwater Management Plan (GWMP) was developed by PBAC.