Restoration of Puna Grasslands

Quantifying Potential Baseflow Improvements

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A Technical Primer on Quantifying Benefits of Watershed Interventions

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The Fund for Watershed Conservation and Water Resources of Lima and Callao, Peru, known as Aquafondo, was established to identify, fund and help implement watershed improvements in the Chillón, Rímac and Lurín basins. These basins are in a critical situation of water scarcity and impaired quality and are of particular concern since they represent an important source of drinking water for Lima. An effort is underway to help establish an operating framework for Aquafondo that can evaluate various watershed interventions in the context of simple, established performance metrics for water quality and water quantity benefits.[1] Coupled with projected costs for such interventions, the water fund will be able to assess, compare and optimize benefits associated with its investments in watershed improvements.

One of the more substantial challenges facing Aquafondo (and other governmental agencies and watershed stakeholders seeking these types of watershed improvements) is the ability to reasonably estimate water quality and/or water quantity benefits associated with specific intervention projects. As such, this Technical Primer[2] represents an initial examination of how Aquafondo and others may scientifically estimate a localized benefit of a particular agricultural intervention in the upper reaches of the Lima watersheds. This approach relies upon existing studies in the Andes mountains, as well as quantification methods derived from relevant conservation programs in North America. Although the assessment of cumulative benefits is not addressed in this primer, these interventions can be expected to provide broad, catchment-wide benefits to improved stream baseflow when implemented throughout the basin.[3]

[1] Kieser & Associates, LLC [K&A] (2012) Identification of Common Project Goals and Metrics for Aquafondo (Water Fund for Lima & Callao): Phase I Technical Report," Prepared for Aquafondo, Av. Chorrillos 150, Chorrillos, Lima, Peru.

[2] This effort was funded through Forest Trends of Washington, D.C. with support from the Swiss Development Corporation in collaboration with Aquafondo.

[3] Baseflow conditions are defined for this primer as the stream flows that exist during extended dry periods that do not have a substantial surface runoff component.

Proposed Interventions: Livestock Management in Puna Grasslands

The proposed interventions examined herein focus on either: 1) the complete exclusion of livestock from puna grasslands in the Rímac and Chillón watersheds, or 2) on rotational grazing of livestock to allow for full recovery and maintenance of these grasslands. Puna grasslands are a type of ecoregion that occurs in the Andes mountains at high elevations, above the treeline but below the permanent snow line. Vegetation in this ecoregion is dominated by grasses and shrubs, and soils have a rich organic content. Annual precipitation in puna grasslands varies depending on elevation and location, with some punas characterized by wet conditions while others are relatively dry.[4]

Excluding livestock from puna grasslands with fencing is expected to allow natural vegetation to re-emerge, which will lead to better soil health and improved infiltration of precipitation. Alternatively, proper livestock grazing practices, such as rotational grazing, are hypothesized to provide similar benefits as exclusion. Both practices should result in reduced overland runoff and increased soil moisture retention, thereby increasing available groundwater for stream recharge. Such interventions, particularly those close to streams where a larger fraction of soil moisture is released to surface waters, would be expected to produce water quantity benefits through improved stream baseflows. This increase (measured by the performance metric of cubic meters per second, m^3/s) is of particular benefit during drier periods of the year when the river depends predominantly on baseflow. This particular assessment focuses only on water quantity, although there also might be water quality benefits associated with livestock exclusion or proper grazing management reducing the sediment, nutrients and bacteria that reach surface waters. Specifically, this Technical Primer addresses quantifying baseflow benefits but does not address the design, installation, management or

HOW & WHY THE WATERSHED BENEFITS

Intervention →	Primary Soil Characteristic Altered →	Resulting Effect in Soil Profile →	Outcomes	Impact on Baseflow
Elimination of high intensity grazing	Reduced compaction of soils	Reduced soil bulk density	• Increased soil moisture retention capacity	Increased baseflow (*via increased soil interflow*)
	Increased vegetation density	Increased soil organic carbon content		
	Increased vegetation with deeper roots	Increased soil organic carbon content		
	More stems and roots remain, increasing infiltration pathways	Increased surface porosity	• Decreased surface runoff • Increased infiltration of precipitation	Increased baseflow (*via increased soil interflow*)
	Reduced compaction of soils	Reduced soil bulk density		
Elimination of grazing	Vegetative fiber increased	Increased soil porosity	• Increased soil interflow • Reduced flow to deep groundwater	Increased baseflow (*via increased soil interflow*)
Increased vegetation	Slight increase in evapotranspiration possible	Possible reduction in soil moisture over longer timeframes / limited effects during short timeframes	(dependent on setting and vegetation type)	(dependent on setting and vegetation type)

Soils have many characteristics that are interdependent on local vegetation and hydrology. Soils with characteristics that benefit water quality and quantity are said to have "good soil health". Practicing livestock exclusion in heavily grazed settings near streams is one way to improve soil health. This schematic provides an overview of the soil characteristics that can be improved by livestock exclusion intervention. It identifies how a change in a particular soil characteristic is expected to impact stream baseflow. These changes are tied to the pathway that each rain drop may take. Changing the flow pathways through this conservation practice alters the interactions between surface runoff, interflow of moisture through soils, and shallow groundwater. These changes in turn affect the time it takes for moisture derived from precipitation to reach the stream; most are expected to result in reduced peak flows and increased baseflows. Though not all of the changes may result in positive benefits to baseflow, (e.g., evapotranspiration), improvements in soil health via this intervention should lead to overall baseflow benefits.

[4] World Wildlife Fund. Montane Grasslands and Shrublands. Available online at: http://worldwildlife.org/ecoregions/nt1001

monitoring of these interventions (though data and research gaps are discussed in these latter regards).

Calculating Water Quantity Benefits

A water mass budget approach is proposed for calculating the water quantity benefits associated with the selected livestock interventions for puna grasslands. This calculation approach should be considered as just one potential method for quantitatively estimating improvements in stream baseflow associated with the restoration of native puna grasslands. Other calculation approaches may be available, but these also will likely require field monitoring and additional research to assess their capability to assess baseflow improvements as will the proposed mass budget method.

The mass budget approach involves applying the mass budget equation twice – first to represent conditions before the intervention and second to represent conditions after the intervention. The difference between these conditions reflects increased soil infiltration of precipitation and, in turn, increased baseflow of local streams – the watershed benefit of interest.

The generalized steps used to estimate the water quantity benefits using this mass budget approach include:

A. Gathering necessary representative site information

- Precipitation rates
- Estimates of evapotranspiration
- Soil data and comparison to values that reflect enhanced infiltration (e.g., compaction, bulk density, organic content)
- Evidence of surface runoff

B. Calculating intervention benefits

- Apply simplified mass budget equation twice, representing the before and after conditions by
    1. Calculating surface runoff
    2. Incorporating soil organic carbon content
    3. Incorporating soil bulk density and soil depth considerations
    4. Calculating total soil moisture
    5. Calculating baseflow depth
    6. Calculating baseflow volume
- Calculate the difference in baseflow between the before and after conditions
- Estimate the unit cost of increased baseflow ($\$/m^3 \cdot s^{-1}$) based on projected intervention costs

This primer summarizes the details of these proposed calculation steps for puna grassland interventions. Attachment A provides an example calculation using this approach for a hypothetical 10-hectare puna grassland pasture exclusion project. To our knowledge, these steps have not previously been applied to assess potential improvements in stream baseflows. This effort therefore represents an initial approach that can be refined through model calibration and verification with field monitoring of actual project sites and adapted as new research becomes available. This water mass budget approach will provide opportunities to potentially adjust inputs to accommodate differences in soil conditions between exclusion and rotational grazing interventions.

Mass Budget Equation

A watershed-scale water mass budget is represented by the following equation: [5]

$$P = Q + ET + \Delta S + \Delta G + \Delta L \quad (1)$$

Where:

P = precipitation	S = soil moisture
Q = streamflow	G = groundwater
ET = evapotranspiration	L = leakage

This water mass budget equation represents all the inputs and outputs of water in a watershed that occur during a specified period of time. In this equation, **Q** represents the surface flow leaving the catchment basin via a stream. The evapotranspiration component includes transpiration, interception loss and soil evaporation. The groundwater component represents both deep and shallow groundwater. Leakage reflects water movement into and out of the catchment.

The equation can be rearranged to solve for **Q** (streamflow), as this is of particular interest to Aquafondo for the Lima watersheds where this intervention would be implemented:

$$Q = P - (ET + \Delta S + \Delta G + \Delta L) \quad (2)$$

The general mass budget concept and components associated with these conditions are illustrated in Figure 1. As precipitation falls to the ground, the water either flows along the surface or infiltrates into the soil profile. Surface runoff that reaches a stream immediately contributes to increased flow. Water that infiltrates into soil can take multiple pathways and only a portion of this moisture eventually reaches the stream. In the case of precipitation that infiltrates, some soil moisture will taken up by plants and lost through evapotranspiration; there also can be direct evaporation from surface soils. Once soils are saturated from precipitation, moisture can move into shallow groundwater, as well as deeper groundwater over time; a portion of the moisture also will remain in the soil. There also can be water movement through these saturated soils (interflow) to localized surface water.

The mountainous conditions where puna grasslands are located influence how moisture is expected to move through these pathways. At high elevations in the Andes, the bedrock is expected to be relatively shallow. Infiltration to a deep groundwater system may occur through fractures in the rock. However, contribution to baseflows from deep groundwater will likely be relatively far from and downstream of the intervention. Thus, soil moisture interflow and shallow groundwater, as depicted in Figure 1, are expected to be the dominant pathways contributing to increased baseflows in the immediately adjacent streams.

[5] Fleischbein, K. W. Wilcke, C. Valarezo, W. Zech, K. Knoblich (2006) Water budgets of three small catchments under montane forest in Ecuador: experimental and modelling approach. *Hydrol. Process.* 20:2491-2507.

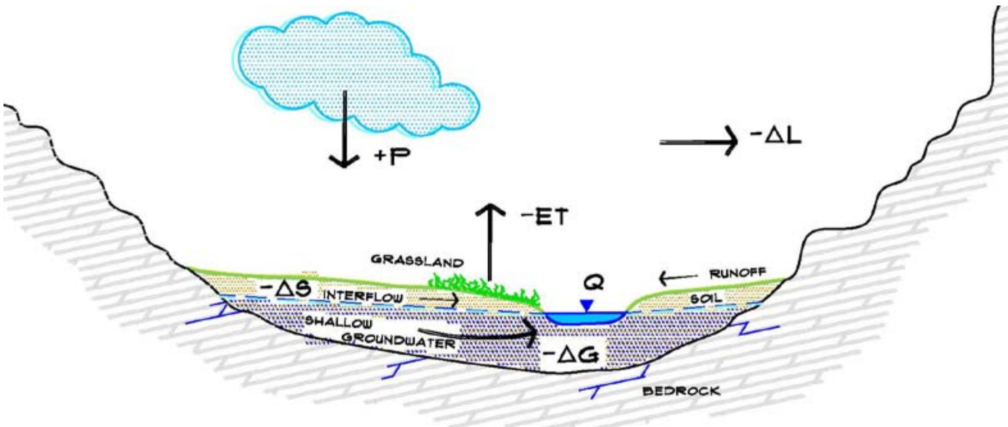

Figure 1. Illustration of general mass budget concept and components. The computational focus is on the contribution of increased soil moisture interflow to improving stream baseflow.

It should be noted that there will be a time lag before soil moisture contributes to stream baseflow. Water flowing through soils is impeded by soil particles, as well as other limiting factors slowing its lateral movement. This results in the soil moisture contribution to stream baseflow being distributed over a longer period of time, a benefit during dryer periods.

Soil Moisture as Critical Component to Baseflow

The calculation approach for estimating baseflow improvements focuses on the change in soil moisture content associated with the intervention. Several factors influence the soil moisture retention capacity and the soil moisture content. These factors include soil bulk density and organic carbon content, which affect soil moisture retention capacity. Factors that increase the ability for precipitation to infiltrate into the soil also affect the soil moisture content. Removing livestock or implementing effective rotational grazing can impact each of these characteristics, and both interventions are assumed to increase the amount of moisture in soils available for improvements in baseflows. As such, these factors must be considered when estimating the increase in soil moisture content associated with livestock management interventions.

Accurately understanding soil moisture processes poses a complex problem. Factors such as soil texture, depth, and slope, as well as vegetation type and density plus climactic factors all affect soil moisture conditions. Quantified estimates for many of these factors are unavailable for the high altitude settings above Lima. Therefore, several assumptions must be made to apply the proposed calculation method. Grouping several of these factors (because they currently cannot be individually estimated), allows an approach for deriving estimates of baseflow improvements. The calculation approach described here therefore accounts for these issues by using an empirical approach with local data that can be calibrated without requiring exact knowledge of each process. (It should be recognized that there remains some level of uncertainty with such an interim calibration step which lacks detailed site information from long-term monitoring).

To isolate the fraction of soil moisture that contributes to an increase in stream baseflow, several influential factors were grouped into a single coefficient, **c**, to account for the soil moisture variable in the mass budget equation. (The example calculation in Attachment A shows how this can be derived. Both precipitation and baseflow increases can be measured with the difference being the coefficient. This value collectively represents the various factors influencing subsurface water movement.) The coefficient represents the percentage of soil moisture that ultimately reaches the stream, as derived from other Andean watershed hydrographs with puna grasslands.[6] [7] The result is an initial estimate of the increase in baseflow attributed to improved soil moisture. This is considered only as an initial approximation, and temporal and spatial factors will impact its accuracy. Despite this limitation, it is useful for the purposes of estimation and can be expressed simply as:

Soil Moisture Contribution to Baseflow ≈ $c^*\Delta S$ **(3)**

Mass Budget Equation Simplifications

The calculation is intended to estimate the change in stream baseflow conditions before and after a livestock intervention is implemented. As such, the equation can be simplified based on several assumptions. It was assumed that deep groundwater loss and basin leakage would remain constant before and after the intervention. The deep groundwater and leakage terms would cancel out in the calculation since the method is based on the change associated with the intervention (**ΔL** in Equations (1) and (2) becomes zero). As mentioned previously, the groundwater term in Equation (1) represents both shallow and deep groundwater. In this simplified approach, effects on baseflow associated with raising shallow groundwater tables will be addressed through the soil moisture component, i.e., **ΔG** in Equations (1) and (2) becomes part of **ΔS**. This is necessary because Equation (3) does not differentiate between soil moisture interflow and shallow groundwater stream recharge pathways. Any introduced errors can be corrected by calibrating the coefficient **c** for soil moisture using actual field data.

This primer uses extrapolated data from other watersheds to create and illustrate the mass budget method. This approach with extrapolated data can be applied initially by accepting the introduced errors and uncertainties until local data can be used to calibrate the method.

The next step in the estimation process is to consider evapotranspiration (**ET**). If the change in **ET** due to the intervention is substantial, no further simplification can be made and the following equation would be applied:

$$Q = P - (ET + c^*\Delta S) \quad (4)$$

If **ET** is not substantially affected by the intervention, the equation can be further simplified and the result is:

$$Q = P - c^*\Delta S \quad (5)$$

The time step for Equation (5) is any pre-defined time period. For this Technical Primer, one calendar year is implied.

[6] De Bievre, B. Acosta, and B. Ochoa (2012) Regional Initiative Monitoring hydrological Andean ecosystems Punas Moors Forests, INTERCLIMA 2012 Lima. 29 -31 October 2012.
[7] Buyteart, W., Célleri, R., De Bièvre, B., Cisneros, F., Wyseure, G., Deckers, J., and R. Hofstede (2006) Human Impact on the Hydrology of the Andean Páramos, Earth-Science Reviews 79:53–72.

Calculating Soil Moisture

The **c*ΔS** component of the equation can be determined by calculating the reduction in surface runoff associated with increased infiltration following the intervention. As an initial method to calculate differences in runoff, the "curve number approach" is recommended for assessing the change in surface runoff. This method is commonly applied in North America and quantifies surface runoff based on precipitation and soil characteristics.[8] Local or regional methods that better address soil infiltration and depth of infiltration can replace the curve number approach once such methods are identified.

The derivation of the curve number equation used in this application is as follows:

$$\mathbf{Q_r = \frac{(P - I_a)^2}{(P - I_a) + S_r}}$$

Where:

Q_r = runoff (mm)	S_r = potential maximum retention after runoff begins
P = precipitation (mm)	I_a = initial abstraction

This equation uses the following relationships:

$$\mathbf{I_a = 0.2S_r}$$

$$\mathbf{S_r = \frac{25{,}400}{CN} - 254}$$

An example calculation illustrating a livestock exclusion application of the curve number approach is provided in Attachment A.

Future Integration of Carbon Content Effects on Soil Moisture

Along with reductions in surface runoff, other factors also will impact soil moisture. These factors should be field measured and included in the calculation process. For this Technical Primer, site-specific information for representative intervention areas was not available to quantify relevant relationships for this application, particularly soil organic carbon and density. As such, these factors were assumed here for the purpose of illustrating the calculation process (they are accounted for in the **c*ΔS** component of the equation).

The importance of integrating these factors when applying the mass budget equation is highlighted here. Livestock exclusion or proper rotational grazing can help improve the organic carbon content of soil, which has a substantial impact on soil moisture. Organic carbon decreases bulk density and increases moisture retention capacity. This relationship is illustrated in Figure 2, as derived from published data from the Andean region of Latin America.[9] The equation generated from the linear

[8] The curve number approach was developed by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). The method is described in the USDA's Technical Release 55 (TR-55), published in 1986 and available online at: http://www.cpesc.org/reference/tr55.pdf

[9] Buyteart, W., *et al*. (2006) Human impact on the hydrology of the Andean páramos. *Earth-Science Reviews* 79:53-72.

relationship presented in Figure 2 can be incorporated into the calculation of increased soil moisture content resulting from the interventions (as demonstrated in Attachment A). This step assumes that an equal or greater increase in drainable soil moisture content will occur, as found for field capacity. This is based on the assumption that the soil moisture retention capacity is representative of an increase in soil moisture content and consequently interflow.

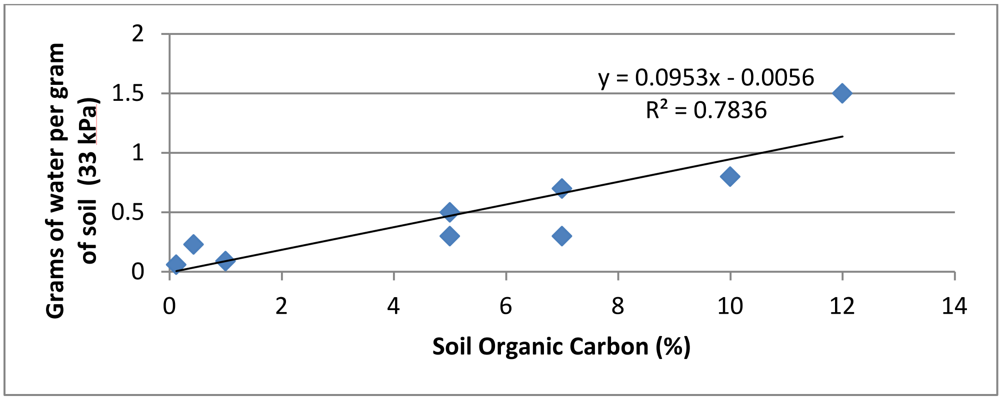

Figure 2. Increasing organic carbon content of soil can substantially increase soil moisture (Buyteart et al., 2006).

Livestock management interventions in critical areas also can decrease soil bulk density and alter the vegetative fiber structure. Dense, compacted soil cannot store as much moisture as less compacted soil. Soil containing vegetative fiber that has undergone little decomposition has higher hydraulic conductivity. Currently, the recommended calculation approach does not consider vegetative fiber content in soil and associated porosity conditions, though field collection of such data could be considered in future monitoring and research applications of the mass budget equation approach.

Future Methodological Improvements

This proposed calculation method provides a reasonable initial approach for estimating potential increases in stream baseflow associated with livestock exclusion or rotational grazing in puna grasslands. There are a number of current unknowns from a generalized watershed perspective that, with clarification, would decrease uncertainty in the application of this method. These include:

- Groundwater/surface water interactions at high altitudes in the watersheds supporting Lima's water supply
- Effects of high altitude on hydrological processes, particularly regarding atmospheric moisture (e.g., humidity and fog)
- Characterization of evapotranspiration processes for the local ecosystem

Professional judgment should be used to apply this recommended water mass budget approach in a manner that is appropriate and effective given known information. The approach can be refined as additional information and site-specific data become available.

In the future, site estimation of water quantity improvements can be improved by conducting the following activities:

- Monitoring implementation sites for soil and groundwater conditions
- Monitoring localized surface hydrology before and after interventions (either above and below interventions and/or via paired watershed studies)
- Verifying or recalibrating the estimation approach based on findings

Key research issues that should be addressed to improve and refine quantitative estimates for this intervention include:

- Gathering peer-review feedback on recommended calculation methods
- Research on:
    - Impact of livestock exclusion and rotational grazing on local soil carbon content
    - Impact of increased soil moisture on baseflow in different seasons and precipitation conditions
    - Preliminary evapotranspiration estimates at high elevations
    - Effects of vegetative fiber content on soil porosity

Attachment A

Example Calculations

Hypothetical Animal Exclusion Calculation Example

The following steps illustrate an example application of the water mass budget equation for a hypothetical, 10-hectare pasture where fencing is installed to eliminate animal grazing and allow for puna re-vegetation. For each step, the values used as inputs into the equation are provided. In some cases, these values reflect local information. However, in many instances such information was not available and example values were applied. Assumptions made in these regards are documented as well as the associated data gaps.

Equation:	**Q = P - ET - c*ΔS - ΔG - ΔL**	
Inputs:	Precipitation: 400mm – 700 mm at altitude of 3,500m – 4,000m (De Bievre et al., 2013)	
Assumptions:	1. ET remains the same before and after intervention 2. Change in groundwater is nominal before and after intervention 3. Leakage remains the same before and after intervention 4. All infiltration initially counted as soil moisture 5. The soil moisture coefficient, **c**, can be used to adjust for assumptions 1-4	
Calculate Runoff Reduction Using Curve Number Approach:		
Equations:	$Q_r = \frac{(P-0.2S_r)^2}{(P+0.8S_r)}$ and $S_r = \frac{25,400}{\text{CN}} - 254$	
Inputs:	CN_0 = 68 CN_1 = 30	Two precipitation values: P = 400mm; P = 700mm
Calculations:	At P= 400mm: Q_0 = 285.39mm; Q_1 = 90.63mm Reduction in runoff = 194.76mm	At P = 700mm: Q_0 = 574.52mm; Q_1 = 287.96mm Reduction in runoff = 286.56mm
Data Gap:	CN values should be field verified	
Incorporate Soil Organic C:		
Equation:	Soil moisture increase due to organic C increase = 0.0953 * change in organic C percentage (based on regression equation derived from Buyteart et al., 2006)	
Inputs:	Organic C content before intervention = 10.19% (Zimmermann et al., 2010) Organic C content after intervention = (10.19+2)% = 12.19%	
Calculations:	Soil moisture increase = 0.0953*2 = 0.191 g water / g soil	
Assumptions:	Two percent increase in soil organic C content	
Data Gap:	Percent increase in soil organic C content should be field verified	
Incorporate Soil Bulk Density and Soil Depth:		
Inputs:	Soil bulk density = 0.48 g/cm^3 (mean value, puna grassland sites, western border of the Manu National Park, Zimmermann et al., 2010) Soil depth = 32.5cm (*ibid*, Zimmermann et al., 2010)	
Calculation:	Increased soil moisture due to organic C increase (with water density at 1 g/cm^3) = = 0.48 g soil/cm^3 * 32cm * 0.191 g water/g soil * 1 g/cm^3 = 2.928cm = 29.28mm	
Data Gap:	Soil bulk density and soil depth values should be field verified	

Calculate Total Increase in Soil Moisture After Intervention:

Equation:	Increase in soil moisture = increased infiltration + increased soil moisture held due to increased soil organic C	
Calculations:	At P= 400mm: 194.76 + 29.28 = 224.04mm	At P = 700mm: 286.56 + 29.28 = 315.84mm

Calculate Increase in Baseflow Depth (mm):

Equation:	Increase in baseflow depth = total increased soil moisture * soil moisture to baseflow conversion factor, **c**	
Calculations:	At P= 400mm: 224.04 * 0.82 = 183.7mm	At P = 700mm: 315.84 * 0.82 = 259.0mm
Assumptions:	1. Increased soil moisture to baseflow conversion factor **c** = 0.82, derived from graphical hydrograph interpretation (as derived from De Bievre *et al*., 2012 comparing soil carbon and baseflow watershed relationships in Andean watersheds with puna grasslands during dry season based on data from Buyteart, W. *et al*., 2006; Page 17). The graphic interpretation measured the difference of the areas under the hydrograph from Huagrauma and Soroche in each of the four surface and baseflow events from January to June 2002. The average of the four ratios of the total area differences between the increases in baseflows to that of decreases in the surface flow peaks in the hydrograph is considered to be the **c** value. The **c** factor remains constant as precipitation varies.	
Data Gap:	Baseflow conversion factor should be field measured or derived from local data if paired watershed studies similar to those of Buyteart, W., *et al*., 2006 and De Bievre *et al*., 2012 are conducted in the puna regions of Lima watersheds.	

Calculate Increase in Baseflow Volume (m^3):

Equation:	Increase in baseflow volume = increased baseflow depth * intervention area	
Input:	Intervention area = 10 hectares	
Calculations:	At P= 400mm: 183.7 /1,000 * 10 * 10,000 = 18,370 m^3/yr	At P = 700mm: 259.0 /1,000 * 10 * 10,000 = 25,900 m^3/yr)
Data Gap:	Should use actual total area of intervention	

Calculate Increase in Baseflow (m^3/s) and Associated Infiltration Rate (m/sec):

Equation:	Increased baseflow = Increased baseflow volume / seconds in all baseflow days	
Calculations:	At P= 400mm: 18,370 m^3 / (180 * 24 * 3,600)s = 0.00118 m^3/s	At P = 700mm: 25,900 m^3 / (180 * 24 * 3,600)s = 0.00167 m^3/s
	Increased infiltration rate for each m^2 of intervention: 0.00118 m^3/s / 10 hectares * 1/100,000 m^2 / hectare = 1.18 x 10^{-8} m/s over 180 days	Increased infiltration rate for each m^2 of intervention: 0.00167 m^3/s / 10 hectares * 1/100,000 m^2 / hectare = 1.67 x 10^{-8} m/s over 180 days
Assumptions:	1. Increased baseflow distribution expected to slowly decline after major rain events occurring throughout the year 2. Baseflow period is 180 days per year (this is an assumed dry period of the year for when the **c** factor is applied for these calculations, which could be easily refined with actual stream discharge data) 3. The calculated infiltration rate can be used as means to estimate increased baseflow benefits (as m^3/sec) for broad application of this intervention in the watershed by multiplying the rate times the area of intervention	

Data Gap:	Baseflow distribution pattern should be derived from local stream hydrographs

Calculate Cost of Increased Baseflow ($\$/m^{3}\cdot s^{-1}$) for 180 days of Baseflow Benefits:

Equation:	Unit cost = total cost of implementing the intervention / total increased baseflow	
Inputs:	Project costs as provided by Aquafondo (see Table A.1) (Rodríguez. A, 2014; personal communication) Total cost of project (US$) = 18,888 soles * 0.36 (monetary conversion rate as of April 1, 2014) = US$6,800	
Calculations:	At P= 400mm: US$6,800 / 18,370$m^{3}\cdot yr^{-1}$ = US$0.37/$m^{3}\cdot yr^{-1}$ * (180*24*3,600)s/yr for $5.8M/$m^{3}\cdot s^{-1}$ for the 180 days of critical dry period	At P = 700mm: US$6,800 / 25,900$m^{3}\cdot yr^{-1}$ = US$0.26/$m^{3}\cdot yr^{-1}$ * (180*24*3,600)s/yr for US$4.0M/$m^{3}\cdot s^{-1}$ for 180 days of the critical dry period
Assumptions:	See Table A.1 for Aquafondo estimated costs	
Data Gap:	Baseflow distribution pattern should be derived from local stream hydrographs	
Note:	If the intervention was in place for 10 years with very limited fence maintenance needs, the cost to increase baseflow volume would be approximately $0.4 - $0.58M/$m^{3}\cdot s^{-1}$	

References:

Buyteart, W., Célleri, R., De Bièvre, B., Cisneros, F., Wyseure, G., Deckers, J. and R. Hofstede (2006) Human Impact on the Hydrology of the Andean Páramos, Earth-Science Reviews 79:53–72.

De Bievre, B., Acosta, L. and M. Janampa (2013) CONDSAN Technical Report N2, Methodology and Application of SWAT Model and Conceptual Hydrological Model in the Basins of the Chillon, Rimac and Lurin.

De Bievre, B., Acosta, L. and B. Ochoa (2012) Regional Initiative Monitoring hydrological Andean ecosystems Punas Moors Forests, INTERCLIMA 2012 Lima, 29 -31 October 2012.

Rodríguez. A., (2014) Personal Communication, Unit Cost Spreadsheet for Rimac Interventions, March 12, 2014. Project Investigator, Aquafondo, Av. Chorrillos 150 - Lima 09, Telf. +51 1 4671802 anexo 111

Zimmermann et al. (2010) No Differences in Soil Carbon Stocks Across the Tree Line in the Peruvian Andes, *Ecosystems* 13:62-74.

ANIMAL EXCLUSION FOR 10 HECTARE PUNA GRASSLAND

	DESCRIPTION	Unit Measure	Amount	Unit Cost S/.	Total Cost S/.	COMMUNITY CONTRIBUTION S/.	FINANCED S/.
I.	**Direct Cost**				**19,446.50**	**1,530.00**	**17,916.50**
	Labor		**51**		**1,530.00**	**1,530.00**	**0.00**
	Fenced						
	Opening Holes	Wage	14	30.00	420.00	420.00	
	Planting	Wage	10	30.00	300.00	300.00	
	Installing livestock Malla	Wage	7	30.00	210.00	210.00	
	Improvement and Resettlement						
	Natural composting	Wage	10	30.00	300.00	300.00	
	Sowing	Wage	10	30.00	300.00	300.00	
	Soil Preparation				**640.00**		**640.00**
	Plow	Team	6	80.00	480.00		480.00
	Covered	Team	2	80.00	160.00		160.00
	Materials and Supplies				**17,200.00**	**0.00**	**17,200.00**
	Seeds	Kg	20	30.00	600.00		600.00
	Cuttings	millar	20	120.00	2,400.00		2,400.00
	Posts (6" diameter x 1.80)	Unit	350	10.00	3,500.00		3,500.00
	Livestock Malla (1.20 m Wide X 100 m Long)	Rolls	14	750.00	10,500.00		10,500.00
	Staples	kg	20	10.00	200.00		200.00
	Tools (5% M.O.)				**76.50**		**76.50**
II.	**Indirect Cost**				**972.33**	**0.00**	**972.33**
	Overhead (5% C.D.)				972.33		972.33
	TOTALS/.				**20,418.83**	**1,530.00**	**18,888.83**

FENCING CAN BE DONE WITH BARBED WIRE, MESH STOCKING, STONES, CHAMPA (EARTH BLOCKS)
VARYING ACCORDING TO THE COST OF THE MATERIALS USED.
COMPLEMENT WITH OTHER ACTIVITIES AS INSTALLATION OF PULSES (WHITE CLOVER) AND REPOPULATION
PALATABLE NATURAL PASTURE SPECIES (VIA VEGETATIVE SEED AND BOTANY)

Table A.1. Estimated Project Costs for a 10-Hectare Animal Exclusion Area for Restored Puna Grasslands (A. Rodríguez, 2014; personal communication).

Restoration of Wetlands

Quantifying Potential Baseflow Improvements

April 2014

A Technical Primer on Quantifying Benefits of Watershed Interventions

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The Fund for Watershed Conservation and Water Resources of Lima and Callao, Peru, known as Aquafondo, was established to identify, fund and help implement watershed improvements in the Chillón, Rímac and Lurín basins. These basins are in a critical situation of water scarcity and impaired quality, and are of particular concern since they represent an important source of drinking water for Lima. An effort is underway to help establish an operating framework for Aquafondo that can evaluate various watershed interventions in the context of simple, established performance metrics for water quality and water quantity benefits.[1] Coupled with projected costs for such interventions, the water fund will be able to assess, compare and optimize benefits with its investments in watershed improvements.

One of the more substantial challenges facing Aquafondo (and other governmental agencies and watershed stakeholders seeking these same improvements) is the ability to reasonably estimate water quality and/or water quality benefits associated with specific watershed improvement projects. As such, this Technical Primer[2] represents an initial examination of how Aquafondo and others may scientifically assess a localized benefit of a particular agricultural intervention in the upper watershed of the Lima basins. The proposed approach relies upon standard mass balance principles used in water resources engineering and hydrology. It may be that existing or future field studies in the Andes Mountains, as well as quantification methods derived from relevant conservation programs will be used to refine or ultimately replace this approach. Implemented across numerous locations, these interventions should provide broader catchment benefits to improved stream baseflow[3]. Assessing cumulative benefits is not, however, addressed in this primer.

[1] Kieser & Associates, LLC [K&A] (2012) Identification of Common Project Goals and Metrics for Aquafondo (Water Fund for Lima & Callao): Phase I Technical Report," Prepared for Aquafondo, Av. Chorrillos 150, Chorrillos, Lima, Peru.

[2] This effort was funded through Forest Trends of Washington, D.C. with support from the Swiss Development Corporation in collaboration with Aquafondo.

[3] Baseflow conditions are defined for this primer as the stream flows that exist during extended dry periods that do not have a substantial surface runoff component.

Proposed Intervention: Wetland Restoration

In working with numerous watershed stakeholders, Aquafondo has identified that certain high elevation wetlands in the watersheds above Lima have been drained to provide additional ground for cattle grazing. These wetlands, some originally with direct connections to surface water features, and others likely with no direct connections, may be easily restored by simply blocking or removing artificial ditches or channels constructed to drain standing water from these features. Constructed ditches serve to drain standing water in wetlands as well as lower the localized groundwater table. Both of these hydrologic modifications provide conditions for vegetation establishment suitable for cattle grazing. For the Lima watersheds, eliminating or blocking artificially constructed drainage pathways should allow precipitation to re-hydrate soils, storage of surface water, as well as recovery of localized groundwater levels. It is the recovery of surface storage volume in the dry season that is the focus of quantification for this watershed intervention.

Figure 1a conceptually illustrates how constructed ditches can continuously drain any water that falls on or might otherwise accumulate in the former wetland. Sources of such water include direct precipitation and localized groundwater depending on the base elevation of the ditch bottom in relation to the elevation of the drained wetland's soil surface. Drainage creates a rapid loss of water throughout the year and thus, the former surface water storage of the drained wetland no longer contributes to stream baseflow, particularly in the dry season. As improvements in dry season baseflow are the critically desired outcome from this intervention, the quantification approach focuses solely on dry season benefits. By closing or removing drainage ditches, precipitation can again accumulate (see Figure 1b) bringing surface storage and infiltration to groundwater in balance. Stored surface waters in the wetland provide year-round infiltration to shallow groundwater which in turn, contributes to local stream baseflow (measured in cubic meters/second, m^3/s). The level of water in the wetland is expected to remain in relatively constant equilibrium with groundwater throughout the year as it either lost to groundwater infiltration and by evapotranspiration. Water is then replenished by direct precipitation.

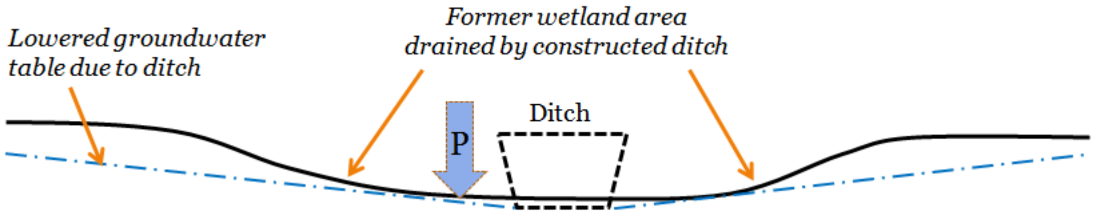

Figure 1a. Conceptual cross-sectional diagram illustrating a drained wetland via a constructed ditch which eliminates surface storage (that would otherwise be contributing to groundwater recharge), and a dewatering (lowering) of the local groundwater table. (P = precipitation)

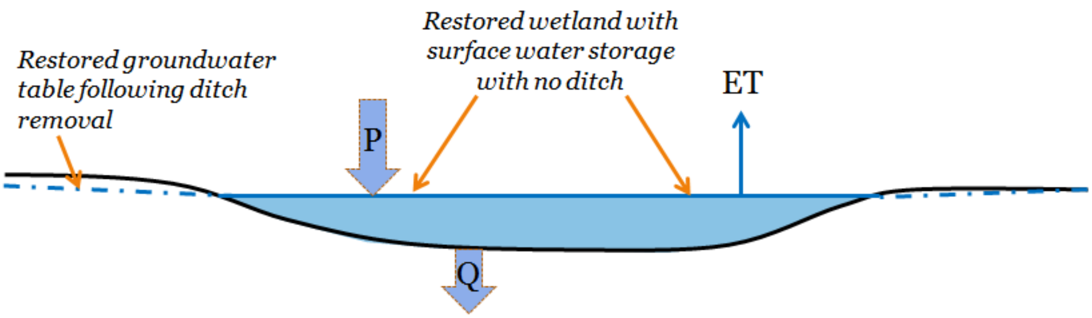

Figure 2b. Conceptual cross-sectional diagram of a wetland restored by removing the drainage ditch. This allows for surface storage, groundwater recharge and restored local groundwater levels. (P = precipitation; ET = evapotranspiration; Q = stream baseflow)

Calculating Water Quantity Benefits

A conservative water mass balance approach is used to estimate the contribution of restored wetlands to stream baseflow. This approach simply assumes that the surface area of the wetland (m^2) times the dry season precipitation (m) will reflect the annual volume of water stored and infiltrated to groundwater, minus evapotranspiration losses in the dry season. It is assumed in this calculation that the surface elevation of stored water in the wetland remains in equilibrium with the local groundwater table. Though the groundwater table may vary seasonally, it is also assumed that standing water will remain in the restored wetland throughout the year. Given that most high altitude wetlands in the upper watersheds for Lima are typically shallow (<0.3m), remain in contact with the groundwater table and do not ever go dry, any new water added to the storage volume via precipitation is assumed to contribute directly to groundwater via infiltration. This groundwater contribution eventually becomes baseflow (m^3/second) assuming no losses to deep groundwater. This is considered to be a conservative estimate of the baseflow benefit as the approach does not account for additional soil storage baseflow contributions with a recovered groundwater table in areas adjacent to surface storage.

The generalized steps used to estimate the water quantity benefits with this mass balance approach include:

A. Gathering necessary information

- Daily to seasonal precipitation (m/time)
- Estimates of evapotranspiration (m/time)
- Surface area of the restored wetland (m^2)

B. Calculate intervention benefits

- Locally recorded dry season precipitation
- Calculation of the volume of water annually stored in the reclaimed wetland using precipitation depth and surface area of the wetland
- Estimation of dry season surface water losses due to evapotranspiration from the wetland

- Calculation of the difference between dry season storage volume and evaporative losses as the dry season contribution to groundwater recharge
- Conversion of this dry season volume to m^3/s
- Estimation of the unit cost of increased baseflow ($\$/m^3 \cdot s^{-1}$) based on projected intervention costs

We summarize as follows the proposed equations to estimate increased baseflow from restored wetlands. Attachment A provides an example calculation using this approach for a hypothetical one-hectare wetland restoration project.

Mass Balance Equation

A mass balance equation is applied to site-specific wetland restoration applications by the following equation:

$$Q = (A * P) - (A * ET)$$

Where:

Q = dry season stream baseflow increase (m^3/second)
A = area of restored wetland (m^2)
P = precipitation (m/dry season)
ET = evapotranspiration (m/dry season)

If evapotranspiration is negligible, the equation can be simplified to just the area of surface storage in the wetland times dry season precipitation. The concept of this equation is illustrated in the previous Figure 1b. This approach will likely underestimate contributions to baseflow as it does not account for a recovery in groundwater elevations and associated soil storage as noted in groundwater elevation differences between Figure 1a and 1b. The localized portion of the groundwater table that is drawn down by the constructed ditch would otherwise contribute to baseflow. This scenario also assumes that there is no deep groundwater losses (especially given characteristics of typical wetlands retaining year-round surface water), and no inflow or outflow. The latter condition can be assumed to have zero net effect as inflow would equal outflow minus evaporative losses (which are already considered in the equation).

Future Methodological Improvements

This proposed calculation method provides a reasonable initial approach for estimating potential increases in stream baseflow associated with wetland restoration during the dry season. At a minimum, the only site-specific data needed would be for the area of the restored wetland so long as there were regional data for:

- Total dry season precipitation
- Total dry season evapotranspiration estimates

Local data collection will help to verify that this equation can reasonably approximate baseflow increases. Such information would include:

- Daily or seasonal precipitation total (during the dry season)
- Seasonal evapotranspiration rates
- Seasonal wetland water level elevations (storage volume)
- Seasonal groundwater elevations before and after the intervention
- Frequent flow measurements (above and below, before and after) of a nearby stream
- Paired watershed flow measurements

Site-specific data could be used to estimate actual baseflow improvements as well as to document these benefits during the critical dry season period. These data would also allow for calculation of stored groundwater water table benefits to baseflow which are not computed in the mass balance calculation.

Attachment A

Example Calculations

Hypothetical Wetland Restoration Calculation Example

The following steps illustrate an example application of the mass balance equation for a hypothetical, one-hectare restored wetland. For each step, the values used as inputs into the equation are provided. In some cases, these values reflect local information. However, in many instances such information was not available and example values were applied. Assumptions made in these regards are documented as well as the associated data gaps.

Equation:	**Q = (A * P) – (A * ET)**
Inputs:	Total dry season precipitation: 150 mm (De Bievre, personal communication, 2014)
Assumptions:	1. ET is zero 2. There are no inflows/outflows from the restored wetland
Calculate Increase in Annual Baseflow Volume (m^3):	
Equation:	Increase in annual baseflow volume = dry season rainfall depth * intervention area
Input:	Intervention area = 1 hectare
Calculations:	0.15 m * (1 hectare * 10,000 m^2/hectare) = 1,500 m^3
Data Gap:	Use actual total area of intervention (i.e., water storage surface area that would otherwise have been drained)
Calculate Increase in Baseflow (m^3/s) and Associated Infiltration Rate (m/s):	
Equation:	Annual baseflow increase = Annual baseflow volume / seconds in all baseflow days
Calculations:	1,500 m^3 / (180 days * 24 hours/day * 3,600 seconds/hour) = 0.000096 m^3/s for dry season
	Infiltration rate for each m^2 of intervention: 0.000096 m^3/s / (1 hectare * 10,000 m^2/hectare) = $9.6 * 10^{-9}$ m/s for dry season
Assumptions:	1. Increased baseflow distribution is expected to slowly decline after major rain events occurring throughout the year 2. Baseflow period is 180 days per year (this is an assumed dry period of the year) 3. Absent seasonal precipitation data, there is no accounting for seasonal variations 4. The calculated infiltration rate can be used as means to estimate increased baseflow benefits (as m^3/sec) for broad application of this intervention in the watershed by multiplying the rate times the area of intervention. Thus, 5,000 hectares of wetland restoration under assumptions for this example would provide an addition 0.48 m^3/s of additional baseflow during the dry season.
Data Gap:	Baseflow distribution pattern should be derived from local dry season precipitation data
Calculate Cost of Increased Baseflow ($/$m^3 \cdot s^{-1}$) for 180 days of Baseflow Benefits:	
Equation:	Unit cost = total cost of implementing the intervention / total increased baseflow
Inputs:	Project costs as provided by Aquafondo (see Table A.1) (Rodríguez. A, 2014; personal communication) Total cost of project (US$) = 252.15 soles * 0.36 (monetary conversion rate as of April 1, 2014) = US$90.76
Calculations:	US$90.76 / 1,500 $m^3 \cdot yr^{-1}$ = US$0.06/$m^3 \cdot yr^{-1}$ * (180*24*3,600)s for US$933,120/$m^3 \cdot s^{-1}$ for 180 days of the critical dry period
Assumptions:	See Table A.1 for Aquafondo estimated costs (these do not denote size of the wetland, however, do appear to represent the intervention of simply placing a dam across a drainage ditch, and thus are

	likely representative of a typical wetland restoration intervention of any expected size)
Data Gap:	Baseflow distribution pattern should be derived from local stream hydrographs
Note:	5,000 hectares of restored wetland yielding 0.48 m^3/s of additional baseflow (see above) might cost approximately $447,898 using Aquafondo cost estimates.

References:

De Bievre, B. (2014) Personal Communication, April 14, 2014. Coordinador del Área de Cuencas Andinas, Condesan, Av. La Molina 1895. Lima, Perú.

Rodríguez. A., (2014) Personal Communication, Unit Cost Spreadsheet for Rimac Interventions, March 12, 2014. Project Investigator, Aquafondo, Av. Chorrillos 150 - Lima 09, Perú.

Table A.1. Estimated Project Costs for a 1-Hectare Restored Wetland (from A. Rodríguez, 2014; personal communication).

WETLANDS RESTORATION						
DESCRIPTION	Unit Measure	Amount	Unit Cost S/.	Total Cost S/.	COMMUNITY CONTRIBUTION S/.	FINANCED S/.
I. DIRECT COSTS				**2,583.00**	**2,460.00**	**123.00**
Construction of small dams (100 ml)		82		2,460.00	2,460.00	
Measurement and strokes	Wage	2	30.00	60.00	60.00	
Court of Champa	Wage	20	30.00	600.00	600.00	
Moving champas	Wage	10	30.00	300.00	300.00	
Dam construction and compaction	Wage	50	30.00	1,500.00	1,500.00	
Tools (5% M.O.)				123.00		123.00
II. INDIRECT COSTS				**129.15**	**0.00**	**129.15**
Overheads (5% C.D.)				129.15		129.15
TOTAL S/.				**2,712.15**	**2,460.00**	**252.15**

Restoration of Amunas

Quantifying Potential Baseflow Improvements

May 2014

A Technical Primer on Quantifying Benefits of Watershed Interventions

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One of the more substantial challenges facing Aquafondo (and other governmental agencies and watershed stakeholders seeking these same improvements) is the ability to reasonably estimate water quality and/or water quality benefits associated with specific watershed improvement projects. As such, this Technical Primer[2] represents an initial examination of how Aquafondo and others may scientifically assess a localized benefit of a particular intervention in the upper watershed of the Lima basins[3]. This approach relies upon existing efforts in the Lima watersheds for both technical information and costs. Implemented across select locations, these interventions should provide broader catchment benefits to improved stream baseflow[4]. Assessing cumulative benefits is not, however, addressed in the primer.

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[1] Kieser & Associates, LLC [K&A] (2012) "Identification of Common Project Goals and Metrics for Aquafondo (Water Fund for Lima & Callao): Phase I Technical Report," Prepared for Aquafondo, Av. Chorrillos 150, Chorrillos, Lima, Peru.

[2] This effort was funded through Forest Trends of Washington, D.C. with support from the Swiss Development Corporation in collaboration with Aquafondo.

[3] Alternativa (2012) "MEJORAMIENTO DE CANAL DE AMAMANTAMIENTO PACCHIPUCRO-HUAMANTANGA: Región Lima, Provincia Canta, Distrito de Huamantanga," Centro De Investigacion Social y Educacion Popular.

[4] Baseflow conditions are defined for this primer as the stream flows that exist during extended dry periods that do not have a substantial surface runoff component.

Proposed Intervention: Ancient Diversion Channel Repairs

Repairs of ancient, high altitude surface water diversion channels (known as "amunas") in the headwaters of the Chillon River (District of Huamantanga) are providing improved surface water transport to historic infiltration ditches. Though there will be many variations with the actual physical structure and function among these ancient channels, this Technical Primer principally focuses on one set of these for which staff from Aquafondo have provided to K&A. Increased infiltration from this particular type of amuna is expected to translate to increased baseflows associated with groundwater recharge. These ancient diversion channels (see Photo 1a and 1b) in select upper reaches of Lima watersheds conveyed stream flows to infiltration ditches (Figure 2a) constructed laterally across mountainsides, or to rocky or stony surfaces (Figure 2b). Infiltrated water would re-emerge down slope in small, constructed micro-pools or in natural springs where water could be withdrawn for agricultural irrigation, or continue to cascade downslope as subsurface flow. With water reaching the infiltration trenches, baseflow of local streams should increase either through: 1) infiltration ditch water recharging shallow groundwater which eventually reaches a stream, 2) the re-infiltration of captured/pooled groundwater, and/or 3) a portion of withdrawn irrigation water being re-infiltrated.

As relayed by Aquafondo, the main objective for restoring functions of the amunas is to increase and extend the flow of springs, thereby increasing available water for use in the areas below these infiltration areas. The strategy begins with the capture of stream flow in flood seasons by constructed stone intakes in the streambed. Diverted waters are conveyed through the constructed diversion channels to the infiltration structures. To maintain and enhance water retention and soil moisture in the infiltration areas, vegetative cover surrounding infiltration structures is important. Vegetation also reduces potential slope erosion. Further, the presence of additional moisture is believed to contribute to the formation of microclimates (effects that may support and maintain biodiversity).

In a repair and reconstruction pilot project in 2012 completed by Alternativa[5], time had diminished the imperviousness of the conveyance channel (Figure 1) such that diverted water from the stream would rapidly re-infiltrate near the head of the diversion channel. Re-infiltrated water would simply re-enter the stream as surface flow and thus, not provide water to the more distant infiltration ditches. Re-grouting the diversion channels with cement conveys substantial portions of diverted stream flow to the infiltration ditches. Repairs made to the diversion channel in this pilot were manageable and the increased flow to infiltration ditches readily quantifiable. (Attachment A of this Technical Primer illustrates how these benefits are quantified.) More than thirty additionally identified projects of a similar nature are possible in this area according to Alternativa[5] though not all were of this particular form and function as described in this Primer.

[5] Ávila, J. (2012) Personal Communication. Alternativa Representative in Meeting with Aquafondo and Kieser & Associates, November 7, 2012 to Present a Pilot Project in the Chillon Basin.

Aquafondo[6] has identified the benefits of Amunas as:

- Increasing the availability of water in springs and micro-pools for much of the year
- Reducing peak streamflows during wet weather conditions which in turn reduces the risk of downstream flooding and erosion conditions
- Retaining and enhancing soil moisture in and around infiltration ditches, springs and micro-pools which fosters development of localized vegetation
- Supporting the social fabric of the high elevation agrarian communities, their historic culture, and governance through improved water supply

Figure 2a. Operating Diversion Channel (Amuna) in the Upper Chillon River Basin. (Photo courtesy of S. Bleeker, 2012)

Figure 1b. Diversion Channel (Amuna) in the Upper Chillon River Basin under repair. (Photo courtesy of S. Bleeker, 2012)

Figure 2a. Infiltration ditch receiving water from a repaired diversion channel in the Upper Chillon River Basin. (Photo courtesy of S. Bleeker, 2012)

Figure 2b. Stone/rock base infiltration structure in the Upper Chillon River Basin. (Photo courtesy of S. Bleeker, 2012)

6 Bleeker, S. (2013) Unpublished Summary of Aquafondo Intervention Projects. Secretaria Tecnica Aquafondo, Cooperante de Progressio/Grupo GEA, Avendia Chorrillos 150, Chorrillos, Lima, Peru.

For the purposes of this examination, it is assumed here that all water reaching the infiltration ditches from diversion channels makes it to shallow groundwater, though some losses through evapotranspiration and removal by irrigation need to be considered. Shallow groundwater (minus losses) is considered to become baseflow, particularly during the dry season.

Calculating Water Quantity Benefits

A simple water mass balance approach is proposed here to estimate potential baseflow benefits of this intervention. Additions to stream baseflow are equated to the surface water diversion channel contributions to infiltration ditches, minus irrigation withdrawals, losses to groundwater out of the baseflow stream catchment, and evapotranspiration. Because infiltration is concentrated to narrow ditches and is not distributed across broad areas of vegetation and soils (such as for puna restoration; K&A, 2014), various soil moisture and related conditions (e.g., soil carbon) will not be applicable, or at most, of minimal influence on the calculation. Conceptually, the proposed mass balance estimation approach is illustrated in Figure 3.

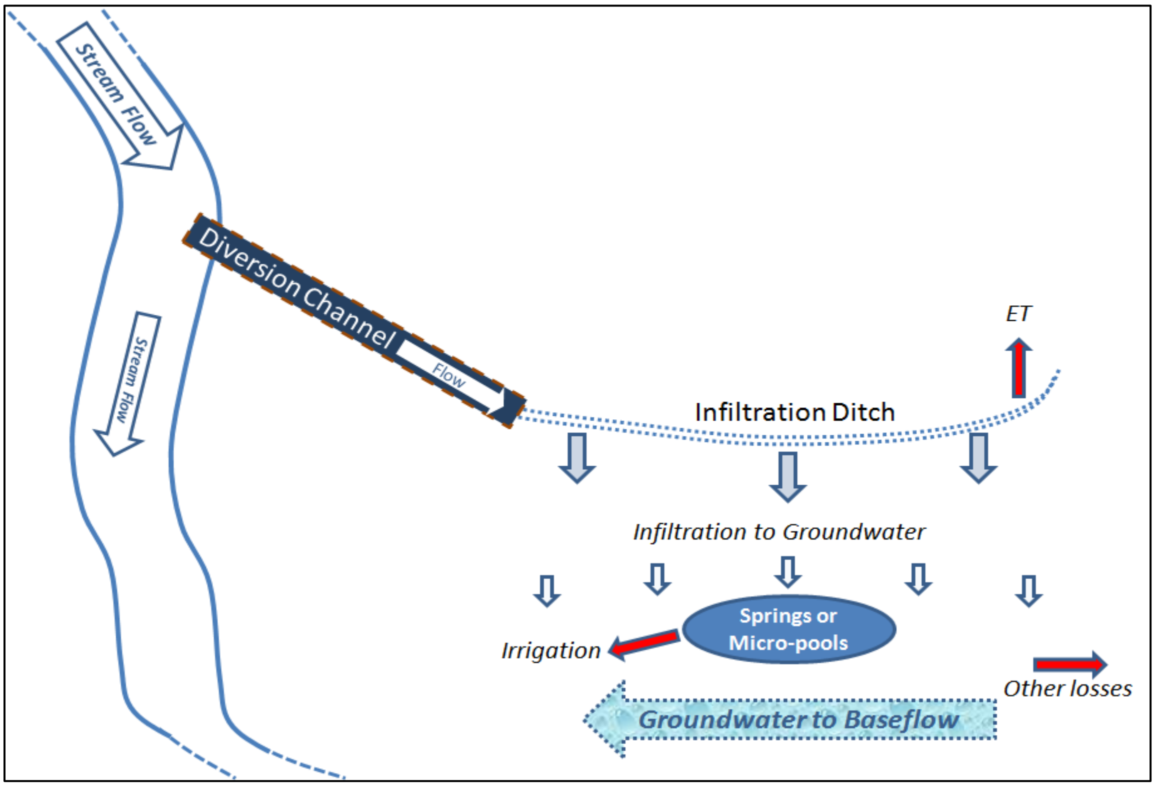

Figure 3. Conceptual schematic (plan view) of a diversion channel directing flow to an infiltration ditch increasing groundwater recharge and eventually, stream baseflow of the original stream during dry periods. (Transport pathways are italicized. Arrows indicate flow path; red infers a loss from baseflow contributions.)

Losses via evapotranspiration are applicable to the infiltration ditch footprint during the time when water is flowing through these structures, and from surface springs and micropools. “Other losses” refer to where the infiltration trench may extend and/or terminate in an area beyond direct drainage to a stream of interest. Such water could still re-enter stream surface flows in another location, though it would not be measureable in the monitored stream of interest. Topography and mapped surface drainage in relation to the mapped location of the infiltration ditch should reveal such a condition. Irrigation withdrawals from micro-pools or springs will be subject to evapotranspirative losses on irrigated lands, but may also have some level of re-infiltration if soils become saturated.

Absent these potential losses identified in Figure 3 (which may only be amenable to coarse estimation through site observation), this approach is quite simplistic and can be readily used with minimal site-specific flow monitoring data from the diversion channel outlet to the infiltration ditch. The generalized steps used to estimate the water quantity benefits with this mass balance approach therefore include:

A. Gathering necessary information

- Year-round flow measurements at point of discharge from diversion channel to infiltration structure (m^3/second; or m^3/s) with greater frequency of measure during the wet season
- Estimates of evapotranspiration for the infiltration ditch footprint and micro-pools
- Estimates of any irrigation (or other) withdrawals during the dry season (m^3/s)

B. Calculate intervention benefits

- Estimate wet season flow volume to the infiltration ditch
- Estimate potential losses from evapotranspiration and irrigation withdrawals during the dry season
- Estimate the unit cost of increased baseflow ($\$/m^3 \cdot s^{-1}$) based on projected intervention costs

We summarize as follows the proposed calculation steps to estimate increased baseflow for restored amunas as conceptualized in Figure 3. Attachment A provides an example calculation using this approach for an actual restoration project using the following approach.

Mass Balance Equation

A mass balance equation is applied to site-specific application by the following equation:

$$Q = Q_{out} - [(Q_{ag} - Q_{return}) + G_{out} + ET]$$

Where:

Q = stream baseflow increase (m^3/s)
Q_{out} = Discharge from diversion channel to infiltration ditch (m^3/s)
Q_{ag} = Agricultural withdrawals for irrigation (m^3/s)
Q_{return} = Agricultural irrigation water return to groundwater (m^3/s)
G_{out} = Loss to deepwater, field capacity of soil, and/or loss out of the localized stream catchment (m^3/s)
ET = Evapotranspiration (m^3/s) for the infiltration trench and micropool footprint

This approach assumes that wet season diversions will be much more substantial than dry season diversions for contributing to downstream baseflow benefits in dry months. Therefore, these wet season diversions are the focus for estimation of baseflow increases. Such diversions will result in groundwater storage which, transported via subsurface flows to the local stream through the wet season, will provide dry season benefits. Over time, more sophisticated year-round monitoring of a variety of these conditions could be used to quantify such benefits. There is no focus on dry season diversions in this calculation. These are likely limited and at best, may provide some local benefit of storage. For downstream users, dry season diversions only constitute a displacement of water from the existing stream flow, and likely will diminish downstream baseflow benefits. This suggests that optimal downstream baseflow benefits will come from managing wet season diversions.

Because it could be prohibitively expensive to monitor agricultural or other withdrawals from springs or micropools, as well as groundwater leaving the basin and evapotranspiration, we suggest the use of a correction factor, **c**, for simplifying initial estimates of increased baseflow. This can be expressed by:

$$Q = Q_{out} * c$$

This factor, when assigned as something small in the dimensionless range of 0 to1, can be used as a conservative discounting factor where best professional judgment is necessary absent robust field information to document potential losses. For example, if **c** were set at 0.5 as a coarse best guess on losses, this would translate to an estimate that only 50% of the wet season diverted streamflow into the infiltration ditch contributes to dry weather baseflows. Such an assumption may be useful for early decision-making for investment in either an amuna restoration project or a different intervention.

The calculation in Attachment A uses such a discount factor to determine unit costs for the example presented. In addition, as measurements of streamflow from before the intervention are compared with post-implementation data for both streamflow and diversion flow, **c** could serve as a correction factor for observed improvements in baseflow. These conditions can be expected as increased downstream baseflow will most likely always be less than Q_{out}. Ideally, there would be future opportunities to measure site-specific loss factors, but absent these, **c** derived from limited site measurements could be transferable for estimating other similar project benefits with a simple understanding of potential diversion channel flows.

Future Methodological Improvements

Monthly flow monitoring at the end of the diversion channel before water flows to infiltration ditches can be used to estimate Q_{out} in the recommended mass balance calculation equation. More frequent monitoring than monthly should be considered in the wet season. Where diversion channels are constructed with a consistent geometry (e.g., Figures 1a and 1b), it would be relatively easy to develop a rating curve for a depth to discharge conversion. Once the rating curve is constructed, only a depth measurement is necessary for finite flow monitoring. Absent the ability to readily gather other field measurements on agricultural withdrawals, evapotranspiration or groundwater diverted out of the catchment, the **c** factor could be applied as a discount factor.

Other monitoring considerations would include:

- Corresponding flow measurements above, potentially within, and below the area of intervention in the stream where improvements would be expected to more carefully bound the range for **c** factor use
- Measurement or estimation of dry and wet season withdrawals
- Dye studies (or similar) to determine the time it takes for the diverted water to eventually show up in the spring/micropool, and further downstream in the receiving stream
- Though potentially difficult to find a similar nearby setting, paired catchment streamflow measurements to verify that observed baseflow benefits are attributable to the intervention
- Shallow groundwater level monitoring on monthly intervals at micro-pools or springs compared to similar areas where diversion channel interventions have not been implemented to determine increased groundwater recharge

Though not critical to the baseflow improvement estimation, additional monitoring options could include:

- Corresponding flow monitoring at the beginning of the diversion channel to identify the efficiency of delivery to the infiltration ditches
- Additional sampling of stream flows conducted above and below the stream diversion to understand seasonal availability, however, measurements of diversion channel outlet flows will provide information on seasonal capacity for increasing baseflows in the area of the infiltration ditches

Other site information needs should include a physical description of the channels and infiltration ditches to characterize the general nature of the structures. Because each diversion channel was uniquely constructed, it is not possible to estimate diversion/infiltration/baseflow increases without specifically observing each structure and measuring diverted flow. Engineering studies exist for a currently repaired diversion channel and other similar not-yet-repaired diversion structures in a select area of the upper Chillón basin[3]. These can and should be used to forecast potential benefits. In some specific settings, there appear to be data available to calculate potential stream diversion capacity of these structures. Assuming channel repairs are highly effective, these data can be used to estimate volumes delivered to infiltration structures.

Attachment A

Amuna Calculation Example

Amuna Restoration Calculation Example

The following steps illustrate an example application of the mass balance equation for an amuna restoration project implemented in the upper Chillón basin and referenced in the Technical Primer. For each step, the values used as inputs into the equation are provided. In some cases, these values reflect local information. However, in many instances such information was not available and example values were applied. Assumptions made in these regards are documented as well as the associated data gaps.

Equation:	$Q = Q_{out} - [(Q_{ag} - Q_{return}) + G_{out} + ET]$ **Simplified as:** $Q = Q_{out} \times c$
Inputs:	$Q_{out} = 1\ m^3/s$ of diverted flow during the wet season
Assumptions:	1. Diversion and infiltration take place exclusively during the wet season 2. Values for the separate loss terms are not available, therefore, all losses combined are assigned here as 50% of Q_{out}
Calculate Increase in Annual Baseflow Volume (m^3):	
Equation:	Increase in annual baseflow volume = Q = Qout × c
Input:	$Q_{out} = 1\ m^3/s$, **c** = 0.5
Calculations:	$Q = 1\ m^3/s \times 0.5 = 0.5\ m^3/s$
Data Gap:	**c** value needs to be determined either through field water balance measurements or best professional judgment
Calculate Cost of Increased Baseflow ($\$/m^3 \cdot s^{-1}$) for Baseflow (Dry Season) Benefits:	
Equation:	Unit cost = total cost of implementing the intervention / total increased baseflow
Inputs:	Project costs as provided by Ávila (2012) Total cost of project (US$) = 12,000
Calculations:	Increased baseflow for 180 days from 180 days of wet season diversion: Q ×180/180 = $0.5\ m^3/s$ Cost: US$12,000/0.5 m^3/s = US$24,000/$m^3 \cdot s^{-1}$
Assumptions:	1. These are actual project costs (Ávila, 2012) 2. Wet season is 180 days as well
Data Gap:	Baseflow distribution pattern (or days of wet season vs. dry season) should be derived from local stream hydrographs

References:

Ávila, J. (2012) Personal Communication. Alternativa Representative in Meeting with Aquafondo and Kieser & Associates, November 7, 2012 to Present a Pilot Project in the Chillon Basin.