Current and Prospective Water Management in the Apurimac River Basin, Peru. A Modeling Approach

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To my dad, mom, and Luna

Table of Contents

List of Tables vii

List of Figures viii

Abstract ix

Acknowledgements x

1. Introduction 1
   1.1. Problem Statement 1
   1.2. Previous Studies in the Apurimac River Basin 2
2. Case study: The Apurimac River Basin 4
   2.1. Physical Description of the Apurimac River Basin 4
   2.2. Decision on the Hydrological Model/ Software 7
   2.3. Two-Bucket Model 9
   2.4. One-Bucket Model 10
3. Model Implementation 11
   3.1. Climate Data 11
      3.1.1. Precipitation 12
      3.1.2. Temperature 13
      3.1.3. Relative Humidity 14
      3.1.4. Wind Velocity 14
      3.1.5. Latitude 14

3.1.6. Melting and Freezing Point ... 14
3.1.7. Reference Crop Evapotranspiration ... 15
3.2. Land Use ... 16
3.2.1. Area of Sub-Catchments ... 16
3.2.2. Area and Percentage of Land Use ... 17
3.2.3. Crop Coefficient ... 17
3.2.4. Runoff Resistance Factor ... 17
3.2.5. Preferred Flow Direction ... 18
3.2.6. Root Zone Conductivity ... 18
3.2.7. Soil Water Capacity ... 18
3.3. Calibration ... 19
3.3.1. Control Point 1 - La Angostura ... 21
3.3.2. Water Balance ... 24
3.4. Verification ... 27
4. Water Management Strategies ... 29
4.1. Current and Future Water Demands ... 31
5. Results ... 33
6. Conclusions ... 36
Reference ... 38
Appendix A. List of Hydrologic Model/ Software ... 43

Appendix B. Climate Data 45

Table B.1 Monthly average precipitation in twenty catchments 45

Table B.2 Monthly average temperature in twenty catchments 46

Table B.3 Precipitation sensitivity analysis at La Angostura (CP-01) 47

Table B.4 Temperature sensitivity analysis at La Angostura (CP-01) 47

Table B.5 Average relative humidity and average wind velocity 47

Table B.6 Latitude, melting point, freezing point, and initial snow 48

Figure B.1 Comparison of a monthly average precipitation 49

Figure B.2 Comparison of a monthly average temperature 49

Appendix C. Land Use Data 50

Table C.1 Percentage of land use 50

Table C.2 Monthly crop coefficient in different types of land use 51

Table C.3 Root zone conductivity 52

Table C.4 Preferred flow direction 52

Table C.5 Runoff resistance factor 53

Table C.6 Default and adjusted values of soil water capacity 54

Appendix D. Model Parameters 55

Figure D.1 Sensitivity analysis in precipitation and temperature 56

Appendix E. Calibration and Validation 57

Table E.1 Calibrated values of predicted streamflow (a) 57

Table E.2 Calibrated values of predicted streamflow (b).. 57

Figure E.1 Water availability at control point 1.. 58

Figure E.2 Water availability at control point 2.. 58

Figure E.3 Water availability at control point 3.. 59

Figure E.5 Water availability at all four control points.. 59

Figure E.6 Comparison of observed and predicted volume in Apurimac and Hornillos.......... 60

Figure E.7 Comparison of Apurimac and Hornillos shared volume and in percentage............ 61

Appendix F. Water Management Strategies... 62

List of Tables

Table 1. List of hydrologic modeling tools and features 3

Table 2. Summary of inputs, parameters, and outputs in the proposed one-bucket model 12

Table 3. Area of sub-catchments in km^2 and in percentage.. 16

Table 4. Comparison of observed and predicted streamflow in volume and percentage 23

Table 5. List of three main components and conditions used to evaluate scenarios 29

List of Figures

Figure 1. An overview of input, method, and objectives used to accomplish the objectives 1

Figure 2. Map of the Apurimac River Basin along with the sub-catchments 5

Figure 3. Schematic map of the Apurimac River Basin 6

Figure 4. Schematic of Water Evaluation and Planning System model 8

Figure 5. Conceptual diagram of two-bucket model (soil moisture method) with equations......... 9

Figure 6. Conceptual diagram of one-bucket model with inputs, parameters, and outputs.......... 11

Figure 7. Monthly average temperature and precipitation values in the Apurimac River Basin.. 13

Figure 8. Previous predicted ETo vs. current predicted ETo vs. ETo from Penman-Monteith method... 15

Figure 9. Calibration process flow chart 20

Figure 10. Calibration tool diagram for Apurimac River Basin 20

Figure 11. Map of La Angostura which is the potential location for building a reservoir 21

Figure 12. Comparison of annual average streamflow observed versus predicted....................... 22

Figure 13. Observed and predicted volumetric percentage at four control points 25

Figure 14. Schematic map with corresponding four control point ratio to CP-1.......................... 26

Figure 15. Comparison of observed and predicted streamflow values 27

Figure 16. Current and future water demands in the Apurimac River Basin 32

Figure 17. Comparison of current water volumetric reliability with and without reservoir in the current scenario 33

Figure 18. Comparison of current water volumetric reliability with and without reservoir in the future scenario... 34

Figure 19. Monthly variation of water annual demand in the mainstream 35

Abstract

Designing sustainable water resources systems is challenging given the natural scarcity of water resources in certain regions of the world and increasing anthropogenic water demands. South American countries have a conflict over the sharing of Amazon River water supplies both in downstream and upstream regions. The distribution of the Apurimac River, which is the headwater of Amazon River, is becoming a political issue with increasing tensions over the control of water supplies. The overall goals of this study are: (a) developing, calibrating, and verifying a rainfall-runoff model called one-bucket model in the basin, (b) building a water allocation model, and (c) evaluating the water supply reliability under different scenarios. The proposed one-bucket model adequately represents the streamflow distribution quantity and timing throughout the project and allows for groundwater storage. An integrated water management software (Water Evaluation and Planning system, WEAP) was used to develop a water management system for the upper basin of the Apurimac River in Peru and to evaluate different water allocation scenarios based on the requirements of the Arequipa and Cuzco Regional governments. Results show that the current water supply and storage system are unable to meet the anticipated higher water demands in the near future. Improvement may be found through building a reservoir or reducing water demands. Beyond the implications for the Arequipa and Cuzco regions, this study demonstrates the use of a hydrologic modeling tool to analyze the relationship between water availability and water demands.

Keywords: hydrologic model, water allocation model, one-bucket model, calibration

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1. Introduction

1.1. Problem Statement

The overall goals of this study are: (a) developing, calibrating, and verifying a rainfall-runoff model called one-bucket model in the basin, (b) building a water allocation model, and (c) evaluating the water supply reliability under different scenarios (see Figure 1).

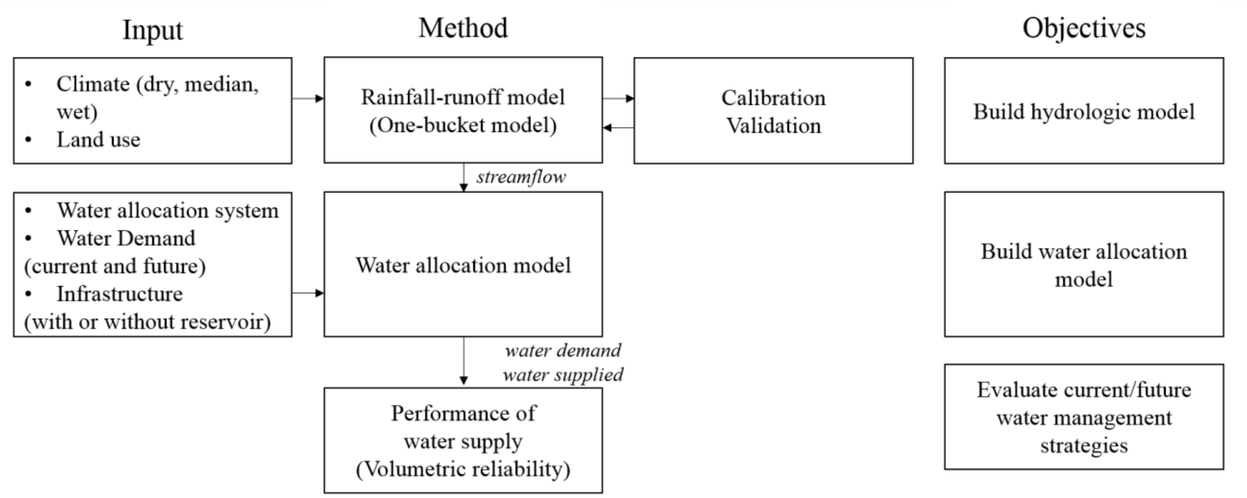


Figure 1. An overview of input, method, and objectives used to accomplish the objectives

The organization of this work is as follows: The rest of this chapter layouts the initiation of the Apurimac River Basin project, including a list of different modeling software that were considered in other previous studies. The second chapter begins with a story of how the case study in the ARB in more detail, follows by a physical description of the site, explains the decision on the hydrologic modeling, and describes proposed one-bucket model. The model implementation, development of calibration tool, and verification is shown in Chapter 3. The water allocation system, water management scenarios and results are included in Chapter 4. The results of running 36 permutation scenarios based on the three strategies components are explained in Chapter 5. Chapter 6 concludes all the findings, limitations, and some uncertainties involved in this project.

1.2. Previous Studies in the Apurimac River Basin

The Apurimac River Basin has been an area of conflict between Cuzco region and Arequipa region. In November 2012, Peru’s constitutional court announced that a study will be conducted for the upper basin of the Apurimac River to identify the sustainable alternatives for improved water resource management. This study was managed by the United Nation Office for Projects and Services and was technically supported by the United Nation Environment Program for a period of ten months. The study also looked at basin surface water supply resources from the Espinar province in the Cuzco region to Caylloma province in the Arequipa region. At the beginning of this project, the following three different methods are used to evaluate the water supply reliability: Lutz-Scholtz, Hydrologic Engineering Center 4, and transposition flow. When these models were applied as main modeling tools, they were found insufficient to adequately describe the heterogeneity of the river basin and the analysis of current and future scenarios.

Choosing a correct hydrologic model for this study basin can be difficult. Research available models and incorporate those finding into selecting the appropriate model for the Apurimac River Basin. A wide variety of approaches to hydrologic modeling of this river basin were evaluated to select, develop and interpret the models (Surfleet, Tullos, & Chang, 2012). These hydrologic and reservoir operation models are regarded as an accurate representation of hydrologic processes that could be achieved with the current data and computational resources. Table 1 shows the hydrologic tools that were considered to be used in this project. For more information on other models, see Appendix A.

Table 1. List of hydrologic modeling tools and features

Model	Description
Aquatool	Aquatool is a generalized decision-support system for water resources planning and operational management. It is capable of basin simulation, optimization modules, and risk assessment (Andreu, Capilla, & Sanchís, 1996).
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System is a rainfall-runoff model which provides an estimation of runoff volumes, peak flow, and timing of flows in the basin model (Halwatura & Najim, 2013).
MIKE-SHE	MIKE-SHE is a watershed simulation model for hydrological components such as movement of surface water, unsaturated subsurface water, evapotranspiration, etc (Golmohammadi, Prasher, Madani, & Rudra, 2014).
RiverWare	This is a generalized river basin modeling tool for operations and planning that are flexible to model any river basin, manage input and output data, and provide a set of solution algorithms (Zagona, Fulp, Shane, Magee, & Goranflo, 2001).
WEAP	Operating on the basic principles of water balance, Water Evaluation And Planning software is applied to complex river systems to govern the allocation of available water to meet the different water needs (Höllermann, Giertz, & Diekkrüger, 2010).
WRIMS	A new name for the CalSim software. A reservoir-river basin simulation model developed by the California Department of Water Resources and the U.S. Bureau of Reclamation. This is a data-driven simulation model and water allocation model that routes water based on the user-defined priorities or weights (Draper et al., 2004).

2. Case study: The Apurimac River Basin

2.1. Physical Description of the Apurimac River Basin

The Amazon River is the world largest river by discharge of water located in the South America. At the farthermost headwaters of the Amazon River there is Apurimac River (Río Apurímac) known as the second longest tributary that flows through the Arequipa and Cuzco regions in Peru (see Figure 2). The water comes from the glacial melt at the ridge of the Mismi (5,597 m) mountain in the Arequipa in southern Peru and flows generally northwest past Cuzco. The major tributaries of Apurimac River Bain include Oropesa, Velille, Pachachacra, Pampas, and Mantaro with a total area of 3,819 km^2. After 850 km, the Apurimac joins the Mantaro River and becomes the Ene River (Ziesler & Ardizzone, 1979).

The Autoridad Nacional del Auga (ANA) and regional government provided data from the four stream gauge stations that are connected to the corresponding control points in the schematic map (see Figure 3). Those gauge stations include La Angostura, 3 Canones Apurimac, Yauri Apurimac, and outlet. Despite similar physical characteristics of the sub-catchments, most of the precipitation falls into the headwaters which include Alto Apurimac and Hornillos sub-catchments. According to the recent measurement done by ANA and regional government, approximately 75% of water is attributed to the Alto Apurimac and Hornillos, and the rest 25% to downstream. These two sub-catchments carry much larger volumes of water than the rest of the sub-catchments. As shown in Figure 3, La Angostura (control point 1) is the intersection of these two which is a potential location for building a reservoir. Also, notice that in Figure 3, the headwaters of this catchment start from the bottom of the map and water continues to flow towards the outlet.

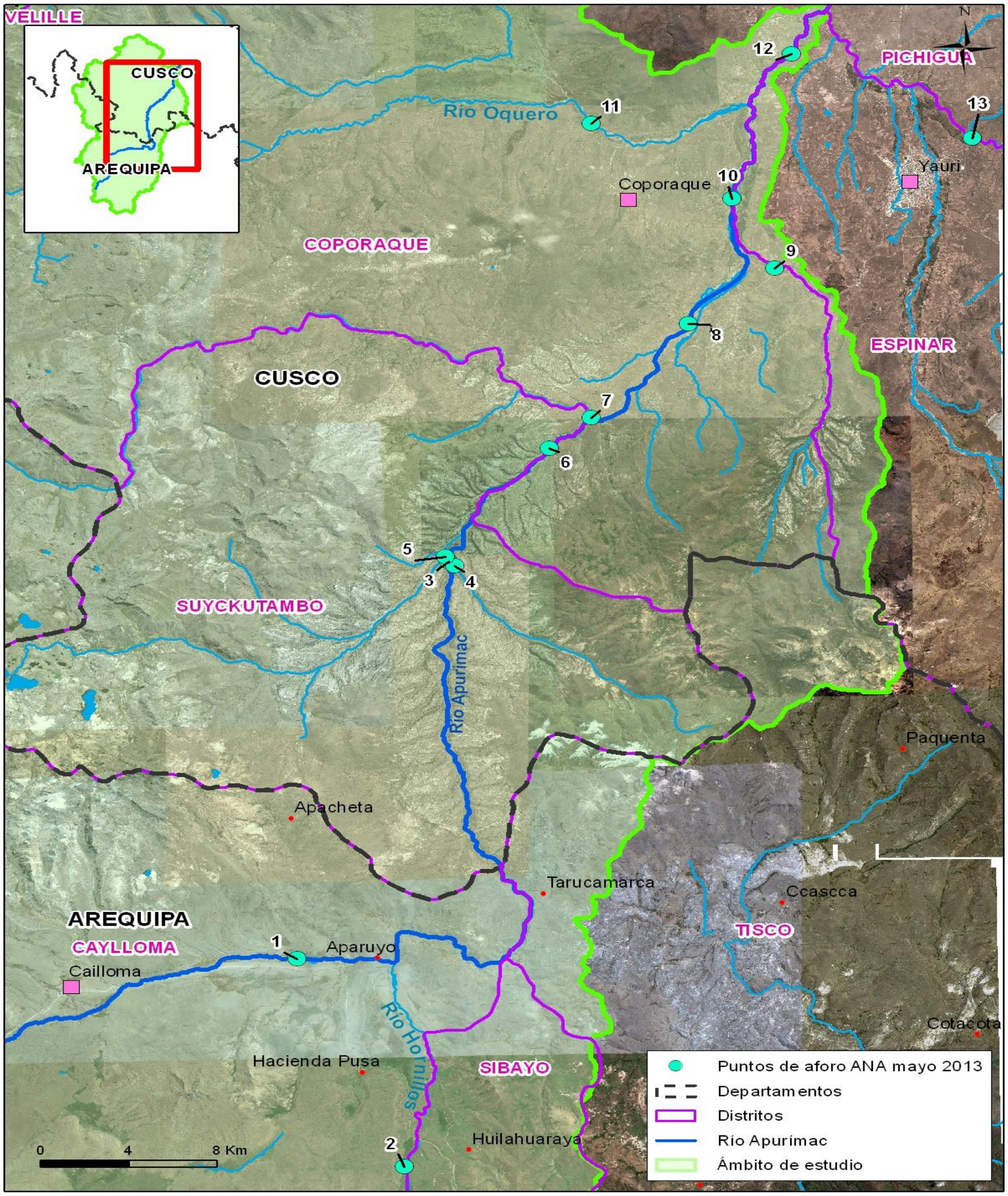


Figure 2. Map of the Apurimac River Basin along with the sub-catchments

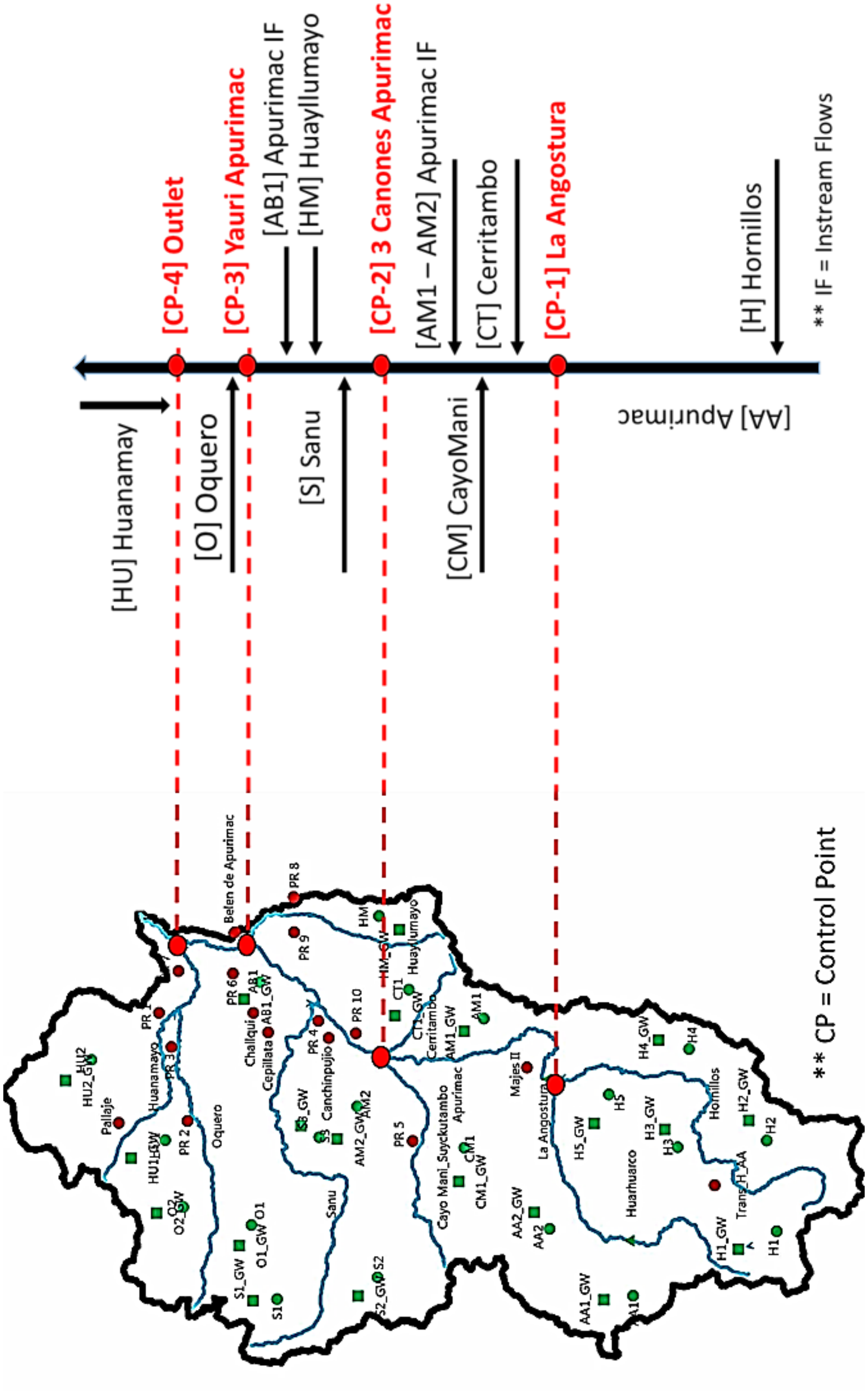


Figure 3. Schematic map of the Apurimac River Basin

2.2. Decision on the Hydrological Model/ Software

The Stockholm Environment Institute developed the WEAP software for modeling water management systems (Yates, Sieber, Purkey, & Huber-Lee, 2005). WEAP has been applied in a variety of contexts include: integrated water management (Sandoval-Solis, Teasley, Mckinney, Thomas, & Patino-Gomez, 2013), groundwater (Nouiri, Yitayew, Maßmann, & Tarhouni, 2015), rainfall-runoff models (Harma, Johnson, & Cohen, 2012), water allocation (Juízo & Lidén, 2010), and climate change (Strzepek et al., 1999). Using WEAP allow model builders to develop different water management scenarios to simulate a changing climate pattern and growing water demands (Comair, Gupta, Ingenloff, Shin, & Mckinney, 2013). A basin is subdivided via WEAP into multiple sub-catchments, which are then detailed into hydrological process based on a combination of climate data and land use properties.

This integrated water management tool was used to evaluate whether building a reservoir will alleviate the current water shortage in the sub-catchments of Arequipa and Yarabamba, Peru (Swiech, Ertsen, & Pererya, 2012). Similarly, this study also built a model using WEAP to evaluate different water allocation strategies, the consequences of new reservoirs, and to assess current and future water needs based on the requirement of the regional government of Arequipa and Cuzco (see Figure 4). WEAP provides a kit for developing and running site-specific models and it can be easily coupled to other models. With climatic data, different scenarios were built. With these scenarios, the present situation and the possible influence of the reservoir on the Apurimac River basin was evaluated in WEAP, a two-bucket model.

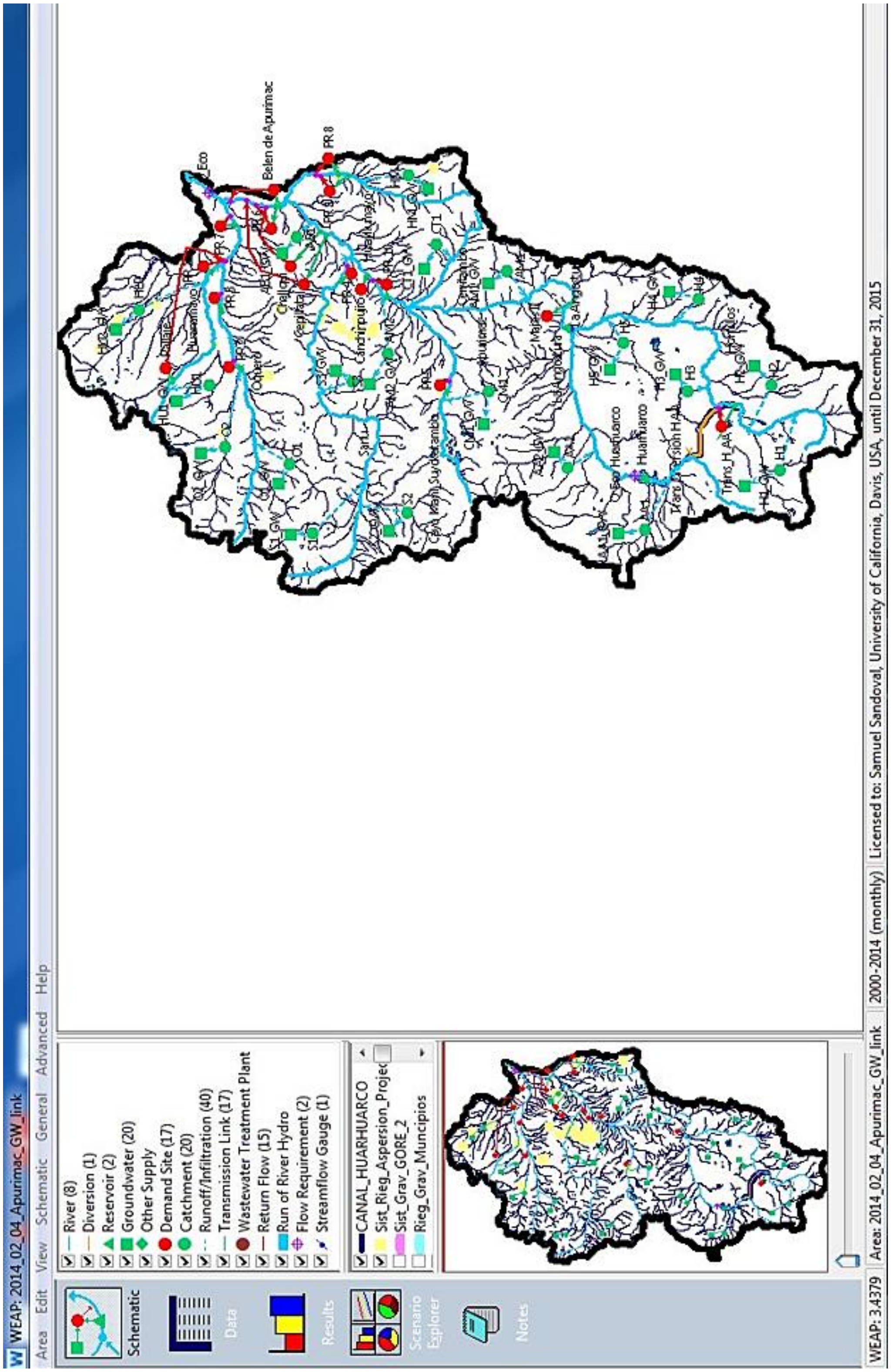


Figure 4. Schematic of Water Evaluation and Planning System model

2.3. Two-Bucket Model

A conceptual model was used to forecast how much it runoffs using a continuous budgeting process (Mandeville, O'Connell, Sutcliffe, & Nash, 1970). The soil water balance bucket model (Manabe, 1969) is a classic example of a hydrologic sub-model, which is a simplified description of the hydrologic cycle (Todini, 1988). The soil moisture method estimates the quantity of water contained in the soil moisture. Modifying Manabe's model introduced the daily bucket with bottom hole model, which includes a single layer bucket, gravity drainage and capillary rise (Kobayashi, Matsuda, Nagai, & Tesima, 2001). Yates presented a two-bucket model, a conceptual model composed of an upper bucket (bucket 1) and a lower bucket (bucket 2) (Yates, Sieber, et al., 2005) (see Figure 5).

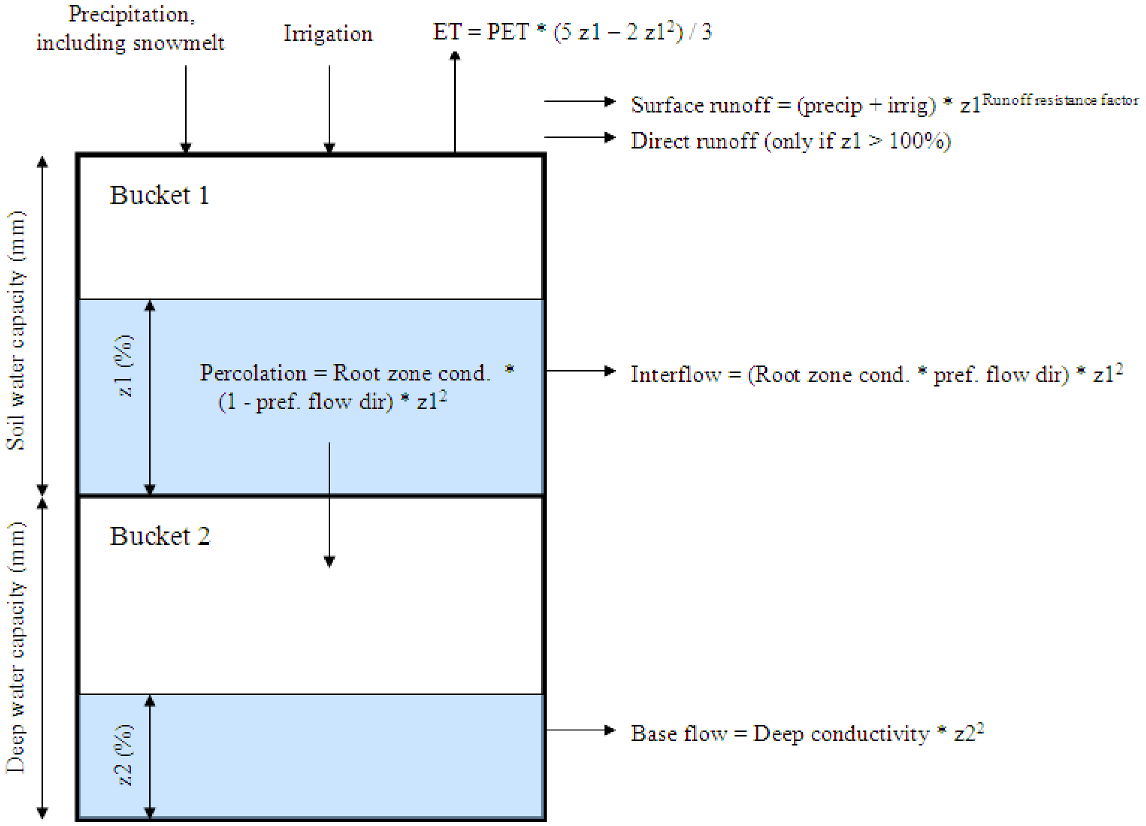


Figure 5. Conceptual diagram of two-bucket model (soil moisture method) with equations

Conceptualization of the rainfall-runoff process and the different pathways that water can take within a catchment is presented in Figure 5. As a bucket 1 is filled, the direct surface runoff occurs; otherwise, water flows out as interflow and percolates into bucket 2. Water stored in bucket 2 can only leave this bucket as baseflow. This is a rainfall-runoff model suitable for landscapes that convert all the rainfall inflow into either evapotranspiration or surface runoff without groundwater component in the system. Some limitations of two-bucket model are that it shows an infeasible solution when there is more inflow from bucket 1 into bucket 2 compared to the storage capacity and the outflow of bucket 2 as baseflow; it does not include a groundwater component. The one-bucket model was developed for this study that considers both surface runoff processes and groundwater.

2.4. One-Bucket Model

The one-bucket model adequately represents the streamflow distribution quantity and timing throughout the project and allows for groundwater storage. The one-bucket model implements empirical equations composed of various parameters that help to calculate the water balance. A conceptual diagram of the model is presented in Figure 6. The focus of developing the one-bucket model was to improve the representation of rainfall-runoff process without introducing the full complexity of the Apurimac River Basin model. During the rainfall events, either water flows as surface runoff, or percolates into the bucket. When the bucket is filled up by rainfall, extra water either jointly flows out as interflow and baseflow or goes into a groundwater (see Figure 6). The groundwater station was implemented to all sub-catchments (see Figure 4). This model is considers a groundwater component that was not originally included in the two-bucket model, but it is limited by jointly estimating the interflow and baseflow.

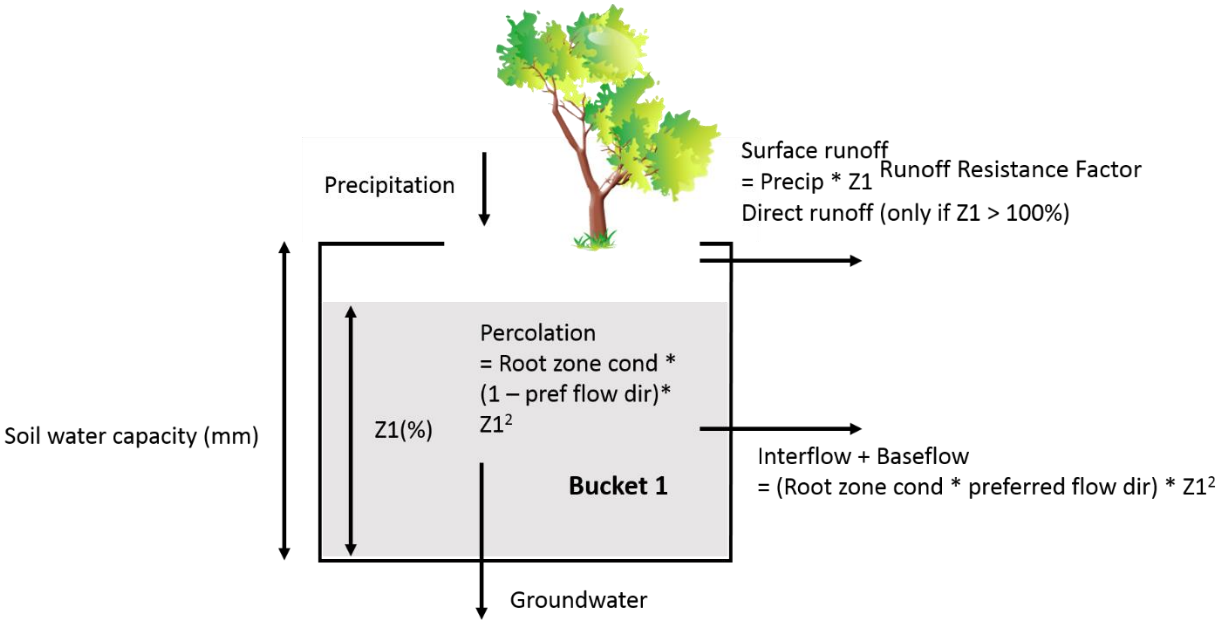


Figure 6. Conceptual diagram of one-bucket model with inputs, parameters, and outputs

3. Model Implementation

3.1. Climate Data

Based on the one-bucket model, Apurimac River Basin requires the following as inputs: (a) climate data (precipitation, temperature, snowmelt, relative humidity, wind velocity) and (b) land use information (area, crop coefficient) (see Table 2). These input data come from different sources of information. The climate data are mainly provided by ANA and the regional government of Arequipa and Cuzco, collected raw data by participating consultants from previous studies in the basin and from similar studies in other Andean watersheds in Peru. The series of the input data were discussed with Peruvian researchers in hydrology and received useful feedbacks from the team of United Nation Office for Projects and Services.

Table 2. Summary of inputs, parameters, and outputs in the proposed one-bucket model

Inputs		Parameters	Outputs	
Land Use	Area	Runoff resistance factor	Runoff	Direct runoff
	Crop Coefficient	Preferred flow direction		Interflow
Climate	Precipitation	Root zone conductivity		Baseflow
	Temperature	Soil Water Capacity	Groundwater	
	Latitude			
	Snowmelt			
	Relative humidity			
	Wind velocity			
	Freezing point			
	Melting point			

3.1.1. Precipitation

Peru has a diverse geography and thus the weather vary throughout the basin. The annual average precipitation in the basin is 1486 mm and 75% of the rainfall occurs during the winter season (from December to March). The Alto Apurimac and Hornillos sub-catchments receive 880 mm of annual rainfall, which is more than half of the total annual precipitation. Given the limited number of stream gauge stations across the basin, four control points are carefully selected to ensure maximum availability of observed precipitation records at the monthly scale (see Figure 3). The model was built using one set of climate data for each sub-catchments, which was subdivided into height intervals of 300 m. To estimate the relationship between height and precipitation, the rainfall in the catchment was weighted by the area. Adding rainfall-height relationships was a significant advance in the present study compared with the previous study. Heavy rains in the mountain last from December to April (see Figure 7). The monthly average precipitation values per sub-catchment can be found in Appendix B.

3.1.2. Temperature

As for temperature, WEAP specifies that they must be a weighted average between the minimum and maximum temperature (see Appendix B). There are no specific rules mentioned in the previous studies on how these temperature must be calculated for the Apurimac River Basin model. Given that very few stations provide reliable temperature data, it was tested with different weights for temperatures, in order to obtain potential values close to the values given by formulas (Sieber & Purkey, 2009). This calculated temperature data was used to compute potential evapotranspiration.

In the Arequipa and Cuzco regions, dry periods last from April to August. On average, the warmest month is December to February and the coolest month is July (see Figure 7). The rainy season is seen from January to March, while dry periods last from May to September.

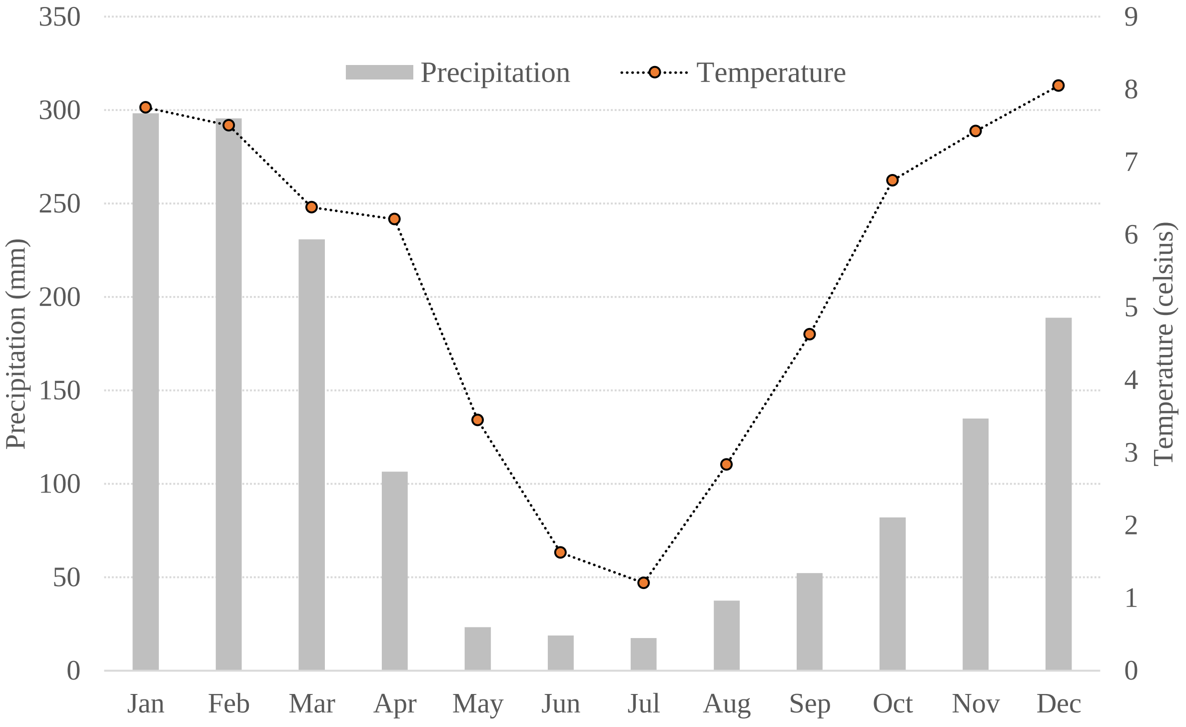


Figure 7. Monthly average temperature and precipitation values in the Apurimac River Basin

3.1.3. Relative Humidity

With regard to the relative humidity, uniform values are used for each of the sub-catchments which is a common practice in WEAP regardless of the basin to be used (Sieber & Purkey, 2009). The monthly average values are reported in Appendix B. The relative humidity ranges from 35% (dry) to 69% (humid) over the course of the year. On average, February is the most humid while August is the least humid month.

3.1.4. Wind Velocity

Similar to relative humidity, wind velocity was around uniform throughout the entire basin, although it varies seasonally (see Appendix B). Over the course of the year, wind velocity vary from 4.4 m/s (light breeze) to 5.7 m/s (moderate breeze). The highest average wind speed is 5.4 m/s from July to December and the lowest average wind speed is 4.7 m/s from January to June.

3.1.5. Latitude

While there are different factors that affect general climate in an area (i.e. location relative to mountains/oceans, height above/below sea level), latitude is an important factor in determining which type of climate a location will have. Latitude of catchment was extracted from Google Earth and was incorporated into the model (see Appendix B).

3.1.6. Melting and Freezing Point

The model requires the specification of initial conditions for the equivalent height of water due to snow and the percentages of water storage in the soil for one-bucket model. As initial conditions, an equivalent height of zero is declared as water due to snow. The melting point at Alto Apurimac and Hornillos are adjusted and the rest of the sub-catchments are set up as default values (see Appendix B). Likewise, the freezing point for these two sub-catchments were adjusted, while others are inputted as default values.

3.1.7. Reference Crop Evapotranspiration

The reference crop evapotranspiration (ETo) is the estimation of the evapotranspiration relative to the reference surface (Penman, 1948). The Food and Agriculture Organization Penman-Monteith method is used to determine the ETo (Yates, Purkey, Sieber, Huber-Lee, & Galbraith, 2005). Further descriptions of this method is out of the scope for this study. The predicted ETo values from the previous studies are plotted with the predicted ETo values from the current study and the values derived from the Penman-Monteith method (see Figure 8). The observed data from the previous studies tend to be much higher than the values calculated using Penman-Monteith method. The newly predicted data nicely falls into the median of the range, which shows that the model is consistent.

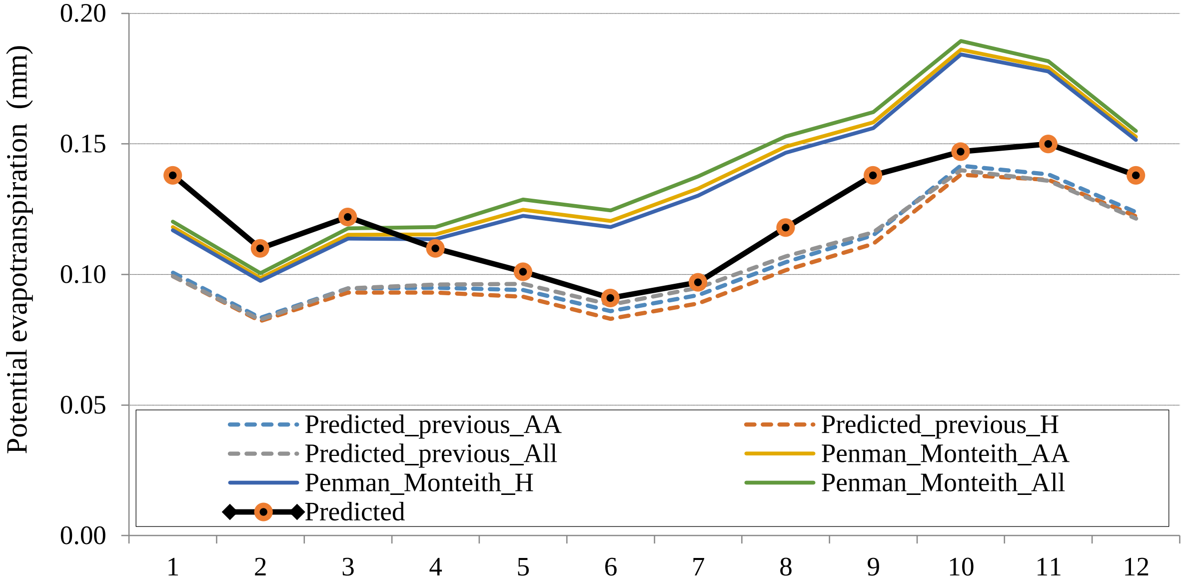


Figure 8. Previous predicted ETo vs. current predicted ETo vs. ETo from Penman-Monteith method

3.2. Land Use

Sub-catchments are characterized by different types of cover and land use information, which plays a fundamental role to describe how soil meets and transfers water through the watershed. These land use information are included in the model by a heterogeneous group of land use data (i.e. area of land use, crop coefficient), which naturally vary throughout the basin.

3.2.1. Area of Sub-Catchments

This catchment was first sub-divided into ten, and then these were divided again into even smaller area. There are in total of twenty sub-catchments in the Apurimac River Basin (see Table 3). The hornillos sub-catchment has the largest area followed by Alto Apurimac, which both of them are located upstream of the basin.

Table 3. Area of sub-catchments in km^2 and in percentage

Sub-Catchments		Area	
		km^2	Percentage
Hornillos	H1	162.2	4%
	H2	29.6	1%
	H3	78.0	2%
	H4	204.3	5%
	H5	147.1	4%
Alto Apurimac	AA1	204.0	5%
	AA2	463.9	12%
CayoMani	CM1	204.4	5%
Apurimac Instream Flows	AM1	257.1	7%
	AM2	110.1	3%
Cerritambo	CT1	78.2	2%
Sanu	S1	151.8	4%
	S2	140.9	4%
	S3	320.0	8%
Apurimac Instream Flows	AB1	185.9	5%
Huanamayo	HU1	54.4	1%
	HU2	521.9	14%
Oquero	O1	145.4	4%
	O2	217.3	6%
Huayllumayo	HM1	143.1	4%

3.2.2. Area and Percentage of Land Use

Fifteen different land use types were adopted from the analysis done by the United Nation Office for Projects and Services and raw data collected from the previous studies (see Appendix C). These land use features are used for calculating the total evaporation in the catchment. As land use data are closely associated with the crop coefficient values, they are used to calculate the reference crop evapotranspiration. Before the incorporation of land use into the WEAP model module, certain criteria were applied. First, those uses that occupy less than 0.5% of the area were removed; Second, the values of the area of each land use were rounded, following the guidelines from WEAP applications, so that the use of land in each catchment adds up to 100%. The most abundant land use and the second most abundant land use information can be found in the Appendix C.

3.2.3. Crop Coefficient

The crop coefficients values are provided with temporary variance based on the Food and Agriculture Organization recommendations (see Appendix C).

3.2.4. Runoff Resistance Factor

As the runoff resistance factor increases, the rate of runoff drops because this value is used to control surface runoff response (Sieber & Purkey, 2009) (see Figure 5). Equation 1 was applied to calculate the surface runoff, assuming that irrigation is 0 in this basin. z1 is soil water capacity.

$$\text{Surface runoff} = (\text{precipitation} + \text{irrigtaion}) * z1^{\textbf{runoff resistance factor}} \tag{1}$$

3.2.5. Preferred Flow Direction

The preferred flow direction ranges from 0 (100% of the water flows vertically) to 1 (100% of the water flows horizontally) and it varies by the land class type. It is used to partition the flow out of the root zone layer between interflow and baseflow to the lower soil layer or groundwater. Increasing the preferred flow direction means more surface runoff and faster streamflow occurs, since more water moves down to the bucket (see Appendix C).

$$\text{Interflow} = (\text{root zone conductivity} * \text{preferred flow direction}) * z1^2 \tag{2}$$

3.2.6. Root Zone Conductivity

When the root zone conductivity is fully saturated, water either flows as interflow or basefow or groundwater. This depends on the preferred flow direction (see Equation 2). The storage capacity of water in the root zone can be specified as a function of time in each catchment for each land use. The annual mean values are adopted based on the various field. In general, the thickness of the upper layer is less than 30 cm deep (see Appendix C).

3.2.7. Soil Water Capacity

The soil water capacity is the measure of available water capacity that can be stored in soil and accessible for irrigation purposes (Yates, Sieber, et al., 2005). This variable is a balance between knowledge in the field of water movement relies on model calibration. These values are modified in the order of 200 mm for each sub-catchments and then decreased to adjust the predicted flow in La Angostura (see Appendix C). A small increment of adjustment was made in the soil water capacity values near the headwater, but larger increment of modification was made towards the outlet.

3.3. Calibration

Now that all the input and parameter information are available, the calibration location and periods of record to use were selected. Calibration is the process of choosing parameter values to determine how the model behaves, then to compare the model's prediction (Beven & Binley, 1992). Uncertainty in both data and parameters are important and must be understood to well perform the calibration (Nandakumar & Mein, 1997). Sensitivity analysis in WEAP modeling parameters will provide enhanced confidence about the numerical accuracy of the adjustment level in numerous parameters (Trucano, Swiler, Igusa, Oberkampf, & Pilch, 2006). Performing a sensitivity analysis prior to the calibration gave a better understanding to categorize parameters as sensitive or non-sensitive parameters (see Appendix D).

The Apurimac River Basin model is calibrated from 2000 to 2014 at La Angostura, which is a potential location to build a reservoir (see Figure 11). The trial and error procedure was used as the calibration method to examine how each parameter affects the results that are used to control the changes in parameter values. The calibration of the model for average conditions extended not only to the sub-catchments in the upstream of La Angostura, but also to the entire watershed.

In the Apurimac River Basin, sensitive and non-sensitive parameters are modified to calibrate the model that falls within the acceptable range. Then these parameters are adjusted accordingly to mimic the shape of streamflow line, volume, and percentage to the Apurimac River Basin (ARB) model (see Figure 9). This is an iterative procedure of parameter adjustment and comparison between observed and predicated values. A calibration for hydrologic models often focuses on three characteristics: annual water balance, seasonal and monthly flow volumes, and base flow. Predicted and observed values for each four characteristics are examined and parameters are adjusted to attain acceptable levels of agreement.

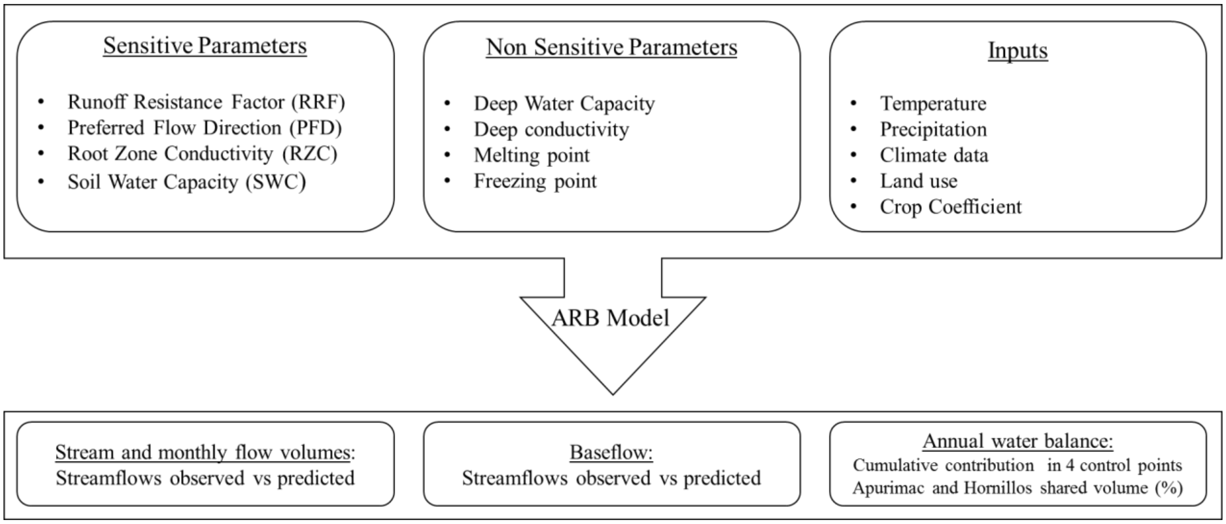


Figure 9. Calibration process flow chart

The trial and error method is commonly used for calibration due to the lack of an automated calibration tool (Seong, Herand, & Benham, 2015). The new calibration model was proposed in this study to make the process efficient. A set of parameters are proposed in the process and the script written in visual basic application runs the model, extracts, and displays the results in the same input Excel spreadsheet (see Figure 10). The proposed calibration tool in this basin is useful in many ways. It can easily perform the repetitive process with adjusting more than one parameters. The inputs, parameters and outputs are displayed and stored in one file, which makes it easier to compare the difference between prior and current model runs.

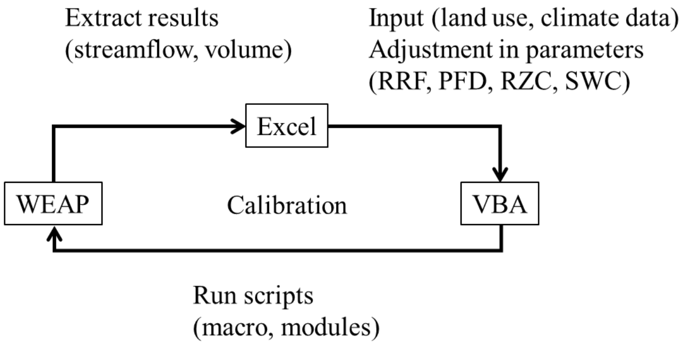


Figure 10. Calibration tool diagram for Apurimac River Basin

3.3.1. Control Point 1 - La Angostura

During the calibration step of the model, a group of hydrological parameters are used to simulate streamflow that resemble the observed streamflow closely as possible. These parameters are adjusted accordingly to mimic the shape of these streamflow line, volume, and percentage (see Appendix E). To achieve this, comparisons between the observed streamflow and predicted streamflow at specific points of the basin, in this case at La Angostura (see Figure 11). There was only one hydrometric station in La Angostura, and some data have been analyzed by earlier authors with varying conclusions. This station drains about a third of the entire basin under the study. This is a potential location to build a reservoir to provide better water supply for current and future demands. Headwaters catchments of Alto Apurimac and Hornillos sub-catchments are used for the calibration purpose.

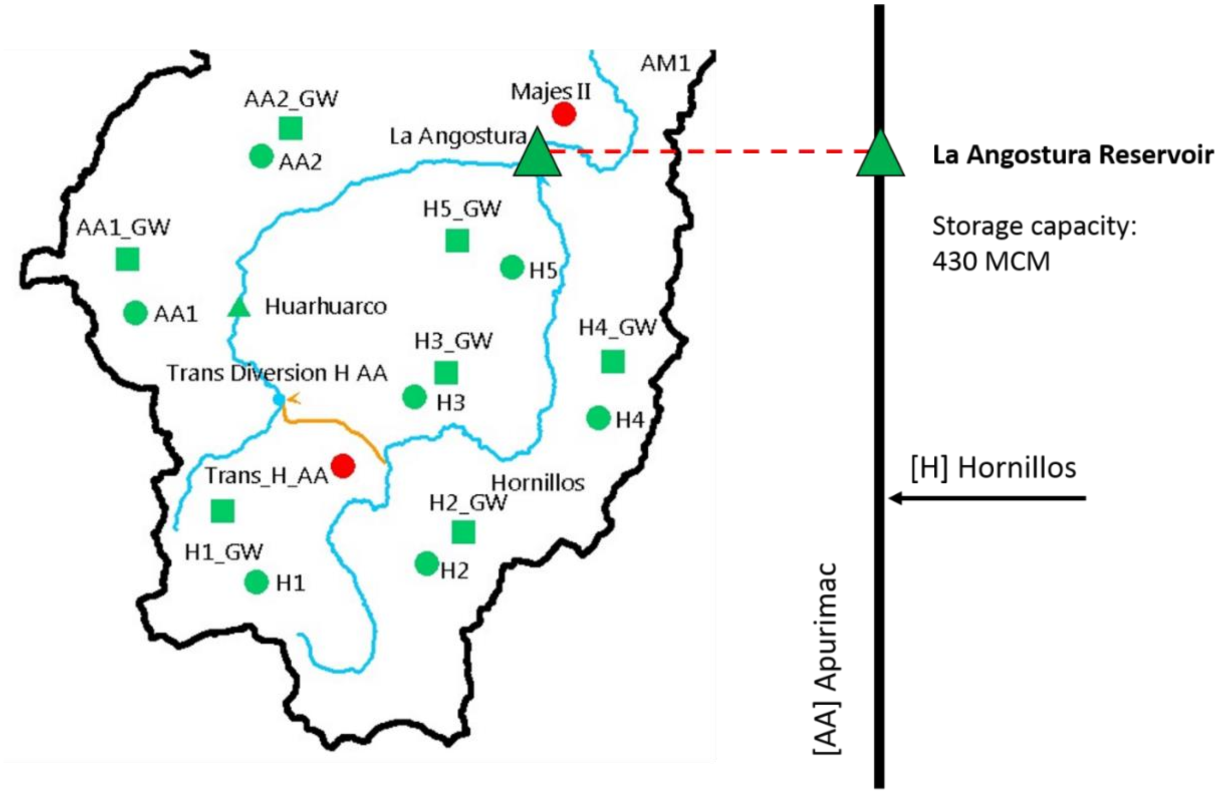


Figure 11. Map of La Angostura which is the potential location for building a reservoir

The model parameters that manage the physical response of the basin are modified in this process within plausible values. The most upstream basin were adjusted first to an acceptable goodness of fit for flow in La Angostura, then the parameters were modified in the lower basin in order to obtain a good distribution of flow for each sub-catchment and properly reflected a flow rate ratio between each control points and La Angostura. Streamflow at different control points and water budgets for all the sub-catchments were calculated to calibrate the model (see Appendix E). For the observed streamflow, the average streamflow values from 1962 to 2010 were used and calibrated from 2000 to 2014 at La Angostura. As the end, the predicted streamflow values are closely calibrated to the surveyed hydrological data for a given period (see Figure 12).

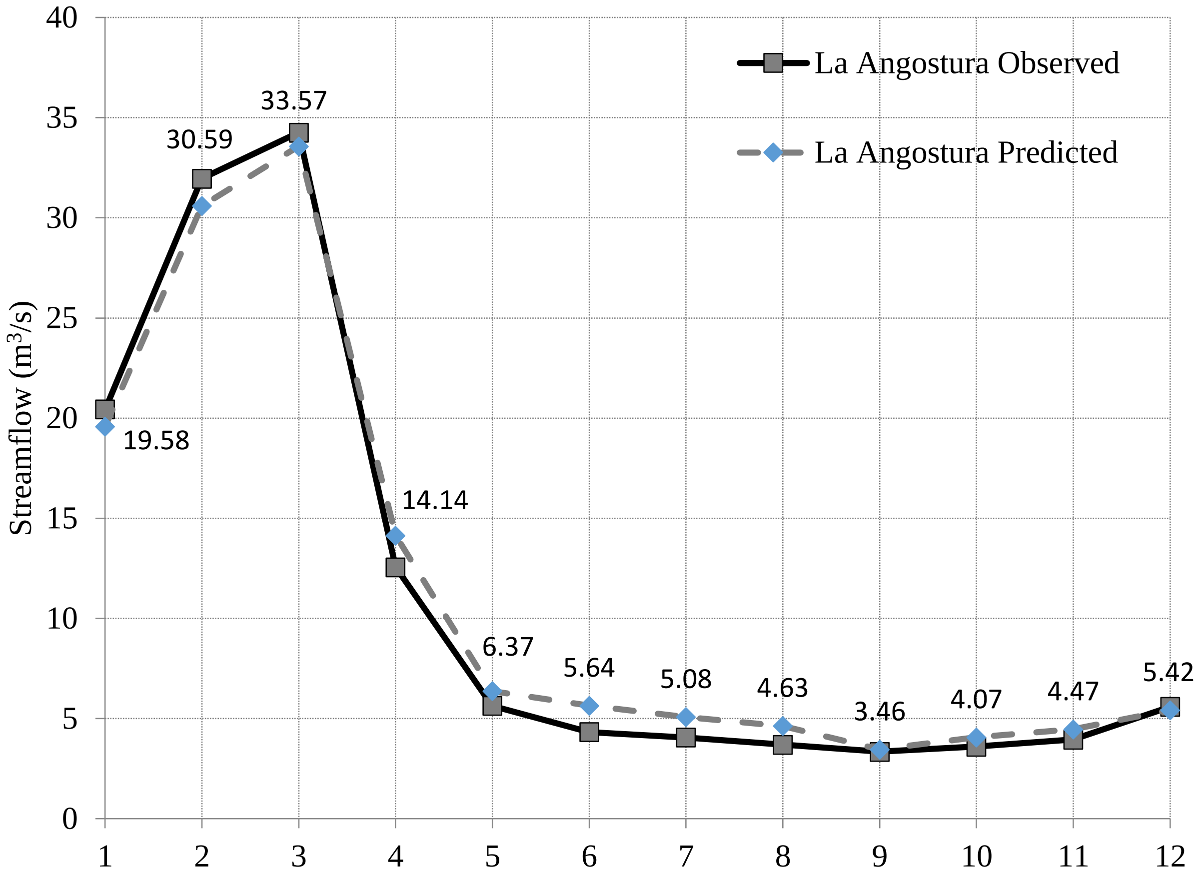


Figure 12. Comparison of annual average streamflow observed versus predicted

The model is well calibrated because the predicted values are very close to the observed streamflow throughout the basin despite the objections mentioned in relation to the comparison of mean values of streamflow and average values of flow in La Angostura (see Appendix E). The model was able to properly simulate the timing of flows in the station to produce a peak flow modeling phase with the measured month. In Figure 12, it lays out the comparison of observed monthly average flow values in a solid line and predicted flow values in a dotted line. There is a decent amount of streamflow during January to April, but for the rest of the months streamflow is very low. While these parameters are adjusted accordingly to mimic the shape of the streamflow line, the volume of water that comes from Alto Apurimac and Hornillos are also modified (see Table 4).

Table 4. Comparison of observed and predicted streamflow in volume and percentage

	Observed Volume* (MCM**)	Predicted Volume (MCM)	Observed Percentage* (%)	Predicted Percentage (%)
Alto Apurimac	226 - 260	236	65 - 75	66
Hornillos	87 - 121	121	35-25	34
Total		357		100

* these volume are empirical values suggested by the experts for calibration purpose

** MCM = Million Cubic Meters

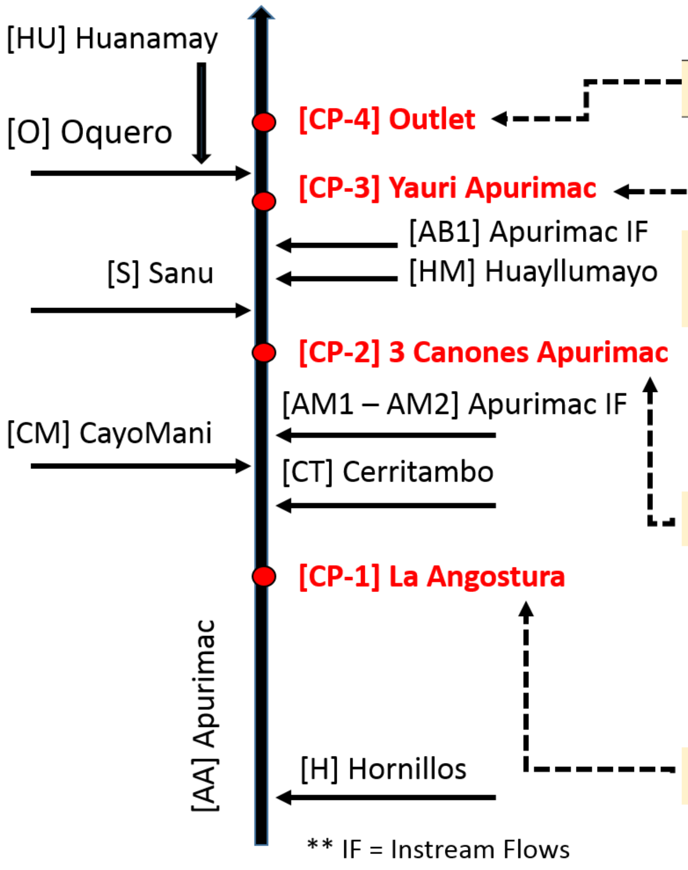
In the Alto Apurimac sub-catchment, the observed volume ranged from 226 to 260 million cubic meters and the predicted volume was 236 million cubic meters, which fell into the range. In the Hornillos sub-catchment, the observed volume ranged from 87 to 121 million cubic meters and the predicted volume was 121 million cubic meters, which also fell into the range. This is one of the three result for showing that the model is well calibrated.

3.3.2. Water Balance

A parametric water balance model was designed to represent the complex hydrologically oriented models with parameters. The main purpose of evaluating the water balance is to have a better understanding on complexity of hydrologic cycle and estimate model parameters based on the collected data (Schaake & Koren, 1996). The water balance was used as one of the verification method in this study.

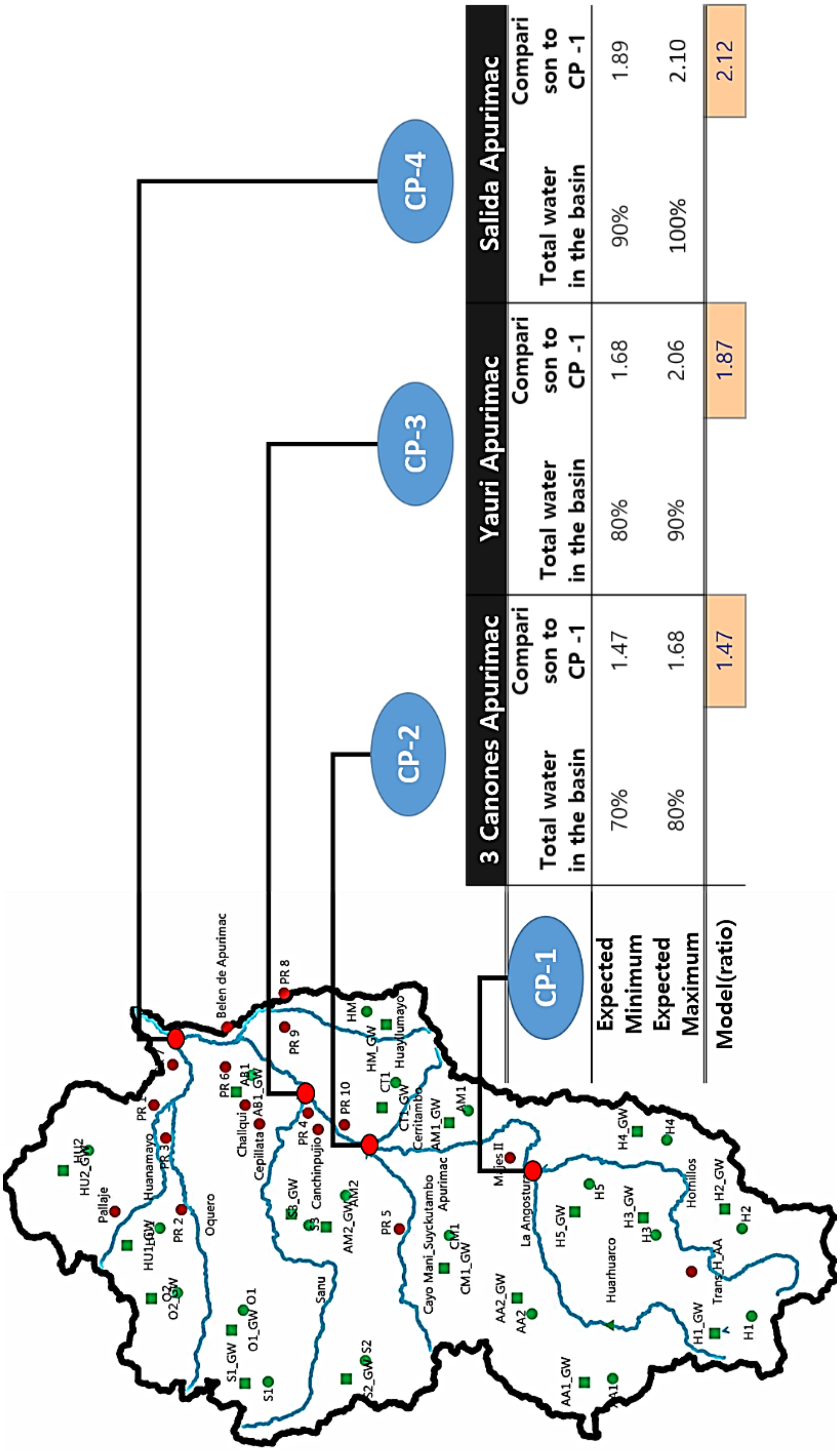
While calibrating at control point 1 (CP-1), all the sub-catchments above CP-1 were activated and the rest were deactivated (see Figure 13). Using the same mechanism, the proposed one-bucket model is fully calibrated until it reached the outlet. During this procedure, predicted and observed percentage of water coming from each sub-catchments for the four control points and all of the sub-catchments were examined. Parameters are adjusted accordingly to attain acceptable levels of agreement. Figure 13 well illustrates the amount of water (in percentage) coming from each sub-catchments and the four control points.

Then, the desired water volume ratio from three control points respect to the CP-1 was evaluated (see Figure 14). Based on the water volume range suggested by the hydrology exports in Peru, it was first calibrated at CP-1 by keeping all the sub-catchments above CP-1 activated, while the rest were deactivated. This process was repeated in the proposed one-bucket model until it reached the outlet. In Figure 14, for example, the ratio of control point 2 (CP-2) respect to CP-1 was 1.47 indicating that the volume of water flowing at CP-2 is 1.47 times greater than the volume of water flowing at CP-1. At the end, each one of the calibrated ratio at four control points fell into the expected range.



Catchments	Observed (%)	Observed Accumulative (%)	Predicted (%)	Predicted Accumulative (%)
CP - 4	**100**		**100**	
HU - Huanamayo	1	100	3	97
O - Oquero	10	99	10	87
CP -3	**89**		**87**	
AB1	8	81	8	79
S – Sanu	12	69	11	68
HM - Huayllumayo	1	68	3	65
CP -2	**68**		**65**	
AM 1 & AM2	3	65	6	59
CT - Cerritambo	1	64	3	56
CM - Cayo - Mani	5	59	9	47
CP - 1	**59**		**47**	
H - Hornillos	14	59	16	47
AA - Alto Apurimac	45	45	31	31

Figure 13. Observed and predicted volumetric percentage at four control points



	3 Canones Apurimac: Total water in the basin	3 Canones Apurimac: Comparison to CP -1	Yauri Apurimac: Total water in the basin	Yauri Apurimac: Comparison to CP -1	Salida Apurimac: Total water in the basin	Salida Apurimac: Comparison to CP -1
Expected Minimum	70%	1.47	80%	1.68	90%	1.89
Expected Maximum	80%	1.68	90%	2.06	100%	2.10
Model(ratio)		1.47		1.87		2.12

Figure 14. Schematic map with corresponding four control point ratio to CP-1

3.4. Verification

The verification is to test if the predicted parameters that are taken into consideration during the calibration are adequate for using in a different period of calibration analysis (Refsgaard, 1997). Usually testing a hydrological model is expected as the indicator of goodness of fit between observed and predicted flow rates after the calibration. The calibrated model is tested for the historical period 1976, which had a very similar value of total annual streamflow (347 m^3/s) to the total annual streamflow in 2014 (364 m^3/s). Despite how well the model was calibrated, the verification did not show the best fit (see Figure 15).

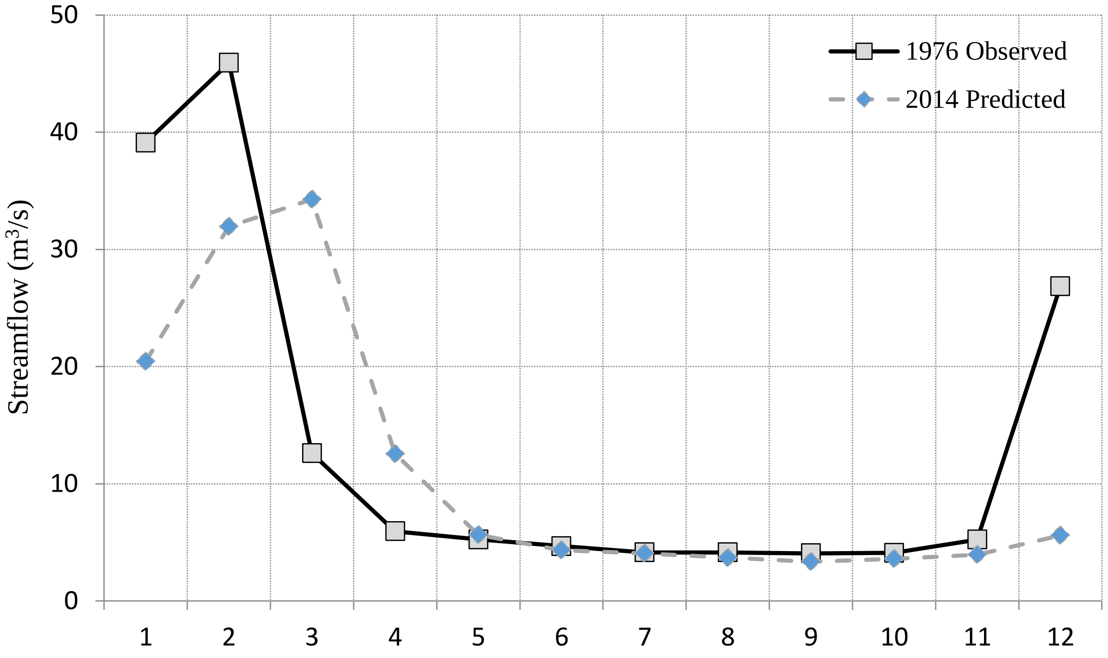


Figure 15. Comparison of observed and predicted streamflow values

The monthly peak flow was off by one month, but the overall shape of the 2014 predicted streamflow graph was similar to the 1976 observed graph. There is a considerable uncertainty involved in this verification process, such as working with a lack of monitoring and consequent quantity of data. The verification results tend to come out better when the calibrated peak streamflow is greater than the validated peak streamflow which is not the case in this study. If calibration were to be done using the extreme event values, most likely, the verification would result in a less extreme event with a better fit.

One of the drawbacks of a hydrologic model is the availability of information necessary for the proper implementation and model verification. Given the lack of access to an essential sector of the basin, the UNOPS team requested the use of complementary and innovative methodologies to determine land use categories present throughout the basin. To adequately represent the sub–catchments and all of the land use information, the calibration is performed by modifying the number of parameters to be handled in the simulations. The purpose of tuning the model is to run a historical period based on the series of meteorological variables and flows in La Angostura.

4. Water Management Strategies

Consider planning to supply enough water for ARB: How much water is available in the rivers? Is reservoir storage needed? If reservoir is built to store water to tide over form times of excess to times of deficiency, the demand sites in ARB will have better water supply both in the present and in the future. Therefore, it is critical to design the storage reservoir so that the current and future water demands for water can be supplied despite variation in river flows and climate change. In this study, assessing water management scenarios provides insight for integrated water resource planning and different options for meeting the future water demands (see Table 5). The synthetic data from 1965 to 2020 are used for current and future water demands.

Table 5. List of three main components and conditions used to evaluate scenarios

Scenario	Condition	
Infrastructure	La Angostura - ON	(0%, 25%, 50%, 75%, 100%)
	La Angostura - OFF	(0%)
Level of development	Current Future	
Climate condition	Dry Median Wet	

The model built in WEAP was applied to evaluate infrastructure, level of development, and climate condition which gives in total 36 possible scenarios to run (see Appendix F). Scenarios are commonly used to investigate a complex hydrologic systems that are unpredictable to enable reasonable predictions. For each scenario, the Apurimac River Basin model was used to simulate water supply in 17 demand sites over a 14 years period. All the demand sites are assigned from priority 1 to priority 3, where 1 is the highest priority and 3 is the lowest priority. Some demand sites share the same priority. The reservoir filling priority was set as default value 99, so that it will fill up only if water remains after satisfying all other higher priority demands (Yates, Sieber, et al., 2005). When water is limited, the algorithm is formulated to progressively restrict water allocation to those demand sites that have been given the lowest priority (Yates, Purkey, et al., 2005). For the current and future scenarios, levels of assured supply are estimated for each demand site and based on the water supply data, sensitive analysis was done.

To evaluate the performance of model scenarios, the following three criteria are evaluated: reliability, resiliency, and vulnerability. These measurements describe how likely a system is to fail (reliability), how quickly it recovers from failure (resiliency), and how severe the consequence of failure may be (vulnerability) (Hashimoto, Stedinger, & Loucks, 1982). The volumetric reliability was the main criteria to evaluate the performance of 36 scenarios in this basin. Measures of volumetric reliability is based on the proportion of demand supplied:

$$\mathrm{R_v} = \frac{\varepsilon(\text{water supply})}{\varepsilon(\text{water demand})} \tag{3}$$

where $\mathrm{R_v}$ is the volumetric reliability, $\varepsilon(\text{water supply})$ is the actual supply from the reservoir and $\varepsilon(\text{water demand})$ is the target demand in the model. Observing at the volumetric reliability, the overall shortfall in water supply occurs in the future scenario, which is a major problem. From the volume based reliability this particular basin is not performing satisfactorily, yet on the assumption of potential planning reservoir, the volumetric reliability is more satisfactory.

4.1. Current and Future Water Demands

How to meet the rapidly growing future water needs in Peru? Predicting an adequate water supply is ongoing challenge as water supply and demands reliability changes over period of time (Randall, Cleland, Kuehne, Link, & Sheer, 1997). It is important to assess the effectiveness of building a reservoir. To provide a better water supply, a WEAP model was developed and applied to demonstrate alternative scenarios for operating a potential reservoir at La Angostura in the Apurimac River. Challenges for potential water infrastructure in Apurimac River include meeting future water demands in a changing climate and managing diverse source of water supply. In times of increasing uncertainty and with a future likelihood to be utterly different from current environment, the future water demands scenario will give a better understand possible pathways into the future and enable preparation about how to supply sufficient amount of water for this region (Sigvaldson, 1976).

In this study, WEAP software used observed climate data and land use information to integrate existing and future water strategies to satisfy the rising water needs. In

Figure 16, the demand sites on the mainstream are in green circles, while those that are not in the mainstream are in blue circles. In the mainstream, current water demands is 29 million cubic meters and the future water demands is 72 million cubic meters, which is 2.48 times greater than the current demands. Assuming that the Apurimac River can provide a same amount of water in the future, it cannot satisfy higher demands. The water demands in Huayllumayo (HM) sub-catchment is very minimal, while Oquero (O) sub-catchment has minor difference in current and future water demands.

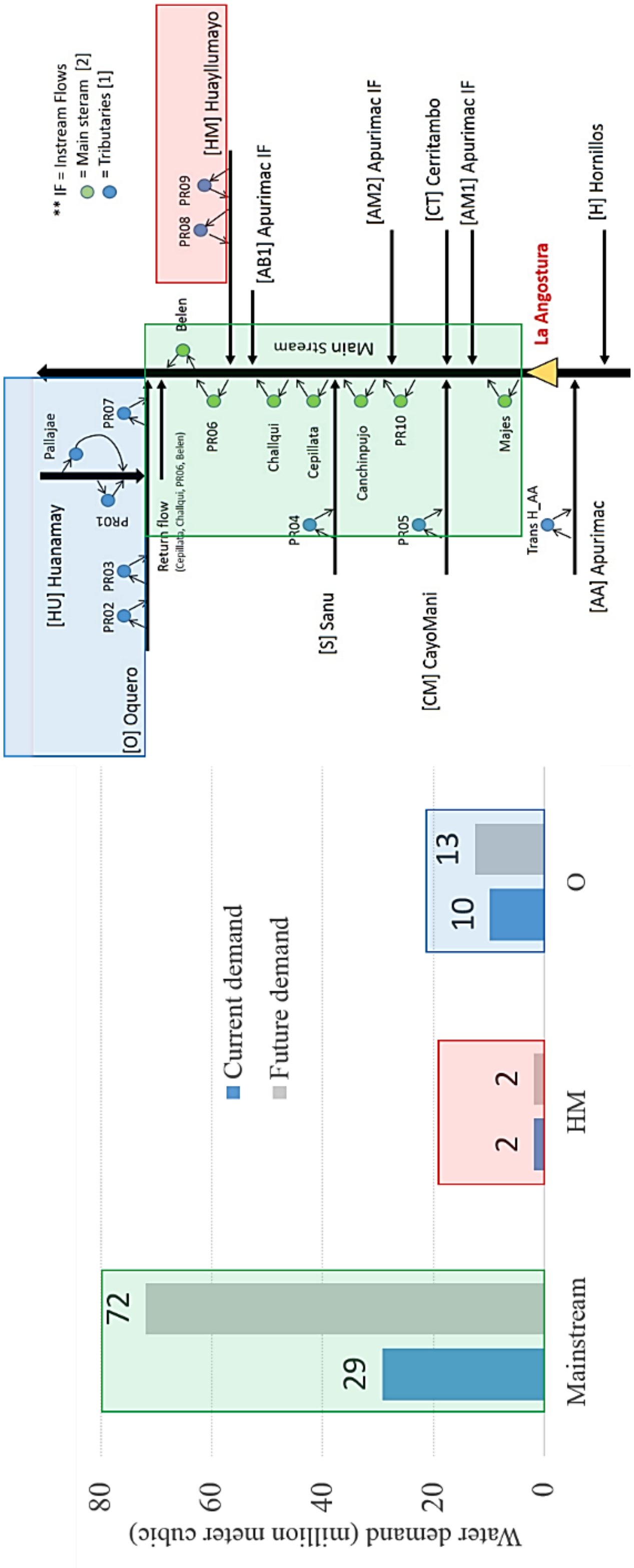


Figure 16. Current and future water demands in the Apurimac River Basin

5. Results

How can we meet the water needs of a rapidly growing urban population in Peru? It is important to assess the effectiveness of reservoir construction. Comparison is made in the results of how well the current and future water demands are satisfied with and without reservoir. To aid in providing a better water supply, a simulation model was developed and applied to demonstrate alternative scenarios for operating one potential reservoir at La Angostura in the Apurimac River. For running scenarios, the synthetic data from 1965 to 2020 are used for current and future water demands.

By running the current scenario (with current water demands), all of the water demands are met with or without reservoir (see Figure 17). Water demands in Sub-catchments HM and O are not part of the mainstream so water supply comes from the precipitation.

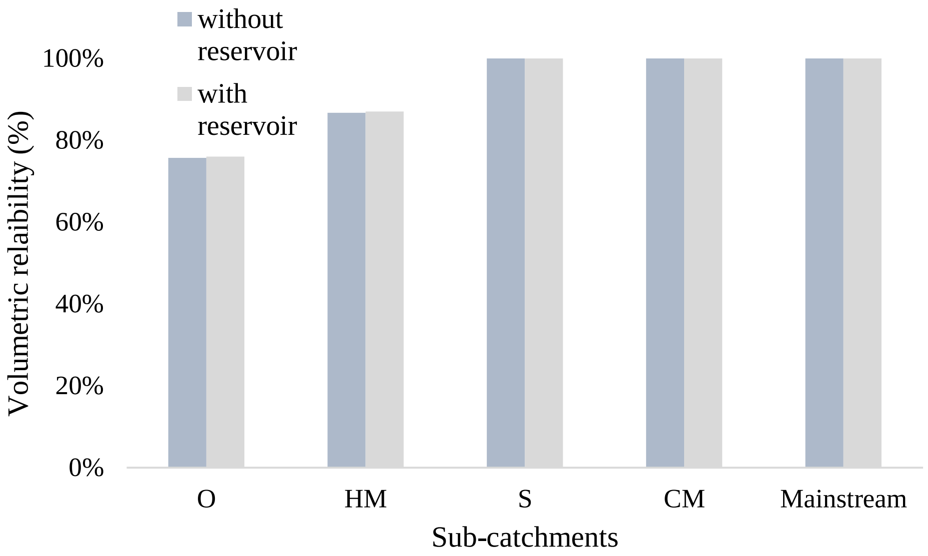


Figure 17. Comparison of current water volumetric reliability with and without reservoir in the current scenario

In the future with higher water demands, it is clearly shows that reservoir improves the volumetric reliability by satisfying most of water demands. However, in catchment O no improvement is shown because with reservoir values are the mean value of dry, median, and wet season and also this region is ranked in low priority (see Figure 18).

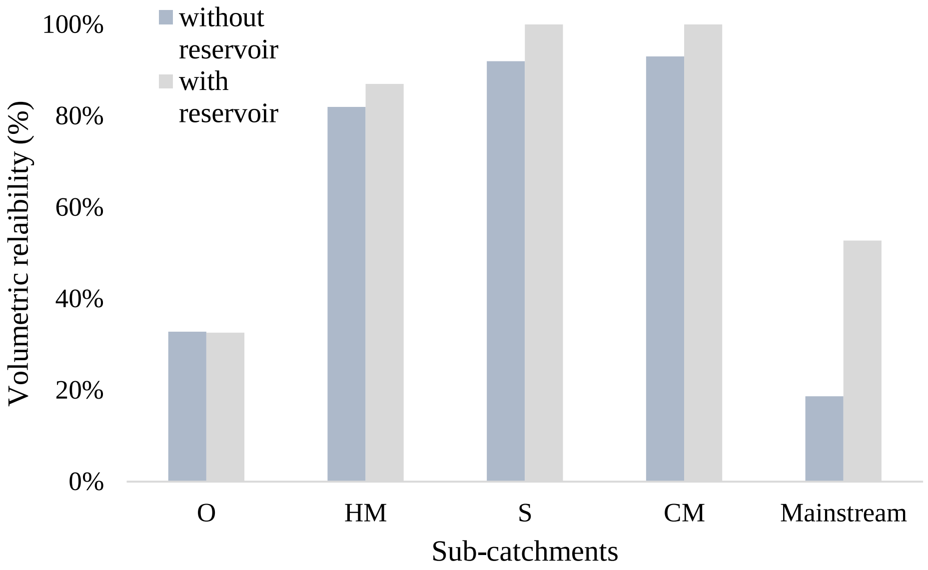


Figure 18. Comparison of current water volumetric reliability with and without reservoir in the future scenario

In the future scenario, the volumetric reliability are much lower compared to the current volumetric reliability in all sub-catchments (see Figure 18). Especially in the main stream, water demands cannot be met without reservoir. Even with the reservoir, the volumetric reliability does not improve no more than 50% because there are not enough water to be supplied even with the reservoir. This is due to the lack of water supply after dispersion of water to irrigation. Total amount of water available in La Angostura is 357 million cubic meters and with 100% of reservoir, 313 million cubic meters is used for the irrigation. When we subtract that, only 44 million cubic meters is left and the water demands is 72 million cubic meters at the mainstream. Even with the reservoir, it is hard to satisfy the water demands in the mainstream. The volumetric reliability stayed the same because the amount of water demands did not change. In the near future with higher water demands, it is clearly shows that reservoir improves the volumetric reliability by satisfying more water demands.

With significantly lower water demands and with and lower priority, sub-catchment O Also, due to the seasonality. These two sub-catchments are not part of mainstream so the water demands is only satisfied by the rainfall. There is a water all year around, but there is monthly variation that does not satisfy when it is during the growing season. Despite some sub-catchments are adjacent to each other, the volumetric reliability is quite different because of monthly variation and monthly water requirement (see Figure 19). Even though it precipitates throughout the year, there is not enough water to supply when there is a demand.

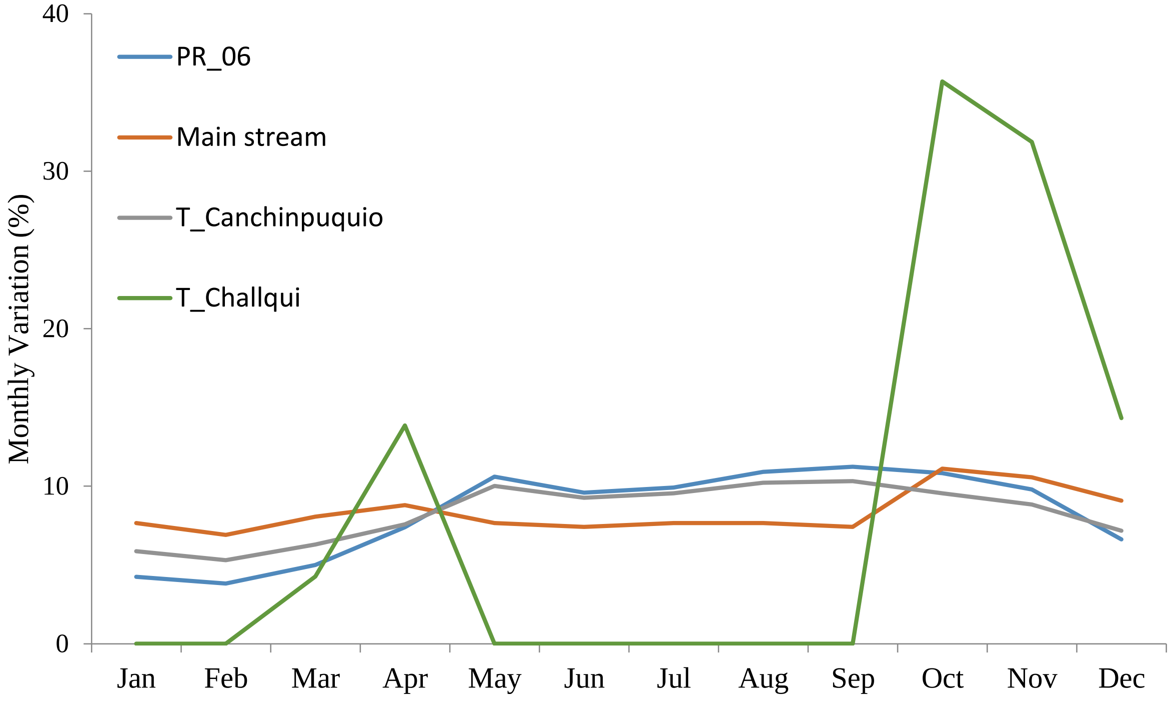


Figure 19. Monthly variation of water annual demand in the mainstream

6. Conclusions

This study demonstrates the method of using a hydrologic modeling tool to analysis the impact of water availability on the current and future water demands. The one-bucket model was proposed in this study. The calibration tool developed in this study can be potentially useful for calibrating other models. Evaluating a set of water management scenarios provided insight into the effect of potential reservoir construction and help stakeholder’s decision-making. The major points in this work are:

1. Software platforms have distinguished characteristics of serving the purpose of different objectives. It is important to understand the main purpose of developed software and have a clear judgment on which one fits the best in the individuals’ case studies.
2. Despite the uncertainties and constraints concerning the model and input data, this study shows that WEAP software offers reasonable results to assist stakeholders in developing recommendations for improved water management.
3. The newly proposed one-bucket model in this study takes both surface water processes and groundwater storage into consideration.
4. The rainfall-runoff model and water allocation models were well built in WEAP to estimate water availability and water supply for current and future water demands.
5. Without model calibration, it would have been difficult to test if adjusted parameters and predictions made with the model are reasonable.
6. The final result of verification in this study may not be the best verification, however, at the end it was presented because it was reasonable to the total annual streamflow in historical period 1976 was very similar to the total annual streamflow in 2014.

7. In the current scenario, the water demands were well satisfied with high volumetric reliability in majority of catchments. In the future scenario without the potential reservoir activated, volumetric reliability dropped dramatically because the river cannot provide enough water for all the demand sites with such a higher water demands.
8. With rising future water demands, it is clearly shown that reservoir improves the volumetric reliability by satisfying most of the demand sites. However, building a potential reservoir may not be the complete solution. Arequipa and Cuzco Regional governments should consider looking into local storages or reducing the water demands or withdrawing from another river nearby.
9. The study illustrates that the value of scenarios provide insight for integrated water resource planning and to evaluate different options for meeting the future water demands.

Several limitations exist in this case study. Improving the current data availability will improve the model. It will be a valuable asset for this model to have more stream gauge stations to collect a complete set of monthly variable that include: precipitation, temperature, wind, land use, etc. The insufficient data resource can indeed limit the research and using as set of synthetic data may have caused some uncertainties. Improvement may be found through building a reservoir or reducing water demands. Beyond the implications for the Arequipa and Cuzco regions, this study demonstrates the use of a hydrologic modeling tool to analyze the relationship between water availability and water demands. Further development and refinement of coupled hydrologic and water allocation models can be a critical step to overcome some of uncertainties of future water planning challenges.

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Appendix A. List of Hydrologic Model/ Software

Models	Description
Anuga	ANUGA is a hydrodynamic modelling tool that allows users to model realistic flow problems in complex 2D geometries.
Avulsion	Stream avulsion model
CREST	The Coupled routing and excess Storage (CREST) model is a distributed hydrologic model developed to simulate the spatial and temporal variation of atmospheric, land, surface, and subsurface water fluxes and storages by cell-to-cell simulation.
Channel-Oscillation	Simulates Oscillations in arid alluvial channels
DHSVM	DHSVM is a distributed hydrologic model that explicitly represents the effects of topography and vegetation on water fluxes through the landscape
DLBRM	Distributed Large Basin Runoff Model
DR3M	Distributed Routing Rainfall-Runoff Model - version 2
FLDTA	Simulates flow characteristics based on gradually varied flow equation
GEOtop	Distributed hydrological model, water and energy budgets
GISS GCM ModelE	GISS GCM Model
GSFLOW	Ground water and surface water flow model
Glimmer-CISM	Dynamic thermo-mechanical ice sheet model
GullyErosionProfiler1D	This model is designed to simulate longitudinal profiles
HSPF	A comprehensive package for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants
HydroTrend	Climate driven hydrological transport model
IceFlow	2D semi-implicit shallow ice approximation glacier model
LOADEST	Software for estimating constituent load in stream and rivers
Landlab	Python software framework for writing, assembling, and running 2D numerical models
MFDrouting	Multiple Flow Direction (MFD) flow routing method
MFDrouting-Successive	Successive flow routing with Multiple Flow Direction (MFD) method
MIDAS	Coupled flow - heterogeneous sediment routing model

MODFLOW	Three dimensional finite difference ground water model
Mrip	Mrip is a self-organization type model for the formation and dynamics of mega ripples in the nearshore.
OTEQ	One-dimensional transport with inflow and storage (OTIS): A Reactive Transport Model for Stream and Rivers
OTIS	One-dimensional transport with inflow and storage (OTIS): A solute transport model for streams and rivers
PIHM	A multiprocess, multi-scale hydrologic model
PRMS	Precipitation runoff modeling system
ParFlow	Parallel, high performance, integrated watershed model
Pllcart3d	3D numerical simulation of confined miscible flows
RHESSsys	Regional Hydro Ecologic Simulation System
SPARROW	The SPARROW Surface water-quality model
SWMM	1D gradually varied flow routine
SWAT	A river basin scale model developed to quantify the impact of land management practices in large, complex watersheds
SWMM	Storm water management model
TELEMAC	a powerful integrated modeling tool for use in the field of free-surface flows
TopoFlow	Spatially distributed, D8-based hydrologic model
TwoPhaseEulerSedFoam	Snowmelt process component (Degree day method) for a D8-based, spatial hydrologic model
UEB	The Utah Energy Balance (UEB) Grid snowmelt model
VIC	Variable Infiltration Capacity (VIC) is a macroscale hydrologic model that solves full water and energy balances

Appendix B. Climate Data

Table B.1 Monthly average precipitation in twenty catchments

Sub - catchments	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AA1	318.0	314.4	243.1	116.6	26.0	20.9	19.3	41.6	57.1	89.8	150.5	205.7
AA2	306.4	303.3	235.8	110.6	24.4	19.6	18.1	39.2	54.2	85.2	141.2	195.7
AB1	248.2	247.7	199.3	80.6	16.4	13.2	12.5	27.1	39.6	61.6	94.7	145.6
AM1	278.5	276.7	218.3	96.2	20.6	16.5	15.4	33.4	47.2	73.9	118.9	171.7
AM2	265.3	264.1	210.0	89.4	18.7	15.1	14.1	30.6	43.9	68.5	108.4	160.3
CM1	306.6	303.5	235.9	110.7	24.4	19.7	18.2	39.2	54.3	85.3	141.4	195.9
CT1	291.8	289.4	226.7	103.1	22.4	18.0	16.7	36.1	50.6	79.3	129.6	183.2
H1	352.6	347.5	264.8	134.4	30.8	24.8	22.7	48.7	65.9	103.9	178.2	235.6
H2	316.8	313.2	242.3	115.9	25.8	20.8	19.2	41.3	56.8	89.4	149.6	204.7
H3	318.2	314.6	243.2	116.7	26.0	20.9	19.3	41.6	57.2	90.0	150.7	205.9
H4	322.6	318.8	245.9	118.9	26.6	21.4	19.7	42.5	58.3	91.7	154.2	209.7
H5	291.9	289.5	226.7	103.1	22.4	18.0	16.7	36.1	50.6	79.3	129.6	183.2
HM	277.6	275.8	217.7	95.8	20.4	16.5	15.3	33.2	47.0	73.5	118.2	170.9
HU1	298.3	295.6	230.7	106.4	23.3	18.7	17.4	37.5	52.2	81.9	134.8	188.8
HU2	264.0	262.8	209.2	88.8	18.6	14.9	14.0	30.4	43.6	68.0	107.3	159.2
O1	304.7	301.7	234.7	109.7	24.2	19.4	18.0	38.8	53.8	84.5	139.9	194.3
O2	286.8	284.6	223.5	100.5	21.7	17.5	16.2	35.1	49.3	77.3	125.6	178.9
S1	313.3	309.9	240.1	114.1	25.3	20.4	18.8	40.6	56.0	87.9	146.7	201.6
S2	320.7	317.0	244.8	118.0	26.4	21.2	19.5	42.1	57.8	90.9	152.7	208.1
S3	285.9	283.7	222.9	100.0	21.6	17.4	16.1	34.9	49.1	76.9	124.8	178.0

Table B.2 Monthly average temperature in twenty catchments

Sub - catchments	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AA1	7.4	7.2	6.0	5.7	2.8	1.0	0.5	2.3	4.2	6.5	7.3	7.9
AA2	7.9	7.6	6.5	6.3	3.6	1.8	1.4	3.1	4.9	7.0	7.7	8.3
AB1	10.1	9.9	9.2	9.2	7.4	6.0	5.7	6.9	8.4	9.9	10.2	10.5
AM1	7.5	7.3	6.1	6.0	3.2	1.3	0.9	2.3	4.1	6.1	6.7	7.5
AM2	8.1	7.8	6.7	6.7	4.1	2.3	2.0	3.3	5.0	6.9	7.4	8.1
CM1	6.4	6.0	4.7	4.5	1.1	-1.0	-1.5	0.2	2.2	4.6	5.4	6.3
CT1	7.0	6.7	5.4	5.3	2.2	0.2	-0.2	1.3	3.2	5.4	6.1	7.0
H1	6.1	5.8	4.4	4.0	0.6	-1.5	-2.1	0.1	2.1	4.8	5.8	6.6
H2	7.5	7.2	6.0	5.8	2.9	1.1	0.6	2.4	4.2	6.5	7.3	7.9
H3	7.4	7.1	6.0	5.7	2.8	1.0	0.5	2.3	4.2	6.5	7.2	7.9
H4	7.2	7.0	5.8	5.5	2.5	0.7	0.2	2.0	3.9	6.3	7.1	7.7
H5	8.4	8.2	7.2	7.0	4.5	2.8	2.5	4.0	5.8	7.7	8.4	8.8
HM	9.0	8.8	7.8	7.7	5.5	3.9	3.5	5.0	6.6	8.4	9.0	9.4
HU1	6.7	6.4	5.1	5.0	1.7	-0.3	-0.8	0.9	2.8	5.0	5.8	6.7
HU2	8.1	7.9	6.8	6.8	4.2	2.4	2.1	3.4	5.1	6.9	7.5	8.1
O1	8.2	8.0	6.9	6.8	4.1	2.3	1.9	3.5	5.3	7.3	8.0	8.6
O2	8.6	8.4	7.4	7.3	4.9	3.2	2.8	4.4	6.1	8.0	8.6	9.0
S1	7.6	7.4	6.2	6.0	3.1	1.3	0.9	2.6	4.5	6.7	7.5	8.0
S2	7.3	7.1	5.9	5.6	2.7	0.8	0.3	2.2	4.0	6.3	7.1	7.8
S3	8.7	8.4	7.4	7.3	4.9	3.3	2.9	4.4	6.1	8.0	8.6	9.1

Table B.3 Precipitation sensitivity analysis at La Angostura (CP-01)

Precipitation Factor	Predicted Volume	Observed Volume	Difference	
			(million cubic meters)	(%)
0.5	120	347	-227	-65
0.6	156	347	-191	-55
0.7	196	347	-151	-44
0.8	243	347	-104	-30
0.9	298	347	-49	-14
1.0	364	347	17	5
1.1	439	347	92	27
1.2	523	347	176	51
1.3	617	347	270	78
1.4	718	347	371	107

Table B.4 Temperature sensitivity analysis at La Angostura (CP-01)

Temperature Factor	Model Volume	Measured Volume	Difference	
			(million cubic meters)	(%)
0.1	348	347	-1	-0.3
0.2	331	347	16	4.6
0.3	315	347	32	9.2
0.4	300	347	47	13.5

Table B.5 Average relative humidity and average wind velocity

	Relative Humidity (%)	Wind Velocity (m/s)
Jan	67	4.5
Feb	69	4.6
Mar	63	4.4
Apr	57	4.4
May	44	4.6
Jun	38	4.9
Jul	36	5.7
Aug	35	5.0
Sep	39	5.2
Oct	41	5.7
Nov	44	5.5
Dec	57	5.1

Table B.6 Latitude, melting point, freezing point, and initial snow

Sub -catchments	Latitude	Melting Point (C)	Freezing Point (C)	Initial Snow (mm)
H1	-15.45	4	0	0
H2	-15.38	4	0	0
H3	-15.33	4	0	0
H4	-15.38	4	0	0
H5	-15.26	4	0	0
AA1	-15.3	4	0	0
AA2	-15.17	4	0	0
CM1	-15.03	5	0	0
AM1	-15.13	5	0	0
AM2	-14.96	5	0	0
CT1	-15.03	5	0	0
S1	-14.88	5	0	0
S2	-14.99	5	0	0
S3	-14.9	5	0	0
AB1	-14.87	5	0	0
HU1	-14.67	5	0	0
HU2	-14.71	5	0	0
O1	-14.82	5	0	0
O2	-14.76	5	0	0
HM	-14.96	5	0	0

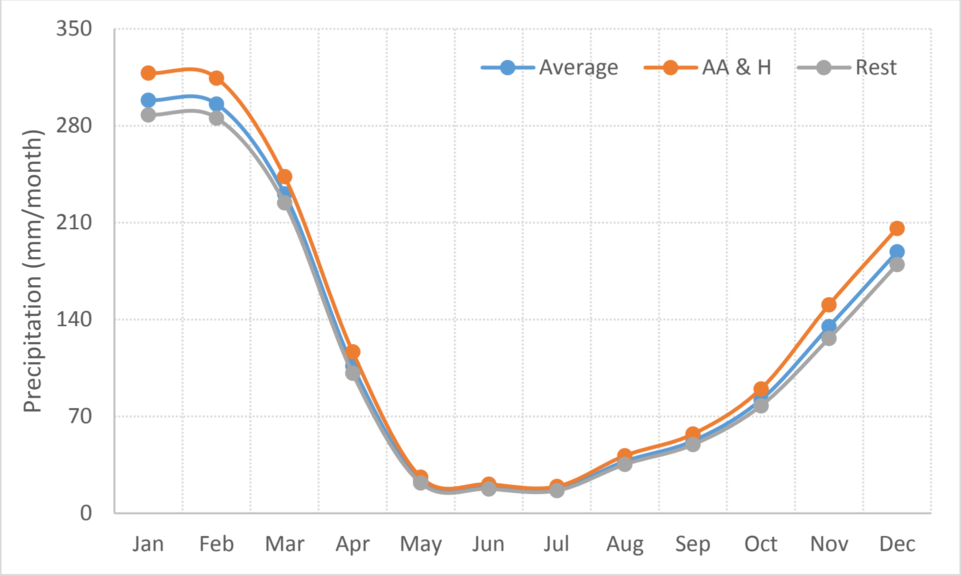


Figure B.1 Comparison of a monthly average precipitation

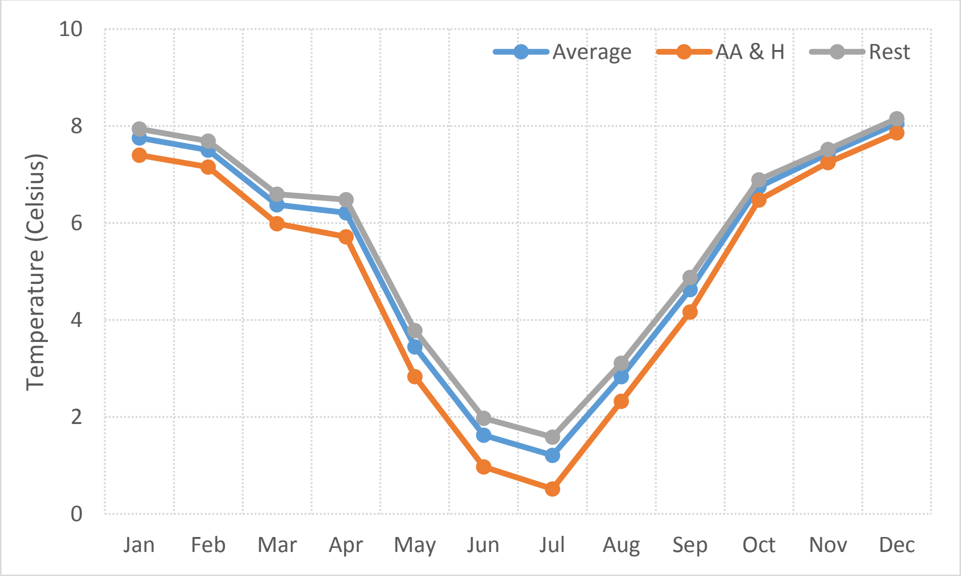


Figure B.2 Comparison of a monthly average temperature

Appendix C. Land Use Data

Table C.1 Percentage of land use

Sub - catchments	Land Use	Percentage of Area
AA1	Unvegetated	26
	Grasslands - Rocky outcrops	19
AA2	Unvegetated	27
	Pajonales - Rocky outcrops	20
AB1	Crop - Natural Pastures	26
	Pajonaies - Rocky outcrops	26
AM1	Pajonaies - Rocky outcrops	56
	Rocky outcrops	25
AM2	Pajonales - Rocky outcrops	51
	Rocky outcrops	17
CM1	Unvegetated	26
	Rocky outcrops	25
CT1	Unvegetated	31
	Rocky outcrops	22
H1	Unvegetated	59
	Grasslands - Rocky outcrops	22
H2	Grasslands - Rocky outcrops	38
	Cesped de pun - rocky outcrops	34
H3	Grasslands - Rocky outcrops	29
	Cesped de pun - rocky outcrops	24
H4	Grasslands - Rocky outcrops	34
	Unvegetated	24
H5	Rocky outcrops	23
	Pajonales - Rocky outcrops	22
HM	Crop - Natural Pastures	41
	Pajonales - Rocky outcrops	31
HU1	Rocky outcrops	77
	Bofedales	8
HU2	Rocky outcrops	37
	Crop - Natural Pastures	21
O1	Rocky outcrops	51
	Cesped de pun - rocky outcrops	18
O2	Rocky outcrops	55
	Pajonales - Rocky outcrops	26
S1	Cesped depuna - pajonales	43
	Unvegetated	19
S2	Unvegetated	28
	Cesped depuna - pajonales	17
S3	Pajonales - Rocky outcrops	38
	Rocky outcrops	22

Table C.2 Monthly crop coefficient in different types of land use

Type of Land Use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Natural grassland	0.30	0.75	0.75	0.75	0.75	0.75	0.30	0.75	0.75	0.75	0.75	0.75
Meadows	0.90	0.95	0.95	0.95	0.95	0.95	0.90	0.95	0.95	0.95	0.95	0.95
Grassland and meadows	0.60	0.60	0.60	1.20	1.20	1.20	1.00	1.00	1.00	0.60	0.60	0.60
Tall grass	0.90	0.95	0.95	0.95	0.95	0.95	0.90	0.95	0.95	0.95	0.95	0.95
Meadows without vegetation	0.90	0.95	0.95	0.95	0.95	0.95	0.90	0.95	0.95	0.95	0.95	0.95
Meadows	1.05	1.05	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Rock and soils	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Without vegetation	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Grassland and grass	0.60	0.60	0.60	1.20	1.20	1.20	1.00	1.00	1.00	0.60	0.60	0.60
Rocky outcrops	0.90	0.95	0.95	0.95	0.95	0.95	0.90	0.95	0.95	0.95	0.95	0.95
High grass, rock and soils.	1.05	1.05	1.05	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Agricultural crops and natural grass	0.40	0.40	0.30	0.30	0.30	0.30	0.30	0.40	1.15	1.15	1.00	1.00
Grass rocky outcrops	0.60	0.60	0.60	1.20	1.20	1.20	1.00	1.00	1.00	0.60	0.60	0.60
Crop, grass, naturally irrigated	0.60	0.60	0.60	1.20	1.20	1.20	1.00	1.00	1.00	0.60	0.60	0.60
Grass without vegetation	0.60	0.60	0.60	1.20	1.20	1.20	1.00	1.00	1.00	0.60	0.60	0.60

Table C.3 Root zone conductivity

Sub - catchments		Default Value (mm)	Adjustment (mm)	Root Zone Capacity (mm)
Hornillos	H1	150	200	350
	H2	180	200	380
	H3	180	200	380
	H4	275	200	475
	H5	180	200	380
Alto Apurímac	AA1	180	200	380
	AA2	200	100	300
Apurímac Instream Flow	AM1	180	200	380
	AM2	250	100	350
CayoMani	CM1	200	150	350
Cerritambo	CT1	230	200	430
Sañu	S1	230	300	530
	S2	110	270	380
	S3	150	400	550
Apurímac Instream Flow	AB1	260	0	260
Huayllumayo	HM1	130	200	330
Oquero	O1	200	400	600
	O2	130	400	530
Huanamayo	HU1	180	400	580
	HU2	130	400	530

Table C.4 Preferred flow direction

Sub - catchments	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H1	0	0.1	0.28	0.1	0.1	0.3	0.3	0.4	0.1	0.1	0.1	0.1
H2	0	0.1	0.28	0.1	0.1	0.3	0.3	0.4	0.1	0.1	0.1	0.1
H3	0	0.1	0.28	0.1	0.1	0.3	0.3	0.4	0.1	0.1	0.1	0.1
H4	0	0	0.28	0.1	0.1	0.3	0.3	0.4	0.1	0.1	0.1	0.1
H5	0	0	0.28	0.1	0.1	0.3	0.3	0.4	0.1	0.1	0.1	0.1
AA1	0.4	0.18	0.31	0.35	0.25	0.3	0.7	0.95	0.65	0.6	0.3	0.15
AA2	0.4	0.18	0.31	0.3	0.25	0.3	0.75	0.95	0.65	0.45	0.25	0.15

Table C.5 Runoff resistance factor

Sub-catchments	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H1	6.0	6.0	10.0	9.8	9.8	9.8	9.6	8.8	9.5	8.8	8.8	9.4
H2	6.0	6.0	10.0	9.8	9.8	9.8	9.6	8.8	9.5	8.8	8.8	9.4
H3	6.0	6.0	10.0	9.8	9.8	9.8	9.6	8.8	9.5	8.8	8.8	9.4
H4	6.0	6.0	10.0	9.8	9.8	9.8	9.4	8.8	9.5	8.8	8.8	9.4
H5	6.0	6.0	10.0	9.8	9.8	9.8	9.4	8.8	9.5	8.8	8.8	9.4
AA1	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
AA2	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
AM1	9.8	9.8	3.0	4.0	1.0	1.0	0.5	1.0	1.0	4.0	6.0	6.0
AM2	9.8	9.8	3.0	4.0	0.5	0.5	0.5	1.0	1.0	4.0	6.0	6.0
CM1	8.0	9.8	2.0	9.8	9.8	1.0	0.5	1.0	1.0	8.0	8.0	8.0
CT1	10.0	10.0	3.5	9.5	9.5	1.0	0.5	8.0	8.0	8.0	8.0	8.0
S1	9.8	9.5	4.5	8.8	9.0	9.0	9.0	5.0	5.0	6.0	6.0	6.0
S2	9.8	9.5	4.5	8.8	9.0	9.0	9.0	5.0	5.0	6.0	6.0	6.0
S3	9.8	9.5	4.5	8.8	9.0	9.0	9.0	5.0	5.0	6.0	6.0	6.0
AB1	9.5	9.6	6.0	8.8	1.0	1.0	1.0	1.0	1.0	1.0	2.0	3.0
HM1	9.8	10.0	6.5	8.8	2.0	2.0	1.0	1.0	1.0	3.0	3.5	4.0
O1	9.8	9.8	5.5	9.8	9.8	9.8	9.4	8.5	9.8	9.8	9.8	9.8
O2	9.8	9.8	5.5	9.8	9.8	9.8	9.4	8.5	9.8	9.8	9.8	9.8
HU1	9.8	9.6	5.5	9.8	9.8	9.8	9.4	7.8	7.8	8.0	8.0	8.0
HU2	9.8	9.6	5.5	9.8	9.8	9.8	9.4	7.8	7.8	8.0	8.0	8.0

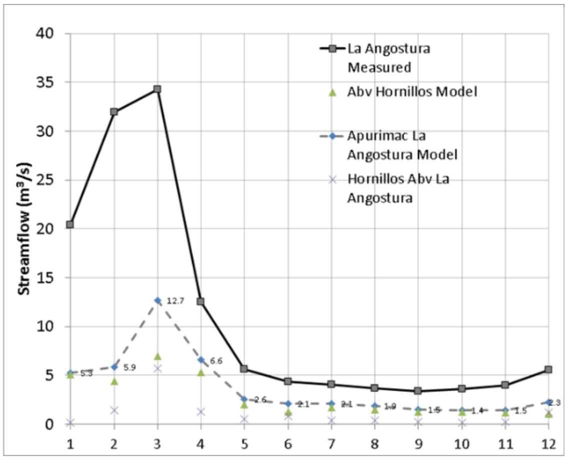
Table C.6 Default and adjusted values of soil water capacity

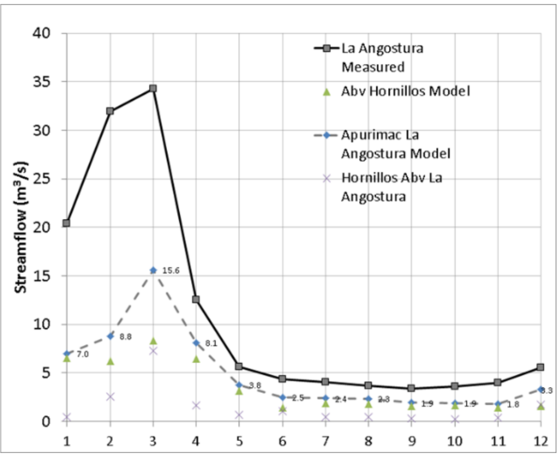
Sub - catchments		Default value (mm)	Adjustment (mm)	Soil water capacity (mm)
Hornillos	H1	150	250	400
	H2	180	326	506
	H3	220	280	500
	H4	275	255	530
	H5	180	314	494
Alto Apurímac	AA1	250	150	400
	AA2	200	234	434
Apurímac Instream Flow	AM1	150	200	350
	AM2	150	200	350
CayoMani	CM1	130	100	230
Cerritambo	CT1	234	200	434
Sañu	S1	135	100	235
	S2	180	200	380
	S3	130	200	330
Apurímac Instream Flow	AB1	215	0	215
Huayllumayo	HM1	200	300	500
Oquero	O1	130	200	330
	O2	130	400	530
Huanamayo	HU1	130	400	530
	HU2	250	300	550

Appendix D. Model Parameters

Precipitation 0.5

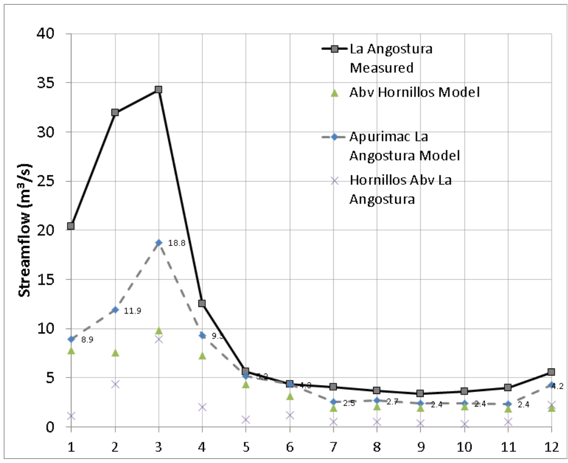
Precipitation 0.6

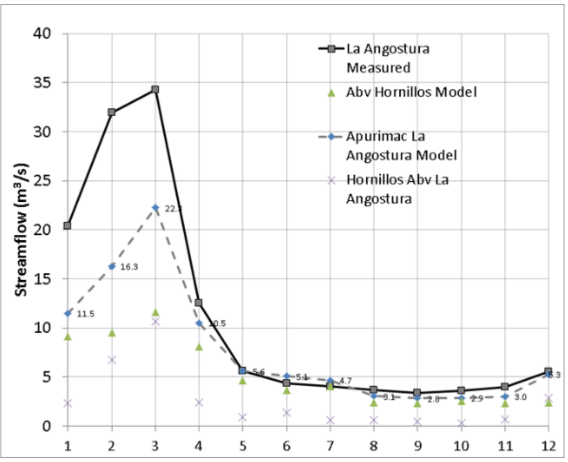




Precipitation 0.7

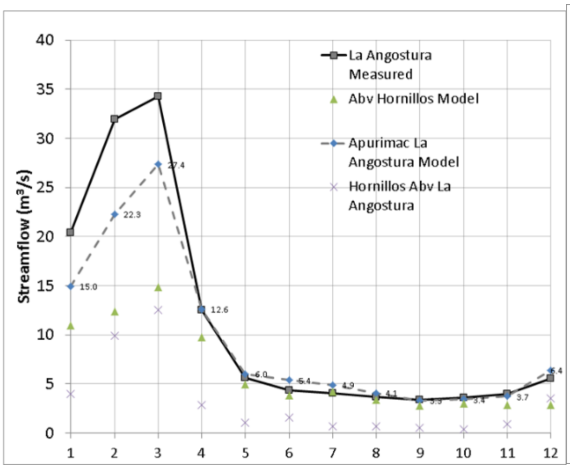
Precipitation 0.8

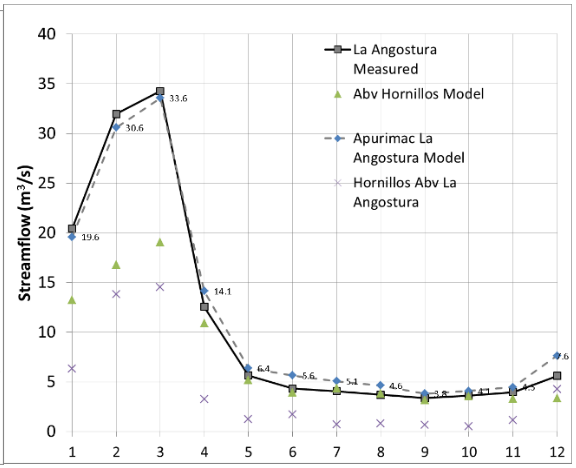




Precipitation 0.9

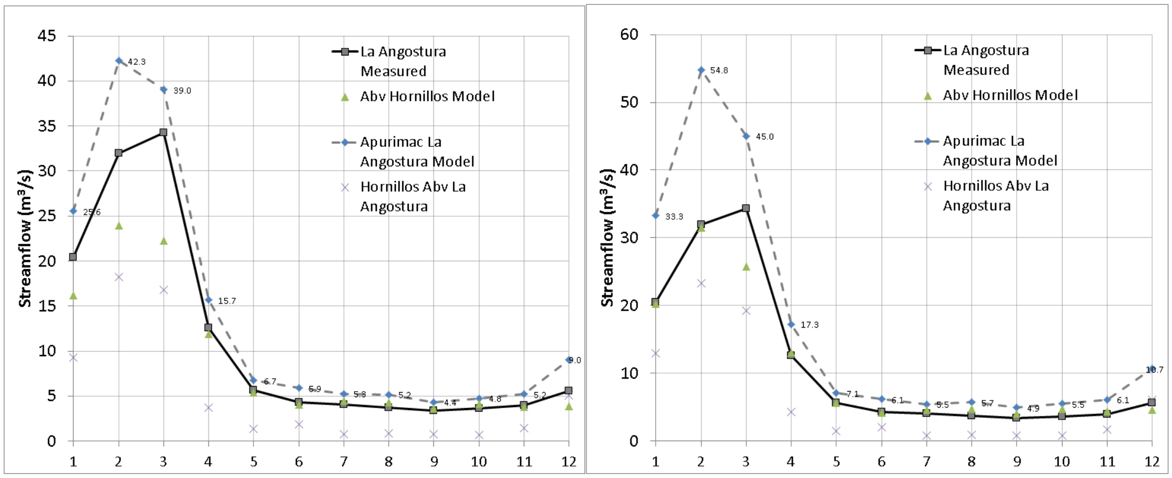
Precipitation 1.0





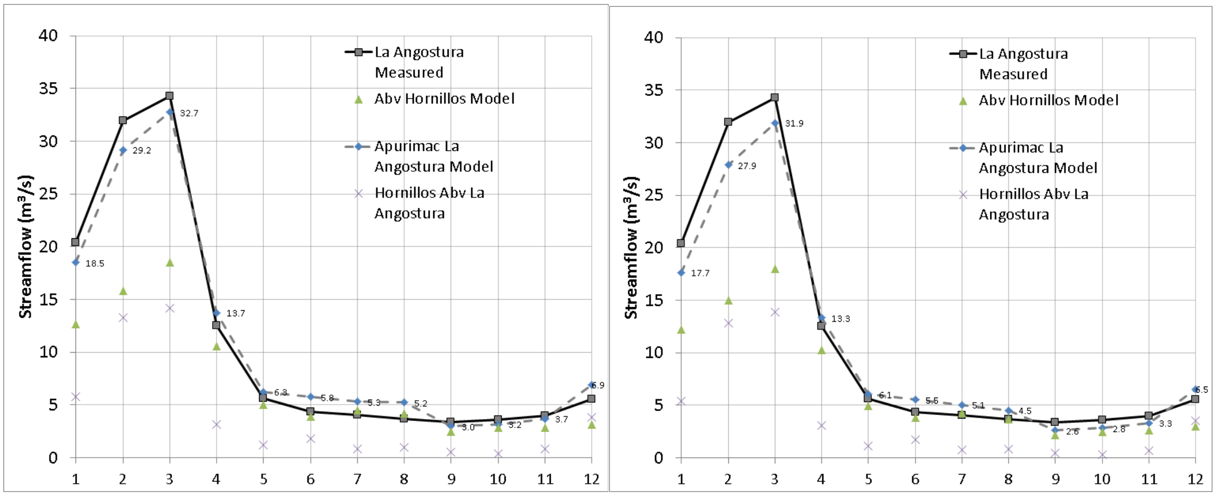
Precipitation 1.1

Precipitation 1.2



Temperature + 0.1 = 0.6 ~ 0.7

Temperature + 0.2 = 0.7 ~ 0.8



Temperature + 0.3 = 0.8 ~ 0.9

Temperature + 0.4 = 0.9 ~ 1.0

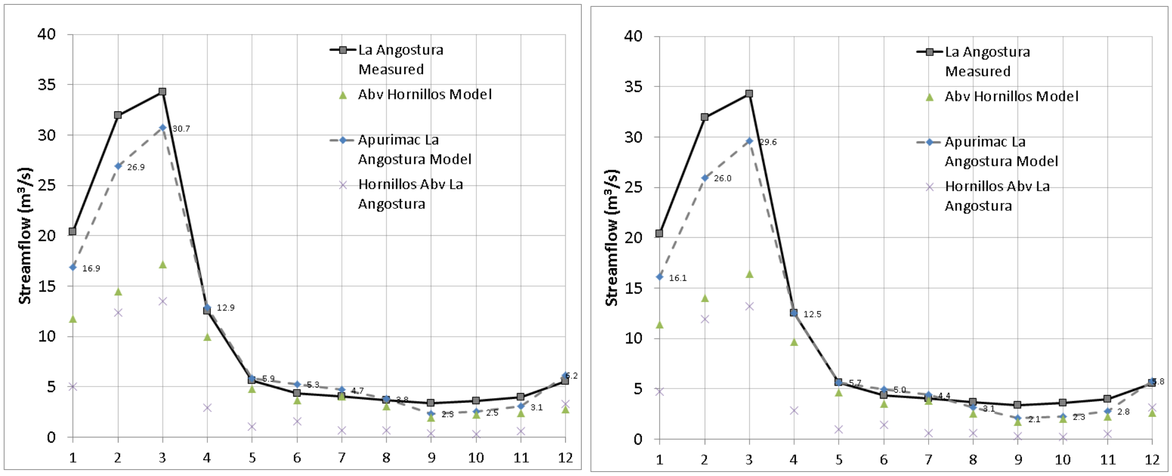


Figure D.1 Sensitivity analysis in precipitation and temperature

Appendix E. Calibration and Validation

Table E.1 Calibrated values of predicted streamflow (a)

	(H1-H5)	(AA1-AA2)		(CM1)	(CT1)	(AM1)	(AM2)		
Month	Hornillos	Alto Apurimac	La Angostura	Cayo Mani	CerriTambo	AM1	AM2	IF	3 Cañones Apurimac
Jan	17	35	52	14	3	1	2	3	72
Feb	33	41	74	15	5	3	3	6	100
Mar	39	51	90	24	7	15	7	22	143
Apr	8	28	37	3	2	2	1	3	45
May	3	14	17	1	1	1	1	3	22
Jun	4	10	15	1	1	1	1	1	18
Jul	2	12	14	1	1	1	1	2	17
Aug	2	10	12	1	0.2	1.1	0.4	1	15
Sep	1	8	9	3	0.3	2.2	0.8	3	15
Oct	1	10	11	1	0.5	0.1	0.1	0	13
Nov	3	9	12	3	1.0	0.1	0.3	0	15
Dec	6	9	15	5	1.7	0.5	0.7	1	22
Total	120	236	357	71	24	29	18	46	498

Table E.2 Calibrated values of predicted streamflow (b)

	(S1-S3)	(HM)	(AB1)		(HU1-HU2)	(O1-O2)	
Month	Sañu	Huayllumayo	IF	Yauri Apurimac	Huanamay	Oquero	Salida Apurimac
Jan	14	2	8	96	8	17	113
Feb	20	4	14	138	12	22	161
Mar	28	6	16	193	18	28	220
Apr	7	2	6	59	7	11	70
May	3	2	3	29	4	5	34
Jun	1	1	1	21	2	2	23
Jul	1	1	1	19	1	1	21
Aug	1	1	1	18	1	1	20
Sep	1	1	2	19	1	2	21
Oct	2	0.3	3	18	1	3	20
Nov	4	0.5	2	22	2	5	27
Dec	7	1.2	4	35	4	8	43
Total	87	22	61	668	60	104	771

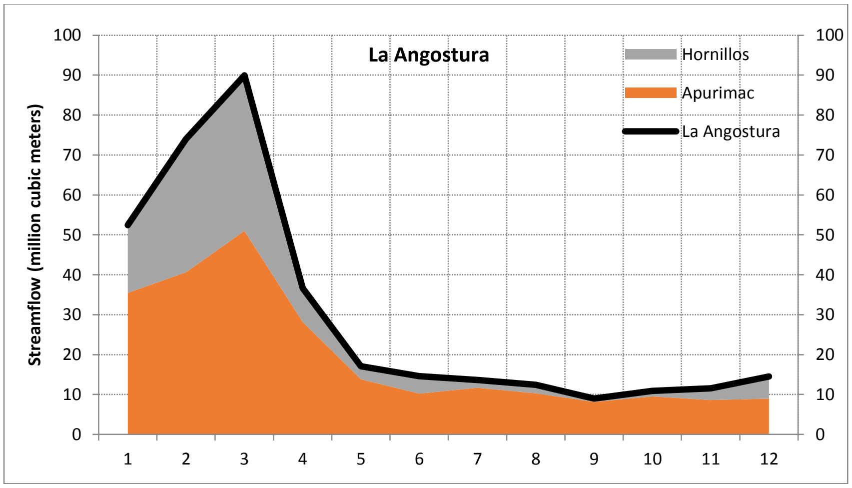


Figure E.1 Water availability at control point 1

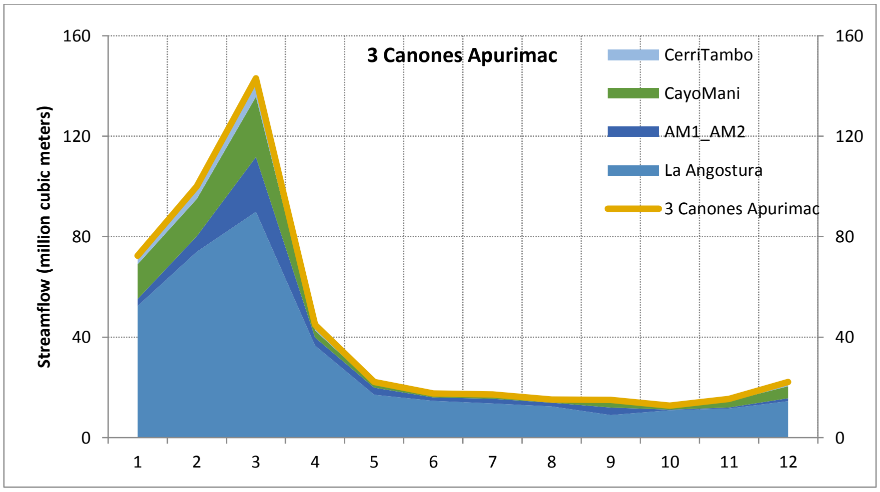


Figure E.2 Water availability at control point 2

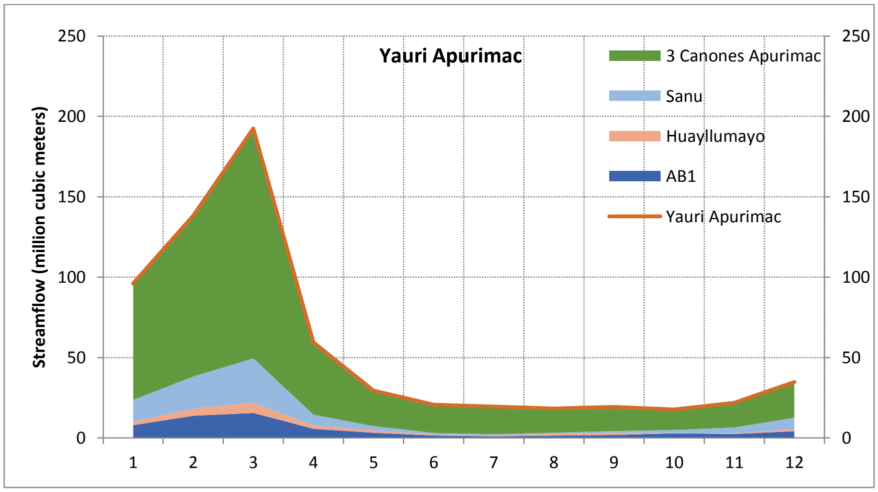


Figure E.3 Water availability at control point 3

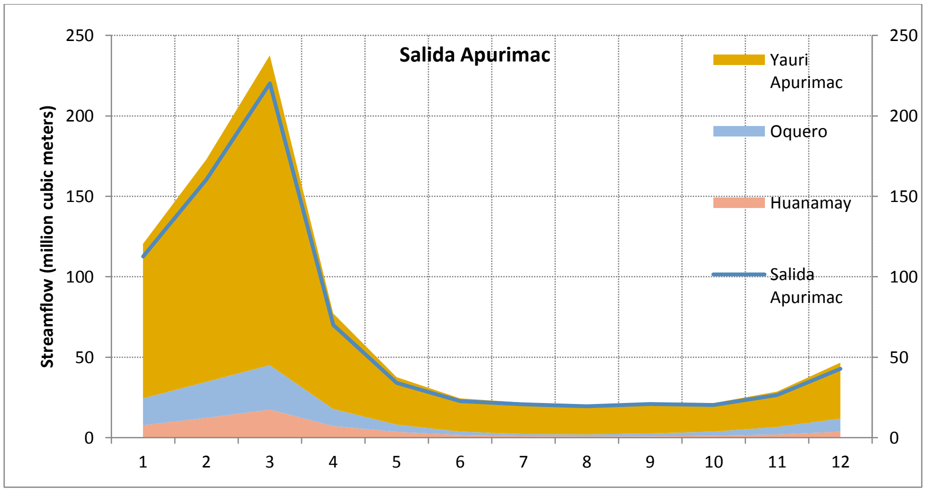


Figure E.4 Water availability at control point 4

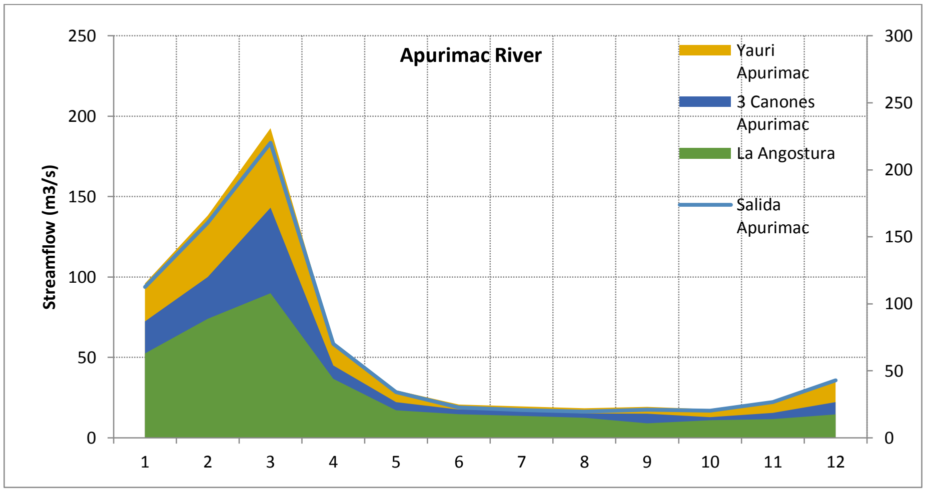


Figure E.5 Water availability at all four control points

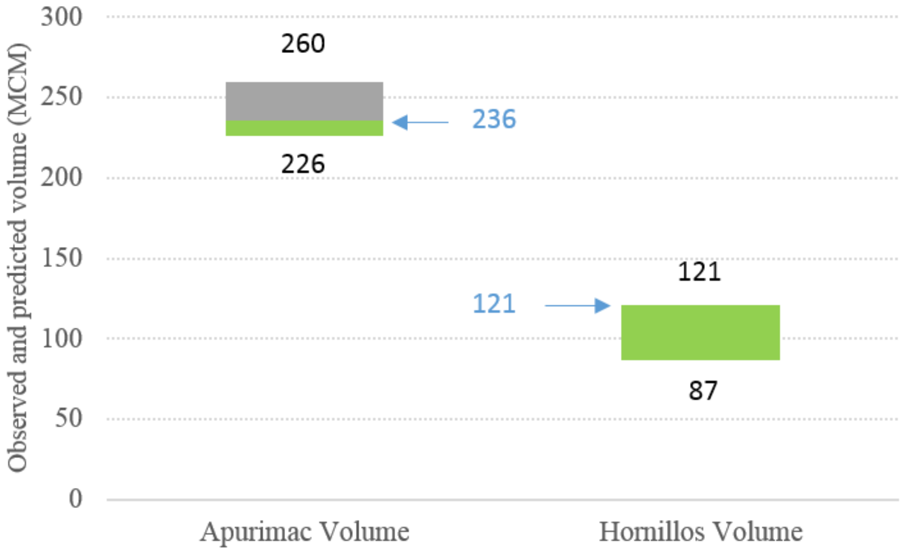
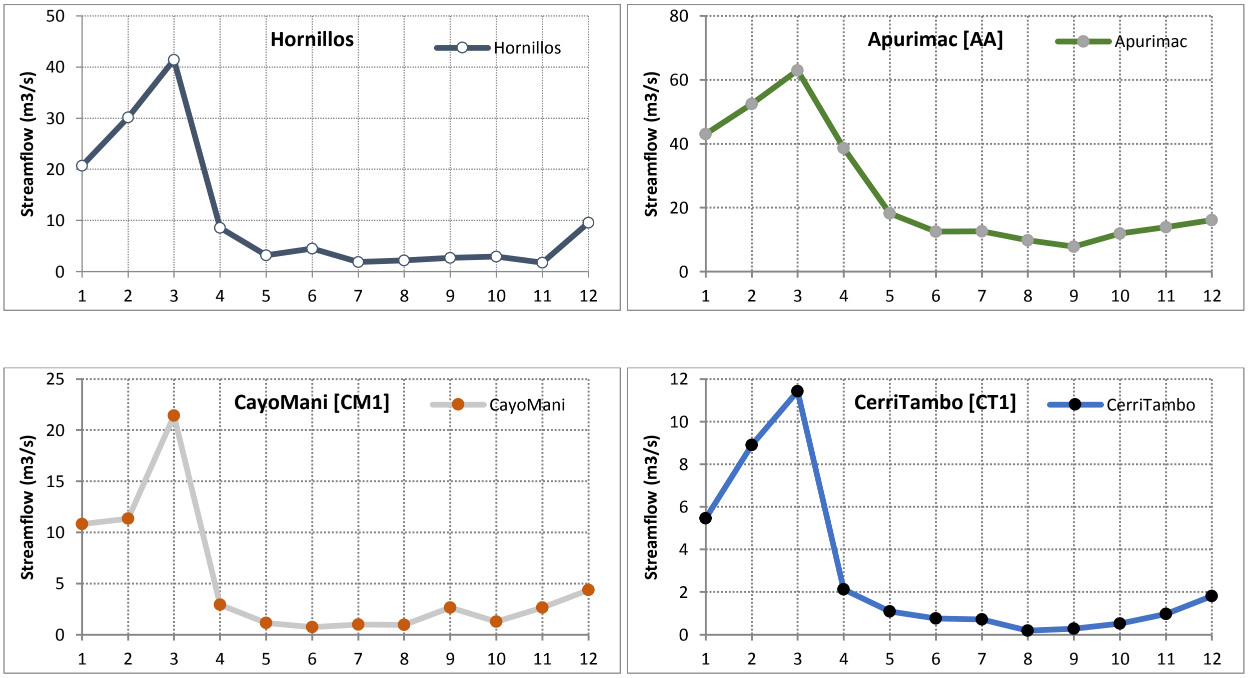


Figure E.6 Comparison of observed and predicted volume in Apurimac and Hornillos



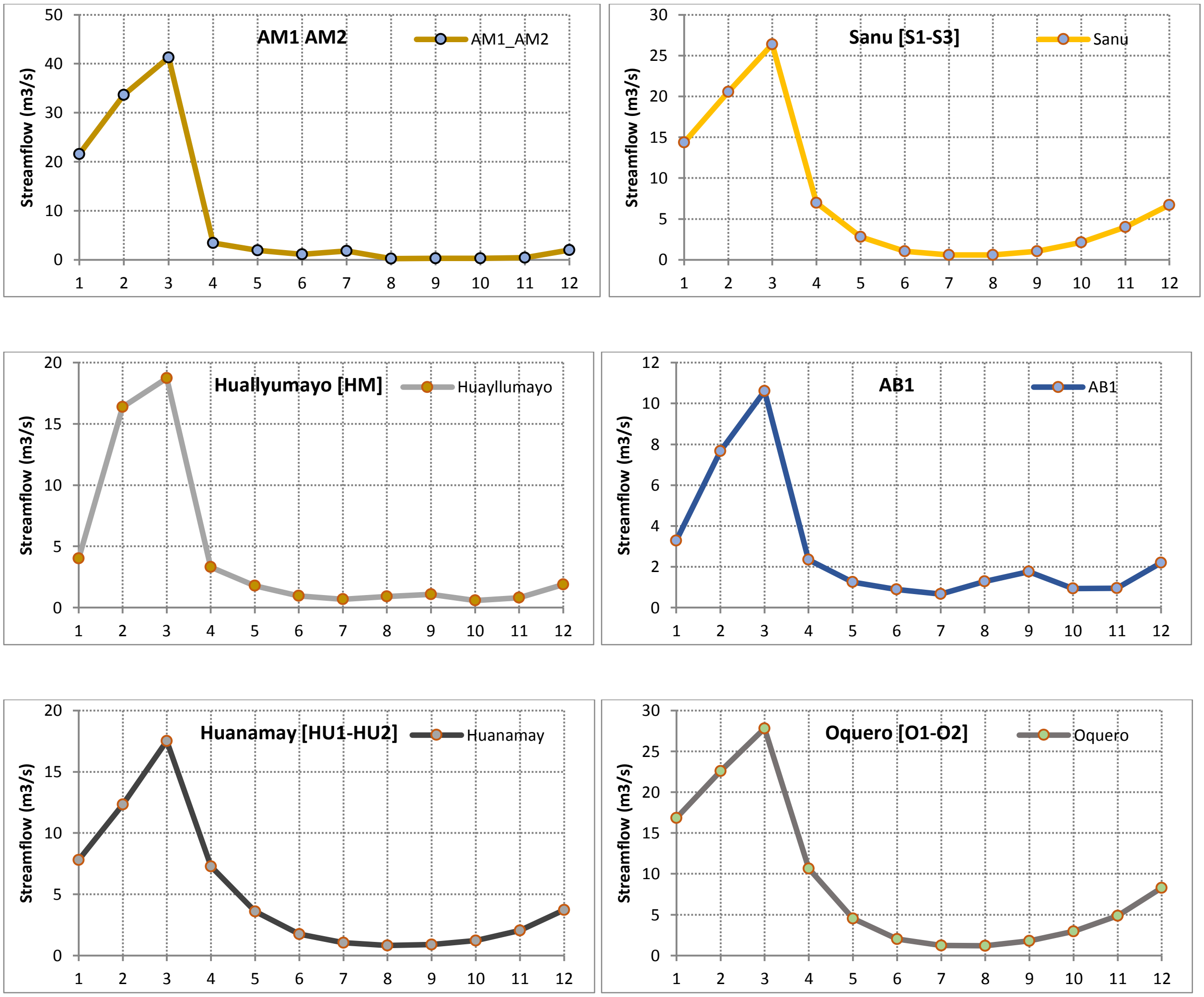


Figure E.7 Comparison of Apurimac and Hornillos shared volume and in percentage.

Appendix F. Water Management Strategies

	Scenario	Sub #Scenario	Run	Angostura Reservoir	%Actual Demand	%Future Demand	% Derivation	Hydrologic Year
1	1	1.1	1.1.1	NO	100	0	0	Dry
2			1.1.2	NO	100	0	0	Avg
3			1.1.3	NO	100	0	0	Wet
4		1.2	1.2.1	NO	0	100	0	Dry
5			1.2.2	NO	0	100	0	Avg
6			1.2.3	NO	0	100	0	Wet
7	2	2.1	2.1.1	YES	100	0	0	Dry
8			2.1.2	YES	100	0	0	Avg
9			2.1.3	YES	100	0	0	Wet
10		2.2	2.2.1	YES	0	100	0	Dry
11			2.2.2	YES	0	100	0	Avg
12			2.2.3	YES	0	100	0	Wet
13	3	3.1	3.1.1	YES	100	0	100	Dry
14			3.1.2	YES	100	0	100	Avg
15			3.1.3	YES	100	0	100	Wet
16		3.2	3.2.1	YES	0	100	100	Dry
17			3.2.2	YES	0	100	100	Avg
18			3.2.3	YES	0	100	100	Wet
19	4	4.1	4.1.1	YES	100	0	75	Dry
20			4.1.2	YES	100	0	75	Avg
21			4.1.3	YES	100	0	75	Wet
22		4.2	4.2.1	YES	0	100	75	Dry
23			4.2.2	YES	0	100	75	Avg
24			4.2.3	YES	0	100	75	Wet
25	5	5.1	5.1.1	YES	100	0	60	Dry
26			5.1.2	YES	100	0	60	Avg
27			5.1.3	YES	100	0	60	Wet
28		5.2	5.2.1	YES	0	100	60	Dry
29			5.2.2	YES	0	100	60	Avg
30			5.2.3	YES	0	100	60	Wet
31	6	6.1	6.1.1	YES	100	0	50	Dry
32			6.1.2	YES	100	0	50	Avg
33			6.1.3	YES	100	0	50	Wet
34		6.2	6.2.1	YES	0	100	50	Dry
35			6.2.2	YES	0	100	50	Avg
36			6.2.3	YES	0	100	50	Wet