Assessing Green Interventions for the Water Supply of Lima, Peru

Cost-Effectiveness, Potential Impact, and Priority Research Areas

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Summary

Lima, Peru is the second-largest desert city in the world. It stands out among major cities in Latin America and the world in the severity of the water stress faced by its approximately 9 million residents. Substantial water quality and quantity challenges threaten the continued economic growth of the city and Peru at large.

Water supply is a particular challenge for Lima during the dry season, when reservoirs, streams, and rivers run low because of low seasonal rainfall.[1] Despite efforts to build additional reservoirs and transport water from the headwaters of the Amazon basin to the thirsty Pacific coast, Lima still faces an average deficit of approximately 3.05 m^3/s of flow in the driest part of the year. In terms of annual volume, the region experiences a deficit of approximately 42.84 million m^3 of dry season water supply.

While substantial built, or 'gray,' infrastructure projects have been planned and implemented to address this crisis, 'green interventions,' or improvements in land use, have not yet been rigorously considered as a part of the solution. This study aims to lay the groundwork to integrate these options by assessing the cost-effectiveness and potential impact of several green interventions in Lima's watersheds. The specific projects assessed were selected based on their ability to potentially improve dry season flows and likelihood of implementation.

This study assessed four such interventions in terms of cost and potential to improve dry season baseflows, namely: animal exclusion from overgrazed puna grasslands, introduction of rotational grazing practices on currently overgrazed puna grasslands, hydrological restoration of drained wetlands, and restoration of ancient infiltration infrastructure (*amunas*).[2]

The assessment found that green interventions could substantially contribute to addressing the current dry season flow deficit at costs that are lower than, or competitive to, proposed gray infrastructure projects. Restoration of ancient infiltration infrastructure stood out as a particularly cost-effective and potentially high-impact green intervention, with the average marginal increase in baseflow costing an estimated \$85,750 per m^3/s. Our estimates indicate that all four green interventions are likely to be cost-competitive with gray infrastructure alternatives, with most well within a \$0.25/m^3 price point.

Further, the analysis suggests that if implemented at full scale these green interventions together could reduce the region's baseflow deficit by 90 percent, or 2.74 m^3/s. In terms of annual volumetric impact, this corresponds to 58 million m^3 of dry season water supply, more than the current dry season deficit in the region. Implementing the full portfolio of green interventions would cost an estimated \$7.9 million per year.

The analysis recognizes that a lack of historical hydrological monitoring in the region leaves room for uncertainty around several of the assumptions used in this study. To account for this, the level of uncertainty associated with each assumption is qualitatively noted, and a range of potential average values is used to create 'low' and 'high' end estimates of cost-effectiveness and potential impact. Even under our most conservative assumptions, amuna restoration and hydrological restoration of wetlands remain more cost-effective than 11 other gray interventions considered. The study also suggests how targeted hydrological monitoring in the region could greatly improve understanding of the impact of green interventions in the region.

The methodological approach used in this report to estimate hydrologic benefits of interventions, included in the annexes to this report along with all calculations, may be applied for a variety of other applications. These include cost-benefit analysis for public investment projects, private sector contributions to water stewardship, and use of a quantifiable metric (baseflow in this case) for prioritizing green intervention projects within a water fund.

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[1] Water quality is also a critical issue for Lima's watersheds, and any effective water resources management plan for the region would need to address both quantity and quality. This study has focused its analysis, however, on baseflow in order to begin to estimate the potential contribution of green interventions to address this important component of the challenge.

[2] *Puna* grasslands are natural grasslands on generally carbon-rich soils, located at high altitudes above the tree-line in the Central Andes.

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Regional context

Lima, Peru faces serious water stress, which is particularly pronounced during the dry season months of May through December. During the rainy season, the region enjoys a surplus of water: reservoirs are full and river flow is high (though contamination remains an issue). However, the dry season sees very little rain and, therefore, shortages of water in reservoirs, streams, and rivers. Figure 1 illustrates the seasonal nature of the region's water quantity challenges with a view of the Rimac River, the principal source of Lima's water.

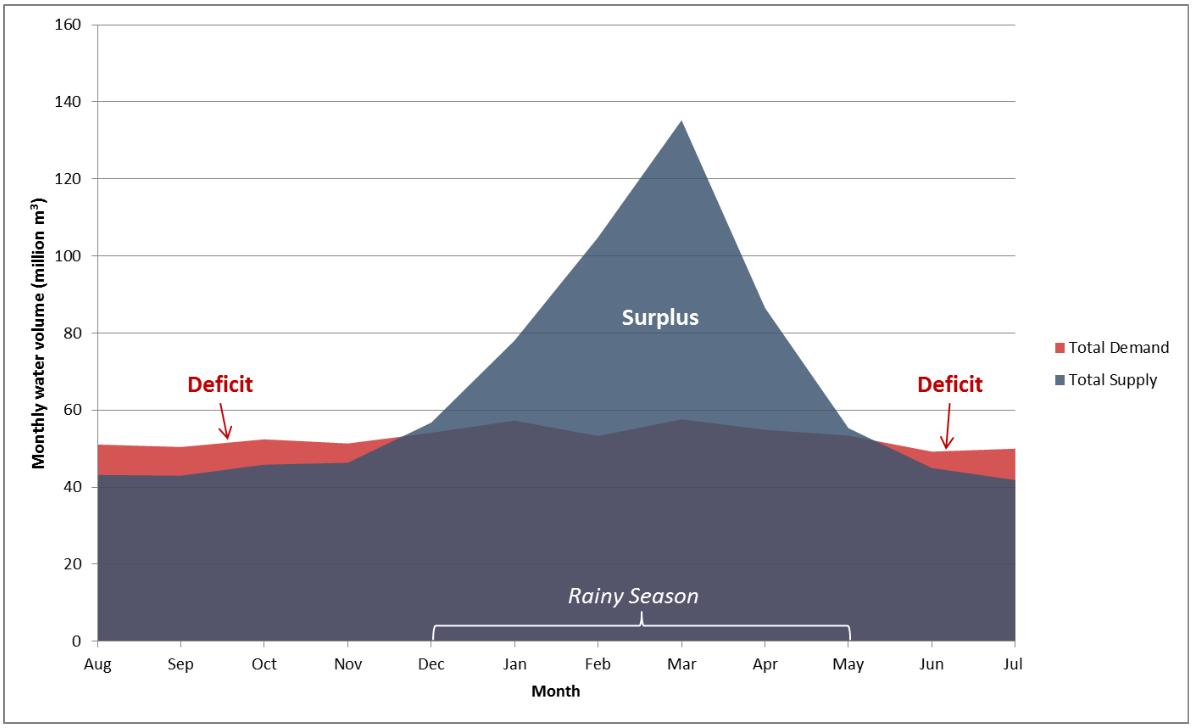

Figure 1. Water supply and demand in the Rimac River watershed. Source: Peru Ministry of Agriculture, 2010.

The figure above clearly illustrates that the water supply reaching Lima, in terms of annual total, is sufficient in quantity to meet the demand of water users in the city. However, much of the surplus supply from the wet season runs through the region and into the ocean.

This deficit is further illustrated by Table 1, which shows the average monthly flow surplus and deficit (m^3/s) for the watersheds that supply water to Lima.[3] The table shows that in the driest month for the Rimac-Alto Mantaro, July, there is an average flow deficit of 0.86 m^3/s. This deficit is particularly critical to the population of Lima, as the largest treatment plant for Lima's water utility, SEDAPAL, is supplied by the Rimac River. The Chillon watershed experiences even more pronounced dry season deficits, with average flows in August, September, and October running so low that there is basically no flow remaining after agricultural withdrawals for SEDAPAL's smaller treatment plant.[4] The Lurin watershed, which also supplies the Lima region but where there is currently no SEDAPAL intake, barely meets the agricultural supply demands in the dry season months.

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[3] These tables show data that combine flow figures for the Rimac and Alto Mantaro watersheds. The Alto Mantaro watershed is otherwise excluded from the scope of this study, as its primary contributions to Lima's water supply occur through gray infrastructure diversions.

[44] SEDAPAL's plant in the Rimac watershed has an operating capacity of 17.50 m^3/s, while its plant in the Chillon watershed has an operating capacity of 2.50 m^3/s (Nippon Koei 2012).

Table 1. Average flow surpluses and deficits (m3/s) for Surface Waters in the Chillon, Rimac, and Lurin Watersheds, by month. Source: Nippon Koei LAC (2011).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Surplus (Deficit) - Rimac-Alto Mantaro watersheds	16.51	30.86	34.49	18.70	3.48	0.08	(0.86)	(0.53)	(0.55)	0.00	1.86	6.48
Surplus (Deficit) - Chillon watershed	4.86	9.14	14.01	4.06	(0.44)	(1.49)	(2.46)	(2.50)	(2.50)	(2.50)	(2.38)	0.72
Surplus (Deficit) - Lurin watershed	3.44	9.05	10.72	4.48	1.66	0.66	0.45	0.00	0.00	0.00	0.00	1.48

In terms of volume, the annual water deficit is about 5.15 million m^3 for the Rimac-Alto Manataro watersheds and 37.67 million m^3 for the Chillon watershed, for a total of 42.84 million m^3. These figures correspond to about 2% of the rainy season surplus for the Rimac-Alto Mantaro watersheds, and about 44% of the rainy season surplus for the Chillon watershed. Lima's water quantity challenges could be substantially mitigated if water entering the Chillon, Rimac, and Lurin watersheds (together, the "ChiRiLu") during the wet season were stored longer in the watershed – in other words, if Figure 1's peak was dampened and its troughs increased.

About this study

Restoration of natural processes and even ancient infiltration practices in the ChiRiLu watersheds can improve the regulation of hydrological flows, helping to spread out the surplus water enjoyed during the wet season over the dry season. Forests, grasslands, and wetlands can act like sponges, absorbing water during the wet season and slowly releasing it through the year. Ancient infiltration techniques were once used to increase water storage and slowly release flow that would re-surface in downslope springs after a time lag of several months can also be part of a landscape strategy. Implementing these types of green interventions can result in additional social, cultural, and environmental benefits, as upstream communities are engaged to support improved management of the region's watersheds and water resources and as natural systems can also filter out water contaminants, stabilize soils, and provide habitat for biodiversity.

Clarifying Terms: Gray Infrastructure, Natural Infrastructure, and Green interventions

Water resource management interventions in reality form a spectrum of green to gray strategies, making a clear distinction between "green" and "gray" infrastructure difficult to draw and perhaps unnecessary. Where these terms are used in this paper, however, we have the following definitions in mind:

- ***Gray infrastructure***: conventional, built infrastructure (e.g., wastewater treatment plants, large projects to divert water from other watersheds, industrial pollution control technologies)
- ***Natural infrastructure***: watershed ecosystems -- like forests, wetlands, and grasslands -- that provide a variety of ecosystem services, or benefits, for water resource management as well as habitat provision, carbon sequestration, pollination services, etc.
- ***Green interventions***: a wide range of actions that protect, restore, or enhance watershed ecosystems and/or sustainable land use in a watershed – for example, may include actions that reduce threats to natural forests, restore wetlands, improve filtration capacity of rangelands, keep cattle away from surface waters, or reduce nutrient run-off of agricultural land.

This study characterizes the potential of green interventions to reduce the dry season water deficit for the city of Lima. While gray infrastructure like reservoirs and diversion projects can also help to close the gap, this study focuses on estimating the impact of green interventions. While proponents of watershed interventions often point to the contributions natural systems can provide to water resource management strategies, the case for green interventions is rarely quantified in a way that allows them to be compared to other alternatives – particularly in emerging and developing economies. Indeed, before this study, no such quantification had been done for green interventions in Lima, or any other region of Peru.

Estimating hydrological benefit is more difficult to do for green interventions in the region than for conventional gray infrastructure, due to a lack of available data regarding the hydrological processes in these very complex mountain catchments. In addition, variations across regions make it difficult to extrapolate the available results from the few existing research sites. Without extensive, rigorous monitoring in the study region over long periods of time, there has been no clear approach for estimating hydrological benefits of watershed interventions. In the absence of this information, this study offers an approach for empirically calculating the potential hydrological benefit of a set of green interventions in terms that allow them to be compared with gray infrastructure. The study also points to priority research areas to fill the remaining knowledge gaps. The analysis team recognizes that this study is just the first step toward producing robust, data-driven estimates of the full potential of green interventions for water resource management for Lima.

This preliminary study was designed and implemented by a consortium of partner organizations representing a unique diversity of expertise. Forest Trends, a US-based non-governmental organization focused on using economic tools and market-like mechanisms to support conservation, designed and coordinated the study. Kieser & Associates, LLC, a US-based consulting firm with decades of experience designing and implementing water quality trading programs and other performance-based watershed services programs, supported the design of the study and compiled preliminary empirical methodologies used to calculate performance of green interventions. Aquafondo, the water fund for Lima and Callao, led the scoping of the study, engagement of key stakeholders, and collection of local data to inform the analysis. CONDESAN, a non-governmental organization focused on sustainable development in the Andes, added regional hydrological expertise to help adapt the calculation methodologies and supplement reliable, regional data. The Swiss Agency for Development and Cooperation funded this study, through the Forest Trends project, *Scaling Up Investment in Watershed Services to Meet the Global Water Crisis.*

Scoping

The primary parameters scoped for this study were the hydrological benefit metric, the interventions, and the geographic scope. Each of these parameters was defined by the analysis team with the input of the National Water Authority and other regional stakeholders.

Hydrological benefit metric

Baseflow was selected as the criteria against which the performance of green interventions would be assessed. Baseflow is defined as the lowest rate of surface water flow in the year and is expressed as cubic meters per second (m^3/s). This study does not specify at which point (altitude or river km) the benefit of increased baseflow occurs.[5]

Given acute strains on both water quality and water supply in the region, the selection of baseflow as the performance criteria was not simple. The project team recognizes that future studies should assess the impact of green interventions in terms of other criteria as well, including reduction of nutrient and sediment pollution.

Baseflow was ultimately selected as the targeted hydrological benefit criteria for this first round of analysis given its priority among stakeholders throughout the watershed, in particular the National Water Authority and SEDAPAL, and the potential to compare the ability of green interventions to increase baseflow to the performance of inter-basin water transfer projects. The team also concluded that, compared to other indicators, it would be most feasible to assess the contribution of green interventions to water resource management results in terms of baseflow.

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[5] Especially with infiltration practices, the location of the re-surfacing is not assessed, but it is clear that this technique provides a benefit at relevant downstream locations.

Interventions

The four interventions, or project types, assessed in this study were selected from a more comprehensive list of interventions prepared by Aquafondo, which was based on a combination of possible watershed interventions identified previously by Kieser & Associates, CONDESAN, and EfCO. The interventions were selected based on the potential contribution to improve baseflow, the ability of the analysis team to identify or construct a methodology to assess the intervention against the performance indicator, and the interest of Aquafondo in pursuing these types of projects within its investment portfolio. The interventions selected were also assessed to be feasible to implement in the region of study, given existing experience and early assessments of willingness of upstream communities to participate in these types of projects. Interventions that were considered in the 'long list,' but excluded from the present analysis, included reforestation, riparian buffers, improvement of irrigation systems, and restoration of pre-Incan terraces. As such, a full portfolio of green interventions for the region of study could include many more types of projects, and much greater potential impact, than what this analysis – limited to four interventions – can suggest.

The four interventions selected are described here, along with a qualitative description of their expected hydrological benefits. Further details are available in the technical primers for their respective hydrological benefit quantification methodologies, attached as Annex 1.

Animal exclusion from natural grasslands (*puna* ecosystems)

Puna grassland ecosystems that exist on carbon-rich soils in the high altitudes of the ChiRiLu watersheds, as most of Peruvian central highlands, are used for cattle and alpaca grazing by local communities. While alpacas have relatively benign impacts on the hydrological properties of the soils because of their cushioned feet and cutting bite, cattle compact the soil, cause soil creep, and, depending on cattle density, can cause incomplete grass cover of the soils. The animal exclusion intervention would result in the closure of these grasslands, removing current grazers, through the construction of a physical barrier or communal governance measures, thus limiting the function of these territories to 'water producing areas.'

Removing animals from the protected zone allows the *puna* ecosystem to recover its positive hydrological qualities. Compacted soils are allowed to decompress, and soil bulk density and infiltration capacity improves. Vegetative cover is also allowed to return, protecting the soil and therefore reducing erosion. Additionally, grass evapotranspiration may decrease over time, especially if grazing was previously associated with burning as often is the case, therefore increasing catchment water yield. Together these results translate into improved capacity for hydrological regulation and reduction of sediments in the water supply, improving baseflows and water quality at the site level and, if implemented over a sufficient area, at the watershed level as well.

Rotational grazing on natural grasslands (*puna* ecosystems)

A variation on the animal exclusion intervention, the rotational grazing intervention supports a transition from year-round (or nearly year-round) intensive grazing to a system of rotational grazing that allows the *puna* ecosystems to regenerate during periods of animal exclusion. Animals are allowed to graze on a rotational basis between alternating areas to avoid overgrazing (e.g., removal of vegetative cover to roots; substantial compaction of soils).

Managing the grazing in rotations improves and maintains the capacity of the *puna* ecosystems to regulate hydrological flows and protect soil from erosion, through the same mechanisms as the animal exclusion intervention discussed above.

Hydrological restoration of drained wetlands

Wetlands in upper elevations have been drained by surface trenching to allow animal access for grazing. Trenches actively drain direct precipitation and localized groundwater, resulting in these water sources being rapidly lost throughout the year and thus not contributing to stream baseflow.

By closing off ditches, wetlands will replenish their stored volumes, and deep infiltration of surface water regulation processes will recover. In turn, the surface storage of water throughout the year will infiltrate to shallow groundwater and contribute to local stream baseflow.

This intervention does not consider the much more involved process of full ecological restoration of drained wetlands, which would likely incur much higher costs than those used for this intervention in this study.

Amuna restoration

Amunas, or ancient diversion channels, in select upper reaches of Lima's watersheds historically conveyed stream flows to infiltration ditches constructed laterally across mountainsides. Infiltrated water would re-emerge in small, constructed micro-pools or in natural springs downslope, over several weeks or months of lag time. Part of this water then could be withdrawn for agricultural irrigation. Over time, whatever form of grout used to make the diversion channel impervious failed. This resulted in any diverted water quickly re-infiltrating near the head of the diversion only to then re-enter the stream where it is rapidly lost in surface flow. Re-grouting the diversion channels with cement results in all the diverted stream flow being conveyed to the infiltration ditches. It is assumed that all water in the infiltration ditches makes it to shallow groundwater. After a portion of the water is withdrawn for local irrigation, the remaining water recharges local groundwater, contributing to baseflow.

This intervention is limited to restoring existing *amunas*, not building new diversion channels and infiltration ditches, which would be more costly. These types of structures are not likely widespread throughout the basin, though more than 30 *amunas* have already been identified in one sub-watershed in the Chillon basin.

Geographic scope

The geographic scope of the study was determined to encompass the Chillon, Rimac, and Lurin watersheds, which together supply almost all of Lima's water. The watersheds from which water is diverted and transported through or over the Andes to Lima constitute the remaining catchments that provide water to Lima. These were not considered in the study. The geographic scope determines the area in which green interventions were considered for potential application.

Estimating marginal cost and total potential impact

This study coarsely evaluated each of the interventions in terms of a) marginal cost and b) total potential impact on baseflows. It should be expected that both of these could be improved with future data collection, as noted later in the Discussion section.

The marginal cost of each intervention was estimated by dividing the annualized total cost of a typical project by the estimated baseflow benefit (or, for $/m3 values presented, the annualized cost was divided by volumetric contribution to dry season flows in one year). Project costs included estimates of materials and direct labor, as well as project management (including community engagement and quality assurance). Because nearly all costs considered were up-front costs incurred in the first year of a project, future costs were not discounted. All costs presented in this study are in terms of U.S. dollars.[6]

The total potential impact of each intervention was estimated by multiplying the typical project-level baseflow benefit by the estimated total number of typically sized projects in the ChiRiLu watersheds. It is important to note that this total potential impact represents a preliminary, high-end estimate of benefits to the entire ChiRiLu region, assuming the interventions are implemented at their fully scaled potential. This analysis is currently not able to estimate the potential impact at a particular point in the watershed, such as the intake for SEDAPAL.

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[6] Where costs were converted from Peruvian Soles (PEN) to USD, the exchange rate 2.8 PEN = 1 USD was used.

For many of the assumptions used in the study, the analysis team identified unfavorable, favorable, and 'best estimate' values to represent the average value among all potential projects for each intervention.[7] These ranges were constructed to account for uncertainties inherent to the analysis, where robust historical hydrological monitoring is not locally available. It is important to note that the variation in these values is not due to inevitable variation of values for specific projects in the region, but rather due to uncertainty around the *average value* for all potential projects in the region.

Value ranges were not used to account for uncertainty around the ability of project developers to implement all potential projects, for example due to lack of interest on the part of upstream communities.[8] As a result, the *total potential impact* figures cited in this report reflect full-scale implementation. Future analyses may consider a range of values to reflect uncertainty around participation rates, if the goal is to estimate the most likely potential impact, rather than the *total* potential impact.

Performance assessment methodologies

The potential hydrological performance of a typical project for each green intervention was estimated using calculations adapted from agricultural programs and credited watershed services markets in the United States as well as local information where possible. The distinct advantage of this approach is that it allows the analysis to estimate green interventions benefits before a robust monitoring program can be carried out to more precisely describe these. Due to limited data input and research on particular hydrological dynamics in the region of study, the results of these calculations are expectedly coarse and err on the more conservative (limited benefit) side of potential outcomes. These order-of-magnitude or better estimates offer some basis for prioritizing investments in the watershed while also allowing the team to assess the sensitivity of performance estimates within ranges of uncertainty – helping to inform where monitoring/research efforts in the region could be most effectively focused.

The calculation methodologies for estimating baseflow benefits associated with each intervention are summarized in here; more detailed descriptions may be found in the technical primers prepared by Kieser & Associates, which are included as Annex 1 of this report. The calculations themselves, as well as data values, sources, and qualitative assessments of uncertainty, are also available as Annex 2 of this report.

Animal exclusion and rotational grazing on natural grasslands

As noted in the scoping section, closing grasslands to grazing and introducing rotational grazing on *puna* grasslands similarly improve the hydrological regulation capacity of the area, to varying degrees. As such, one methodology was prepared to estimate the performance of each.

In both interventions, a watershed mass equation is applied to estimate improved baseflow. Baseflow increase is determined by differences in the estimates of before and after conditions using the equation where streamflow equals dry season precipitation minus losses associated with evapotranspiration, plus changes in soil moisture and deep and shallow groundwater, accounting for streamflows into and out of the area of the intervention. Soil moisture capacity is influenced by soil bulk density, organic carbon content, and vegetative fiber content.

The difference between the animal exclusion and rotational grazing interventions is reflected in data inputs representing soil and vegetation conditions in the grasslands under typical projects of each intervention.

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[7] In general, higher values pertaining to performance were more favorable, while higher values pertaining to costs were unfavorable.

[8] In all but one case, this means that the potential area of application was consistent across unfavorable, favorable, and 'best estimate' calculations. In the exception, *amuna* restoration, the total potential number of *amunas* that could be restored was varied, to reflect significant uncertainty around the number of existing *amunas* that could be restored.

Hydrological restoration of drained wetlands

A conservative calculation of increased baseflow is made with a simple mass balance calculation for the depth of annual rainfall (or dry season rainfall) in meters times the surface area of the restored wetlands (m^2) minus evapotranspiration. This only assumes direct precipitation as the source of water to the wetland with no consideration of increased local groundwater levels and related contributions associated with removal of the artificial trench. The additional volumes can be calculated per annum or per dry season months. Dividing by the number of seconds during either period yields m^3/second of baseflow. The assumption applied is that infiltrated water becomes part of the groundwater recharge that contributes directly to stream baseflow. Surface water recharging groundwater is no longer rapidly lost by surface drainage.

Amuna restoration

The estimation of baseflow benefit from amuna restoration is calculated using a simple water mass balance equation. The restored diversion channel, previously unused, continuously conveys excess water out of a stream during the wet season. The intervention renders the channel impervious, thus conveying the water directly until the point where it is intended to infiltrate. Thus, the amount of water that is assumed to infiltrate into groundwater is determined by the channel flow capacity and by the availability of excess water in the stream (i.e., duration of the wet season).

A correction factor is included for losses by evapotranspiration and upstream local use of the flow. The baseflow benefit calculation assumes that infiltrated water will at some location contribute to baseflow in downstream river reaches, and that time lags are long enough to span from wet to dry season.

Costs

The analysis benefited from regional experience with the interventions considered, particularly in the estimation of costs. In particular, the now-defunct public program PRONAMACHCS had experience with all four interventions in the ChiRiLu region, roughly between the years 2000-2011. AgroRural, the public agency that implemented these programs, generously shared actual direct costs of project implementation, which formed the basis of our cost estimates for the pasture management and wetland restoration interventions. The NGO Alternativa also shared actual costs for an *amuna* restoration project, which was likewise used in our calculations.

In addition to direct material and labor costs, the calculations include estimated costs for community engagement, monitoring, and quality assurance of these projects. Since many projects (in the case of the grazing interventions, averaging 10 ha each) could be implemented in the land controlled by a single community, and since monitoring and quality assurance are likely to be executed through sampling, these costs were estimated at the level of the community and divided by an estimated average number of projects that could be carried out with one community, for each intervention.

The calculations do not reflect direct compensation for opportunity costs, as one might expect in a traditional payments for ecosystem services project. The reason for this is that the interventions are assumed to be implemented in a way that will generate sufficient economic and hydrological returns to the community to incentivize their participation. For example, experience from Aquafondo pilot projects and regional agricultural extension services shows that many ranching practices in the ChiRiLu region are extensive and inefficient, such that rotational grazing practices, combined with technical assistance to improve yields per animal, can at once reduce the footprint of these activities and increase economic returns for community members. Moreover, in many cases the community itself may benefit from improving the capacity of the watershed to regulate hydrological flows, and the increase in dry season flows may be sufficient to incentivize the requisite behavior change. This is largely the case, for example, in an Aquafondo pilot project in the community of Huamantanga in the Chillon watershed, where improvements in baseflows that are expected to result from improved pasture management and *amuna* restoration, is the primary motivator for community engagement in the project. Future analyses may consider potential cost-sharing for these interventions that generate significant local benefits, which would further decrease the cost of project implementation to downstream users.

Area of application

Altitude, ecosystem type, slope, and land use were considered in the estimation of the *total potential area of application* of each intervention type within the ChiRiLu watersheds. This area is meant to suggest the greatest extent of potential application, and therefore does not take into account factors such as disposition of particular communities or landowners to actually participate in a project. As a result, these estimates of application areas are likely higher than what a program on watershed investments would likely be able to achieve. However, it does allow the study to begin to understand the potential for scale for each of the interventions considered.

Area of application for each intervention was constrained by the condition that areas 'assigned' to each intervention could not overlap, or in other words could not be double-counted. This is particularly important since the four interventions considered by this study could not be carried out at the same time on the same area of land. The primary consideration in preventing double-counting related to the pasture conservation interventions. Here, it was estimated that of the total *puna* area in the ChiRiLu watersheds, 50,506 ha, 80% was assumed to be currently overgrazed and therefore potentially could be improved through one of the two interventions discussed here. Of that 80% (40,405 ha), 30% was assumed to constitute the total potential area of application for *animal exclusion* (12,121 ha), and 70% was assigned to the total potential area of application for *rotational grazing* (28,283 ha).

Based on the estimated total potential area of application in the watershed and the estimated average project size, the total potential number of projects was estimated for each intervention. Table 2 reports these figures.

Table 2. Potential area of application for each green intervention

	Potential area of application	Number of communities with which the intervention could be implemented
Animal exclusion from puna grasslands	12,121 ha	50
Rotational grazing on puna grasslands	28,283 ha	50
Restored wetland hydrology	1,268 ha	20
Ancient diversion channel restoration	25-75 channels	4-8

Results

The analysis finds that the green interventions considered in this study have significant potential to dramatically decrease the baseflow deficit for Lima at very reasonable cost.

Figure 2 summarizes this study's findings in the form of a cost curve. The width of each column corresponds to total potential baseflow impact, in terms of cubic meters per second. The height of each column corresponds to the average marginal cost of each intervention, in terms of millions of U.S. dollars per unit increase in baseflow.

Amuna restoration stands out as a particularly cost-effective and potentially high-impact green intervention, being an order of magnitude less expensive than the next most cost-effective intervention, wetland restoration, and potentially closing about 40% of the 3.05 m^3/s regional baseflow deficit (see "Regional Context" section). Hydrological restoration of wetlands is also identified as a cost-effective intervention, though our calculations yield a much lower estimate of total potential impact at full-scale implementation.[9] The two interventions for improved pasture

[9] As discussed in the section below on total potential impact, part of this may be due to the calculation methodology for wetland restoration being conservative, not accounting for any hydrological benefits that could accrue from shallow groundwater infiltration. The potential area of application for wetland restoration is also much smaller than, for example, the grazing interventions.

management on *puna* grasslands suggest significant potential for scaled impact, at 1.44 m^3/s together at full implementation, though estimated average costs are about an order of magnitude higher than wetland restoration.

Under full implementation – that is, if every potential project for each intervention were implemented – the analysis suggests that these four green interventions could improve baseflow by 2.74 m^3/s, equivalent to 90% of Lima's baseflow deficit (3.05 m^3/s), at a total cost of $7.9 million per year.[10] Implementing just the three most cost-effective interventions at full scale is estimated to reduce the dry season deficit by 62%, for approximately $2.1 million per year.

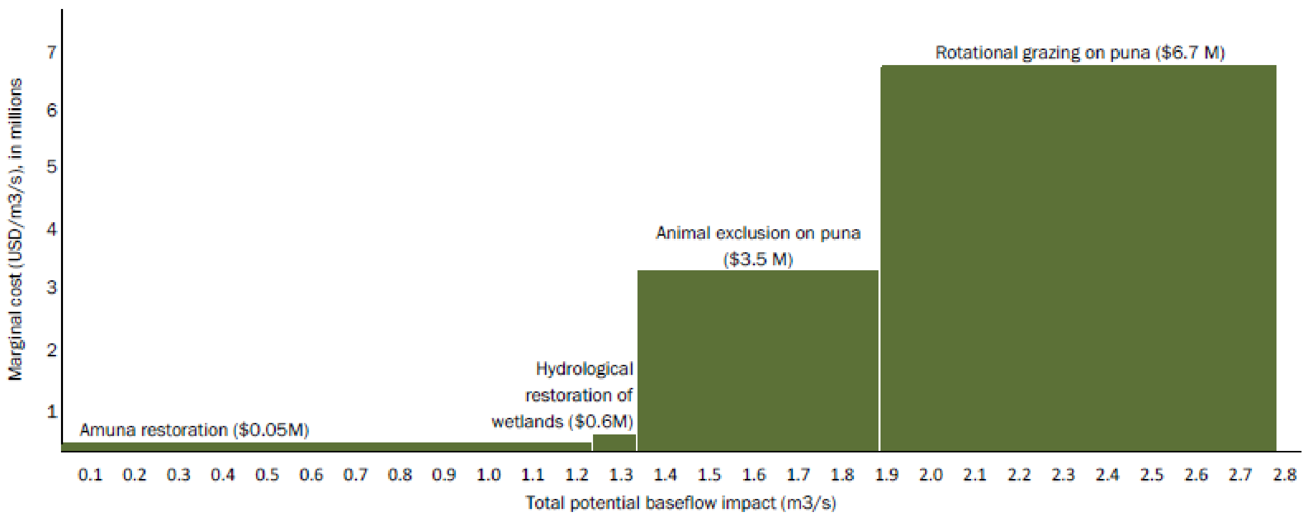

Figure 2. Cost curve of green interventions for improving dry season water supply for Lima.

Under perhaps a more realistic implementation scenario in which one in four potential projects in each intervention is realized, reflecting variability in potential participation rates, the portfolio of green interventions could reduce the baseflow deficit by 0.69 m^3/s, or 23%, at a cost of approximately $2 million per year.

Cost-effectiveness

As Figure 2 illustrates, the assessment found *amuna* restoration to be exceptionally cost-effective. The average unit improvement in baseflow (m3/s) under *amuna* restoration was estimated to cost $85,750. The analysis finds hydrological restoration of wetlands to be the second most cost-effective option, with average baseflow increases about ten times more expensive than that from *amuna* restoration. Our estimates place animal exclusion from *puna* and rotational grazing on *puna* at 5 and 8 times more expensive than hydrological wetland restoration, respectively. Table 3 summarizes these results.

These cost-effectiveness assessments do not show, however, the potential for cost-sharing in project implementation. As mentioned earlier, these interventions are assumed to deliver significant economic benefits to upstream communities; in fact, existing experience with these interventions has been motivated precisely by these rural development benefits. Potential returns to upstream producers could help to defray the upfront costs of these interventions; such arrangements could significantly decrease the marginal cost of improvements resulting from rotational grazing, for example.

[10] Our conservative estimates at full implementation place total potential impact at 0.9 m^3/s (29% of the deficit) and costs at $10.7 million per year. Our favorable estimates at full implementation place total potential impact at 9.43 m^3/s (309% of the deficit) and costs at $6.3 million per year.

Table 3. Estimates of cost per unit increase of baseflow (USD/m3/s) for four green interventions

	USD/m3/s
Amuna restoration	$85,750
Hydrological restoration of wetlands	$661,948
Animal exclusion from puna	$3,457,033
Rotational grazing on puna	$6,695,636

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Potential baseflow impact

The total potential impact on baseflow of these four interventions at full scale is considerable, reducing 90% of Lima's baseflow deficit in our best estimate, at a potential total contribution of 2.74 m^3/s. In terms of annual volumetric impact, this translates into a best estimate of more than 58 million cubic meters of dry season flow. *Amuna* restoration has the greatest potential impact on baseflow, at 1.2 m^3/s.

Table 4. Potential impact of green interventions at full scale, baseflow (m^3/s) and dry season water supply (m^3)

Intervention	Potential baseflow impact (m^3/s)	Potential impact - dry season water supply (million m^3)
Amuna restoration	1.22	25.9
Hydrological restoration of wetlands	0.09	1.9
Animal exclusion from puna	0.58	12.3
Rotational grazing on puna	0.86	18.1
Total	**2.75**	**58.2**

The potential contribution of pasture management is also significant, with animal exclusion and rotational grazing together estimated to contribute a potential baseflow improvement of 1.44 m^3/s at full-scale implementation. Between the two, rotational grazing is estimated to have a larger potential impact, despite its estimated lower average impact at the project scale. The difference at scale is primarily due to the much larger area assigned as the potential area of application for rotational grazing compared to animal exclusion, as it is assumed that upstream communities would likely be more amenable to introducing rotational grazing practices, which would require less significant livelihood changes.

The potential impact of hydrological restoration of drained wetlands is quite small. However, it should be clearly noted that this may not reflect reality as much as the conservatism of the methodology employed for the estimation of watershed restoration baseflow benefits. As discussed in the technical primer for this intervention (see Annex 1), the methodology does not capture hydrological dynamics between restored wetlands and shallow groundwater recharge, which would add significantly to this intervention's estimated hydrological benefit. This element of hydrological benefit is not considered in the calculation methodology because it was considered especially site-specific.

Addressing uncertainty in the analysis

Significant data and knowledge gaps in the region of study required the analysis to supplement monitored data with expert best judgment for several assumptions utilized in the calculations. To account for the uncertainty that these data and knowledge gaps create, the analysis included value ranges for most assumptions that reflect the conservative and favorable bookends of potential average values, and as such produced conservative and favorable estimates of all figures discussed in this report. These value ranges and resulting ranges of cost-effectiveness, potential impact, and so forth can be viewed in detail in Annex 2.

Table 5 lists the assumptions used in our analysis, along with a qualitative scoring of the uncertainty associated with each. As the table shows, there are some clear data gaps – including spatial variability of rainfall or soil water retention characteristics – which field measurements could help significantly to reduce.

Apart from these data gaps, uncertainty appears in some of the more complex aspects of hydrological dynamics in the ChiRiLu watersheds. The time lag between retention of wet season rainfall and baseflow release, for example, is not well-understood in the region of study. Relatedly, the groundwater dynamics, including infiltration to shallow soil or deeper geology, is neither well-understood for the complex mountain catchments under consideration here. Given that these interventions "work" by slowing down flows, such that excess water in the rainy season becomes available in the deficient dry season, understanding this time lag and related groundwater dynamics is a key area for further research.

Table 5. Assumptions made in green intervention cost and performance calculations, with qualitative assessments of uncertainty.

Level of Uncertainty	Variable	Comments
High	Curve Number, with and without project	Factor which estimates surface runoff for pasture management interventions
High	Relationship between soil moisture and baseflows	For pasture management interventions
High	Percentage of water 'lost' to upstream agriculture, evapotranspiration, etc.	"C factor" for amuna restoration
High	Number of abandoned amunas that could be appropriately restored	Estimated for potential area of application for amuna restoration
Medium	Estimated number of communities where project could be implemented	For all interventions
Medium	Community engagement and compliance monitoring costs (for one community)	For all interventions; does not include advanced hydrological monitoring
Medium	Total years of duration, typical project (all interventions)	
Medium	Soil organic carbon – with and without project	For pasture management interventions
Medium	Relationship between increase in soil organic C and soil moisture	For pasture management interventions
Medium	Soil bulk density and depth	For pasture management interventions
Medium	Total potential area of application	For all interventions
Medium	Average wet season discharge from diversion channel to infiltration ditch	For amuna restoration
Low	Direct costs to implement one project (all interventions)	Sourced from actual projects
Low	Annual, wet season, and dry season precipitation	Values maintain variation to reflect year-on-year differences
Low	Number of wet season and dry season days per year	

To transparently deal with this uncertainty in the analysis, conservative and favorable assumptions were made alongside our best estimations of average values, creating corresponding estimates for all of the results reported in this study. Based on these ranges, we can assess the sensitivity of our results to uncertainty around our assumptions.

Overall, the assumption where varying conservative-favorable values have the greatest impact is precipitation. However, this variation reflects more a *risk* of lower effectiveness of the intervention due to a dry rainy season, rather than an uncertainty around historical precipitation rates. Because these interventions work by dampening the peak of these watersheds' hydrographs in order to buoy baseflow, a dry wet season will necessarily make them less effective, on a m^3 or m^3/s basis, in improving dry season flows.

Another key assumption whose variation significantly affects all interventions is the project duration. To the extent that a project can extend the amount of years that initial community engagement and application of materials will last, before efforts need to be re-initiated, projects will become proportionally more cost-effective. This element points to the central importance of ensuring social sustainability of the program and monitoring and communicating upstream benefits to community members, in order to ensure continued support for projects over time.

Among the four green interventions, *amuna* restoration has the greatest factor of difference between favorable and unfavorable estimates of total potential impact: the high end estimate is 18 times greater than the low end estimate. Areas of uncertainty that contribute to this variation include site-level characteristics, like the amount of water that flows through the channel in the rainy season and the amount of infiltrated water that would be lost to evapotranspiration and upstream withdrawals (e.g., for agriculture), as well as significant uncertainty around the number of inoperative *amuna* channels that could be appropriately restored in this region.

There is also significant variation in the rotational grazing intervention, where the favorable estimate of potential impact is nearly 12 times greater than the unfavorable estimate. Variation is less in the animal exclusion intervention, where the favorable estimate is about 5 times the unfavorable estimate. The primary source of uncertainty particular to these interventions is the response of *puna* grasslands to improved management, particularly as it relates to the reduction of runoff. Monitored field experiments will significantly help to reduce uncertainty around these dynamics and thus reduce the variation in final estimates.

For wetland restoration the range of estimates of total potential baseflow benefit that we have produced vary the least of all the interventions, with the favorable estimate being just 1.5 times the unfavorable estimate. Nevertheless, given the very conservative nature of the calculation methodology used in this case, we consider there to be significant uncertainty on the hydrological benefit of this intervention, which could be improved by specific site-level measurements at potential wetland restoration sites.

Discussion

This study lays the groundwork for further consideration of green interventions as part of a strategy to address water scarcity for the city of Lima. One clear benefit of producing estimates of costs in terms of baseflow yield is the ability to compare, on the same grounds, green interventions to conventional, gray infrastructure under consideration (or underway) to address Lima's water supply deficit. While the ability to compare green and gray alternatives in terms of cost-effectiveness is a critical contribution to the current decision-making paradigm for water resources management, we also suggest that other criteria that are beyond the scope of this study – such as risk management or increasing the resilience of a water system – should be considered in the full picture.

Beyond the clearest application of this study as an initial step for robust consideration of green interventions within regional water resource management strategies, the analysis and methodology may be useful for researchers, the private sector, and a variety of public agencies. By identifying the data needs and data gaps for assessing these green interventions for the Lima region, this study also offers important guidance to researchers at government agencies, academic institutions, and research institutes, by identifying large data gaps create the most imprecision in hydrological performance estimates. Additionally, we suggest that the methodological approach applied in this study, and detailed in Annex 1, may be useful for a variety of other applications, potentially including cost-benefit analysis for public investment projects, private sector contributions to water stewardship, and use of a quantifiable metric (baseflow in this case) for prioritizing green intervention projects within a water fund.

Comparing cost-effectiveness: green and gray interventions

Current strategies for increasing the water supply for the city of Lima rely almost entirely on gray infrastructure. These projects include diversion projects that bring over and through the Andes to the Pacific coast and even a desalination plant that is underway. Compared to these gray infrastructure projects, the green interventions considered in this study are cost-competitive, with our best estimates placing all interventions well within the $0.74/m^3 price point of the Agua de Mar desalination plant. [11] Amuna restoration and hydrological restoration of wetlands are more cost-effective than any gray intervention considered, even under our most conservative assumptions.

Table 6 summarizes the range of price points that this study has estimated for the four green interventions in terms of volumetric contribution to dry season flows in one year (USD/m^3). These figures are compared to comparable costs per cubic meter of gray infrastructure considered in a recent study elaborated to inform integrated water resource management planning for Lima, copied here in Figure 3 (Nippon Koei 2011).

Figure 4 illustrates how the green interventions considered in this study compare to eleven gray infrastructure projects, in terms of marginal cost. Green interventions are ordered by their 'best estimate' value, though favorable and unfavorable values are also shown in the stacked bar. The figure clearly shows that all 'best estimates' of green intervention cost-effectiveness place these options well below the $0.73/m3 price point of the desalination plant underway for the city. Amuna and wetland restoration are the most cost-effective of any green or gray intervention considered, and the pasture management interventions could be cost-competitive if actual values fall closer to 'best estimate' or 'favorable' assumption values instead of conservative values.

Table 6. Cost of dry season volume (USD/m^3) benefit for four green interventions

	Cost per unit dry season water volume (USD/m^3)
Amuna restoration	$0.004
Hydrological restoration of wetlands	$0.031
Animal exclusion from *puna*	$0.163
Rotational grazing on *puna*	$0.316

[11] To compare the impact of the green interventions to gray infrastructure, the metric of hydrological benefit changes in this section from m^3/s (baseflow) to m^3 (annual volume of dry season flow). The calculations in Annex 2 walk through this conversion.

COSTO NIVELADO POR METRO CÚBICO SEGÚN FUENTE DE AGUA

Orden	Fuente de Agua	US$/m^3
1	Regulación Jacaybamba en el Río Chillón	0.1048
2	Punrun I Etapa-Río Chillón	0.1216
3	MARCA V: Presa Casacancha	0.1515
4	Intercambio Der. Agua-I Tramo Chosica-La Atarjea	0.1743
5	San Antonio Escondido	0.1774
6	MARCA IV: Huascacocha con derivación hacia el Rímac	0.1821
7	Intercambio Dre. Agua-II Tramo Chosica-La Atarjea	0.1849
8	MARCA II: Derivación Pomacocha-Rio Blanco-1ra y 2da Etapa	0.2280
9	Las Tinajas y PTAP	0.2307
10	Ampliación Tunel Grathon 4 Km.	0.2493
11	Planta Desaladora de Agua de Mar, Lima Sur.	0.7365

Figure 3. Estimated cost (USD/m3) of 11 gray infrastructure projects for increasing water supply to Lima. Source: Nippon Koei LAC Co., Ltd. (2011)

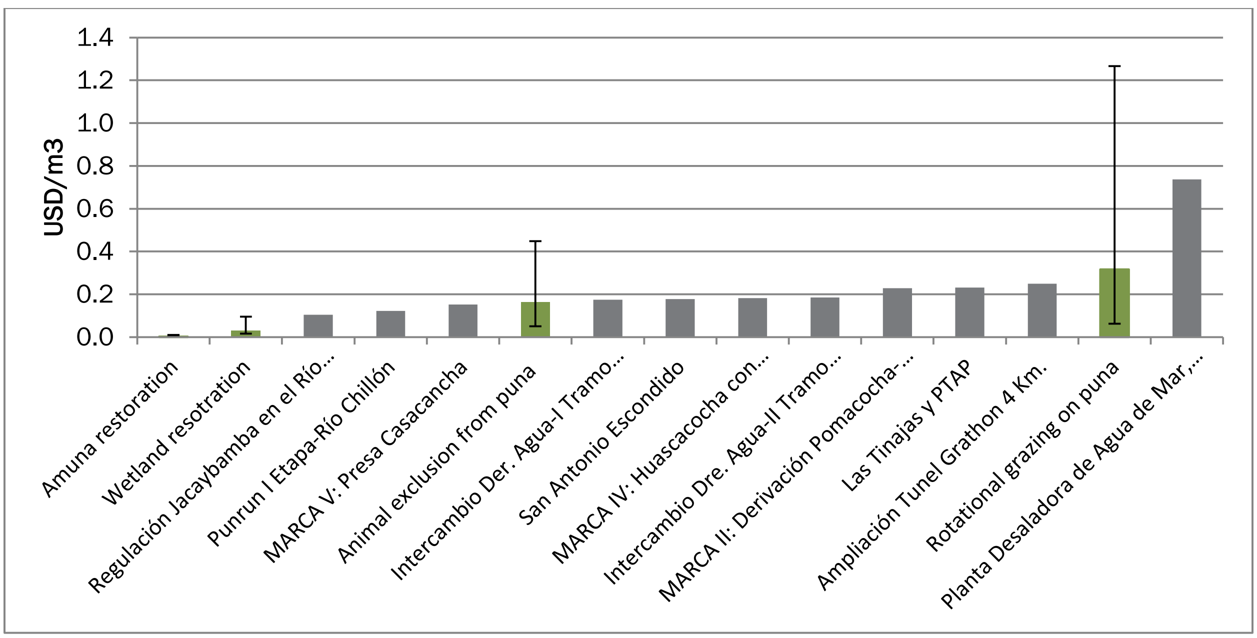

Figure 4. Costs (USD/m3) of green and gray interventions for Lima's water supply. Sources: current analysis and Nippon Koei (2011).

Priority research areas for watershed interventions

As stated earlier, the understanding of flow processes and velocities, once the water is infiltrated, is key for the calculation of benefits in terms of building in time lags in the hydrological system. A number of techniques are available, from simple assessments of electrical conductivities of the water, to more complex analysis of isotopic composition of the hydrogen and oxygen atoms of the water molecule. Tracer experiments would be very helpful in many circumstances. These could be especially useful in confirming the hypothesis of the promising *amuna* restoration intervention that enhanced infiltration is actually bridging towards the dry season. This kind of research has not been done before in these environments.

The interventions that involve changing grazing regimes and rewetting of wetlands, would benefit very much from experimental microcatchment studies that include continuous flow measurements in nearby streams.

Hydrological studies need many years of monitoring to capture the intrinsic variability of hydrological conditions over years. However, research and monitoring designs can be specifically targeted at producing short-term (= few years) results.

Other applications for the calculation methodologies

The calculation methodologies utilized to estimate the hydrological performance of each green intervention can be applied in a variety of other settings.

For instance, Aquafondo may decide to prioritize individual projects for investment based on the site-level cost-effectiveness expected from each project, using the relatively straightforward methodologies that a variety of project development partners could learn to apply. Government agencies could utilize the methodologies to estimate the hydrological benefit of rural technical assistance programs, many of which have implemented projects similar to those assessed in this study, as part of the cost-benefit analysis required for budgetary approval. The private sector might also find these methodologies useful to quantify expected impact of water resource management interventions. A number of emerging standards and certifications, such as the Gold Standard's Water Benefit Certificate and the Alliance for Water Stewardship Standard, offer opportunities for the private sector to value, or to be recognized, for quantified water resource improvements.

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Annex 1: Technical Primers on Quantifying Benefits of Watershed Interventions

These three technical primers describe the calculation methodologies used to estimate hydrological performance of four green interventions on baseflow in this study.

Fang, A., Klang, J., and Kieser, M (2014). Restoration of Puna Grasslands: Quantifying Potential Baseflow Improvements.

Kieser, M. and Boyer, K. B. (2014). Restoration of Wetlands: Quantifying Potential Baseflow Improvements.

Kieser, M. and Fang, A. (2014). Restoration of Amunas: Quantifying Potential Baseflow Improvements

Annex 2: Green Intervention Cost and Performance Calculations (Excel workbook)