Soil and Water Conservation in the Northern Andes of Peru

Die Konservierung von Boden- und Wasserressourcen
in den nördlichen Anden Perus

Dissertation

zur Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften
(Dr. rer. nat.)

am Fachbereich Geowissenschaften
der Freien Universität Berlin

vorgelegt von
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Berlin 2016

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Tag der Disputation: 22.07.2016

Acknowledgments

First of all, I would like to thank my supervisor Professor Achim Schulte for his support and for providing me with the opportunity to work on this topic in such a stunning region of the world. In addition, I wish to thank my 2nd supervisor Professor Robert Jüpner from Technische Universität Kaiserslautern for his guidance during this endeavor. This study is rooted in a research project funded by the Hans Sauer Stiftung. I would like to express my appreciation to the chairman Dr. Ralph Boch and the members of the advisory board: Dr. Hendrick Bölter, Dr. hc Wilhelm Ebert, Monika Sachtleben, and Dr. Ursula Sauer.

Furthermore, I would like to thank all colleagues who contributed to the research papers (in alphabetical order): Sven Abendroth, Carlos Cerdán, Edwin Pajares, Professor Michael Schneider, and Professor Achim Schulte. Special thanks goes to my supervisor Professor Achim Schulte, who proofread the manuscripts with patience and perseverance, thus ensuring their successful publication. In addition, I would like to thank Anne Beck at Freie Universität Berlin's Department of Earth Sciences for revising the English versions of the published manuscripts.

I additionally wish to thank Ana Angulo from El Centro Ecuménico y Acción Social (CEDEPAS) Norte in Cajamarca, Peru for helping me to prepare and conduct my research activities. Special thanks goes to Carlos Cerdán for his assiduous gathering of environmental data and to Edwin Pajares for assistance and networking during the periods of residence in Peru. I would also like to extend thanks to Julio Urbiola from Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), to Ubelser Lezama, Hugo Munioz and Alejandro Villanueva from Empresa Prestadora de Servicios de Saneamiento S.A. Cajamarca (E.P.S. SEDACAJ S.A.) and to Segundo Ever, a resident of Huaquillas, Peru.

I am grateful to my colleagues from the Department of Earth Sciences at Freie Universität Berlin for their productive discussions and feedback and I would also like to thank all of the Bachelor's and Master's students who assisted with the field work and who contributed with their theses to a better understanding of the environmental boundary conditions in the region of Cajamarca. These students are, in alphabetical order: Sven Abendroth, Kerstin Furchner, Jens Hartwich, Christina Hofmann, Soraya Kaiser, Hanna Krüger, Samuel Stettner, Sophia Rohde, and Sonja Taheri Rizi.

I am greatly appreciative to the Peruvian friends who supported me during the field trips and gave me the opportunity to experience Peru from a Peruvian perspective. These individuals are: Jose Davila (AKA Pepe), Helen Garcia, Victoria Bartolo, and Martín Shimizu.

Last but not least I would like to thank my family for their support and patience during recent years, including in particular my wife and beloved kids.

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A	Area
*a, a**	Coefficient
av	Vegetative parameter or index of surface-connected porosity
AC	Air capacity
AHP	Analytic Hierarchy Process
AM	April–March
ARC	Antecedent runoff conditions
ASPADERUC	Asociacion para el Desarrollo Rural de Cajamarca
ASR	Austral summer rainfall
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
*b, b**	Exponent
B.C.	Before Christ
BMBF	German Federal Ministry of Education and Research
c	Exponent
CARE	Cooperative for Assistance and Relief Everywhere
CASCUS	Conservación del agua y suelo en las cuencas de los ríos Chetillano y Ronquillo en la Sierra norte del Perú [in English: The conservation of water and soil resources in the Chetillano and Ronquillo basins in the Northern Sierra of Peru]
CIPDER	Consorcio Interinstitucional para el Desarrollo Regional

CEDEPAS	El Centro Ecuménico y Acción Social
CN	Curve number
CPC	Climate Prediction Center
CR	Consistency ratio
c_r	Runoff coefficient
c_{sr}	Specific runoff coefficient
DEM	Digital elevation model
DESIRE	Desertification mitigation and remediation of land – A global approach for local solutions
DFP	Decentralized flood protection
DJ	December–January
DJF	December–February
DJFM	December–March
DS	Dry season
DSM	Decision support model
DWR	Decentralized water retention
E	Evaporation
ε_i	Deviation of the measured runoff
EN	El Niño
ENSO	El Niño Southern Oscillation
ERSST	Extended Reconstructed Sea Surface Temperature
ETa	Actual evapotranspiration
ETp	Potential evapotranspiration
ETM	Enhanced Thematic Mapper
EPS SEDACAJ S.A.	Empresa Prestadora de Servicios de Saneamiento de Cajamarca S.A.
FAO	Food and Agriculture Organization
FC	Field capacity
GIS	Geographic Information System
GIZ	Deutsche Geschellschaft für Internationale Zusammenarbeit
H2U	Geomorphologic-unit-hydrograph based model
HEC-1	Hydrologic Engineering Center model
HSCC	Hydrologic Soil-Cover Complexes
HSG	Hydrologic Soil Groups
HRU	Hydrological Response Units
I_a	Initial abstraction
Inf_{max}	Maximum infiltration rate
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
IWRM	Integrated Water Resource Management
K	Hydraulic conductivity
k	Constant
k_{st}	Strickler roughness value
LAI	Leaf Area Index
LAPSUS	Landscape Process Modelling at Multi-Dimensions and Scales
LISEM	Limburg Soil Erosion Model
LN	La Niña

LT	Local time
m	Month
MCC	Mesoscale Convective Complex
MCE	Multi-criteria evaluation
MCS	Mesoscale Convective System
MHq	Mean maximum specific runoff
Mq	Mean specific runoff
MUSLE	Modified Universal Soil Loss Equation
n	Manning´s roughness coefficient
n_{el}	Number of elements
n_m	Numbers of months
n_{mt}	Number of measurements
n_{obs}	Number of observations
NASIM	Niederschlag-Abfluss-Simulationsmodell
NOAA	National Oceanic and Atmospheric Administration
NQ_m	Mean monthly low flow
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
ONI	Oceanic Niño Index
OND	October–December
ONDJFM	October–March
P	Precipitation, rainfall
P_{areal}	Areal precipitation
PBIAS	Percent bias error index
POT	Peak over threshold
PV	Pore volume
Q	Discharge
Q_B	Base flow
$\mathrm{Q_{int}}$	Discharge provided by the above-ground catchment area
$\mathrm{Q_{ext}}$	Discharge provided by the catchment area beyond the topographically derived catchment boundaries
R^2, r^2	Coefficient of determination
RA	Extraterrestrial radiation
RCP	Representative Concentration Pathways
RI	Random consistency index
RIW	Relative importance weight
RS	Rainy season
RSR	Ratio of the root mean square error to the standard deviation
S	Storage, potential maximum retention
SACWD	South American continental water divide
SCS-CN	Soil Conservation Service curve number method
SD	Soil depth
SENAMHI	Servicio Nacional de Meteorología e Hidrología del Perú
SI	Seasonality Index
SL	Suitability level
SLI	Suitability level index
SRTM	Shuttle Radar Topography Mission

SST	Sea surface temperature
SWAT	Soil and Water Assessment Tool
SWC	Soil and water conservation
SWCT	Soil and water conservation technique
T	Average daily temperature
TD	Temperature range
TRMM	Tropical Rainfall Measuring Mission
TMPA	TRMM Multi-satellite Prescription Analysis
UKIH	United Kingdom Institute of Hydrology
UNALM	Universidad Nacional Agraria La Molina
UNC	Universidad Nacional de Cajamarca
UNMSM	Universidad Nacional Mayor de San Marcos
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WOCAT	World Overview of Conservation Approaches and Technologies initiative
WOP	Weighted overlay process
Y	Evaluated constituent
yr^{-1}	Per year
λ	Initial abstraction ratio
λ_{max}	Maximum Eigen value

Abstract

This thesis investigates hydro-meteorological boundary conditions in the region of Cajamarca in the northern Andes of Peru and quantifies the impact of selected resource conservation measures on the hydrology of the Ronquillo watershed. The research was undertaken as part of the research project *The conservation of water and soil resources in the Chetillano and Ronquillo basins in the Northern Sierra of Peru (CASCUS)* [in Spanish: *Conservación del agua y suelo en las cuencas de los ríos Chetillano y Ronquillo en la Sierra norte del Perú*]. The project aims to identify opportunities for enhancing water availability and reducing soil erosion in the region of Cajamarca.

Geographically the research focuses on the Ronquillo watershed, which is located in the vicinity of the city of Cajamarca in the northern Andes of Peru. The water resources of the Ronquillo River are of special interest to the city of Cajamarca, as about one-third of the total urban water supply is provided by discharge from this river. However, in recent decades, a growing urban population as well as increasing water demand have resulted in severe water shortages and the interruption of water services in the city for several hours a day during the dry season. During the dry season the availability of water resources to the city of Cajamarca depends almost exclusively on the hydrological functions of nearby mountain ranges. However, the catchments surrounding the city of Cajamarca are severely affected by land degradation and soil erosion. Continued degradation and erosion of the topsoil reduces infiltration rates and water storage capacity, which in turn increases surface runoff and, correspondingly, soil erosion and further degradation. Owing to this self-reinforcing process, the natural water retarding and water storage capacity – and, by extension, the water regulation capacity – of the watersheds is in continuous decline. However, land degradation does not have to be an irreversible process and might be mitigated by the implementation of resource conservation measures.

This thesis aims to contribute to the CASCUS project by strengthening our knowledge base on hydro-meteorological boundary conditions in the research area. It also seeks to advance the envisioned integrated resource management strategy by quantifying the impact of selected resource conservation measures on the hydrology of the Ronquillo watershed. In order to achieve these objectives, research was undertaken in several stages. Specifically, these stages were: (1) the exploration of the meteorological and hydrological boundary conditions, (2) the development of scenarios for the implementation of resource conservation measures, and (3) the assessment of the hydrological impact of resource conservation measures on the catchment by applying a rainfall-runoff model.

The region under investigation is characterized by a complex mountain climate marked by the interaction of a number of meteorological features, including seasonal displacement of the Intertropical Convergence Zone, orographic rainout, rain-bearing mesoscale cloud systems, El Niño Southern Oscillation (ENSO), katabatic drainage flow and local convection, all of which act on different spatial and temporal scales. The Ronquillo watershed displays strong seasonality in stream flow. During the rainy season a large portion of stream flow originates from direct runoff, which drains the watershed rapidly. The main flood formation areas are located in the middle part of the catchment, where soil and land coverage characteristics are most prone to generate surface runoff during strong rainfall. During the dry season a large portion of the discharge of the Ronquillo River originates from the soils covering the high altitude Jalca grasslands. In addition the basement rock aquifers and spring discharge significantly contribute to the dry seasonal discharge.

The main objective of the scenario development phase is to provide implementation scenarios for selected soil and water conservation techniques (SWCTs) in the Ronquillo watershed, in order to evaluate their impact on catchment hydrology by applying a rainfall-runoff model. The present study evaluates various implementation scenarios for SWCTs, which fall under the categories "earthworks," "afforestation," and "check dam construction." The earthworks scenarios are developed on the basis of a decision support model. Therefore a multi-criteria evaluation procedure is used that takes into account environmental site assessment criteria such as meteorology, hydrology, topography, land use, and soil properties. Each environmental site assessment criterion is evaluated using a pair-wise comparison matrix method, known as the Analytical Hierarchy Process. Afforestation scenarios are developed for the planting of pine and eucalyptus species, based on the underlying hypotheses that existing tree coverage areas can build the nucleus for future afforestation and that primarily degraded areas will be subject to afforestation. For the implementation of check dams, two scenarios are developed. In the first, check dams are implemented in all stream channels, whereas in the second, check dams are implemented in intermittent stream channels only.

The impact of different SWCTs on the hydrology of the Ronquillo watershed is assessed using a hydrological modeling approach. Analysis undertaken with the NASIM rainfall-runoff model shows that earthworks (terraces and bund systems) and afforestation scenarios considerably impact the hydrology of the Ronquillo River. By contrast, the impact of check dam scenarios on catchment hydrology is comparatively small. The results imply that earthworks and afforestation reduce surface runoff, and thus mitigate the self-reinforcing process of surface runoff generation and subsequent soil erosion. However, this comes at the expense of a reduction in stream flow. On-site effects such as the reduction of overland flow and enhanced water availability for crop growth *in situ* are counterbalanced by a reduction in water availability off-site. The modeling results imply that within the framework of a water resource conservation strategy, the implementation of earthworks compared to afforestation measures is preferable, as earthworks reduce surface runoff more efficiently compared to afforestation measures, and thus have less impact on water availability downstream.

The implementation of earthworks and afforestation measures redistribute the catchment's water resources by augmenting water availability in the watershed while decreasing water availability downstream. Additional soil water provided by the implementation earthworks is stored in the soil layer and consequently evaporated or transpired by crops, but does not drain as base flow. The climatic conditions of the Ronquillo watershed do not favor long-term water storage in soils under agricultural use.

An integrated watershed management approach should be implemented to ensure optimal redistribution of water resources within the catchment area. Indeed, in the Ronquillo watershed, where water availability does not meet water demand – at least during part of the year – and environmental boundary conditions do not favor long-term water storage in the soils, such an approach is crucial for reconciling upstream and downstream environmental and economic effects during SWCT implementation.

Kurzfassung

Die Dissertation quantifiziert den Einfluss ressourcenkonservierender Maßnahmen auf die Hydrologie des Einzugsgebietes des Ronquillo in der Region Cajamarca in den nördlichen Anden Perus. Das Vorhaben ist Teil des Forschungsprojektes *Konservierung der Wasser- und Bodenressourcen in den Einzugsgebieten des Chetillano und Ronquillo in der nördlichen Sierra Perus (CASCUS)* [in Spanisch: *Conservación del agua y suelo en las cuencas de los ríos Chetillano y Ronquillo en la Sierra norte del Perú*]. Die Ziele des Projektes CASCUS sind der dezentrale Wasserrückhalt und Bodenschutz durch boden- und wasserkonservierende Maßnahmen in der Region Cajamarca. Diese Maßnahmen sollen den Oberflächenabfluss und die Bodenerosion verringern, Hochwasserspitzen reduzieren und das Grundwasservolumen als Wasserspeicher für Trockenperioden erhöhen.

Das Wasserdargebot in der Region Cajamarca wird vor allem durch das saisonale Niederschlagsregime gesteuert. Ein bedeutender Teil des Niederschlags, der in der Regenzeit fällt, fließt oberflächlich ab und führt zum Verlust der Ressourcen Wasser und Boden. Das Fehlen ausreichend großer, natürlicher Speichersysteme führt in der zweiten Jahreshälfte zu Wasserknappheit und Wachstumseinschränkungen in der Landwirtschaft. Fortschreitende Bodenerosion und -degradation verringern das Retentionsvermögen in den Einzugsgebieten und erhöhen die trockenzeitliche Wasserknappheit. Der Forschungsansatz dieser Arbeit geht davon aus, dass der Einsatz von boden- und wasserkonservierenden Maßnahmen eine Möglichkeit ist, die Retention in der Fläche zu erhöhen und dem selbstverstärkenden Prozess der Oberflächenabflussbildung sowie darauffolgender Bodenerosion entgegenzuwirken.

Während der vergangenen Dekaden verzeichnete die Stadt Cajamarca ein stetiges Bevölkerungswachstum und einen steigenden Wasserbedarf. Heute ist während der Trockenzeit die Wasserversorgung der Stadt nicht gewährleistet. Die Wasserressourcen des Ronquillo sind hierbei von besonderer Bedeutung, denn sein Abfluss trägt in etwa zu einem Drittel zu der städtischen Wasserversorgung bei.

Die Arbeit ist in folgende, aufeinander aufbauende Themenkomplexe strukturiert: Zu Beginn steht die Analyse der hydrometeorologischen Randbedingungen. Darauf folgt die Entwicklung von Implementierungsszenarien ressourcenkonservierender Maßnahmen. Schließlich bietet die Forschungsarbeit eine Quantifizierung ihrer Wirkung auf die Hydrologie des Einzugsgebietes des Ronquillo durch Anwendung des flächendetaillierten hydrologischen Modells NASIM (**N**iederschlag-**A**bfluss-**Sim**ulationsmodell).

Die Region Cajamarca ist durch ein Tageszeiten- und Gebirgsklima gekennzeichnet. Hier wirken meteorologische Phänomene auf unterschiedlichen räumlichen und zeitlichen Skalen zusammen; z.B. die jahreszeitliche Wanderung der äquatorialen Tiefdruckrinne, *El Niño*

Southern Oscillation (ENSO), große Gewitter- und Schauergebiete (*Mesoscale Convective Systems*), orographischer Niederschlag, lokale Konvektion und ein ausgeprägtes Hang- und Talwindsystem. Der Abfluss des Ronquillo ist aufgrund der hydrometeorologischen Randbedingungen stark saisonal geprägt. Ein großer Teil des Abflusses in der Regenzeit ist dem Direktabfluss (Oberflächenabfluss und schneller Zwischenabfluss) zuzuordnen. Der trockenzeitliche Abfluss wird zu einem wesentlichen Teil von den Böden der Jalca Höhenstufe (> 3500 m ü.M.) generiert. Weiter tragen lokale Aquifere und Quellschüttungen zum trockenzeitlichen Abfluss bei.

Die untersuchten boden- und wasserkonservierenden Maßnahmen gliedern sich in Maßnahmen in der Fläche: Terrassen- und Erdwallsysteme (*earthworks*) sowie Aufforstung; und Maßnahmen im Fließgewässer: die Errichtung von kleinen Rückhaltedämmen im Gerinne (*check dams*). Die Implementierungsszenarien für Terrassen und Erdwälle basieren auf einer multikriteriellen räumlichen Eignungsklassifizierung. Die Ausweisung geeigneter Flächen für Terrassen und Erdwälle erfolgt in Abhängigkeit von meteorologischen, hydrologischen und topographischen Eignungskriterien sowie der Landnutzung/-bedeckung und der Bodeneigenschaften. Aufforstungsszenarien werden für die in der Region Cajamarca weit verbreiteten Kiefern- und Eukalyptusbestände entwickelt. Die grundlegende Idee hierbei ist, dass die bereits existierenden Aufforstungsflächen die Keimzelle für weitere Aufforstungen darstellen und, dass vorrangig stark degradierte Flächen aufgeforstet werden. Für die Errichtung von Rückhaltedämmen werden zwei Szenarien entwickelt: der Einbau von Rückhaltedämmen in allen Gerinneabschnitten und der Einbau von Rückhaltedämmen in nur periodisch durchflossenen Gerinneabschnitten.

Das Niederschlag-Abfluss-Modell NASIM wird szenarienbasiert eingesetzt, um den Einfluss der untersuchten boden- und wasserkonservierenden Maßnahmen auf die Einzugsgebietshydrologie des Ronquillo zu quantifizieren. Die Modellierungsergebnisse zeigen, dass Terrassen, Erdwälle und Aufforstungen einen erheblichen Einfluss auf die Hydrologie des Ronquillo haben. Der Einfluss von Rückhaltedämmen ist hingegen von untergeordneter Bedeutung. Die Maßnahmen in der Fläche verringern die Oberflächenabflussbildung und reduzieren die Hochwasserspitzen; aber gleichzeitig nimmt die Abflussmenge ab. Die Aufforstung mit Kiefern- und Eukalyptusbeständen erhöht gegenüber der natürlichen Vegetation oder der landwirtschaftlichen Nutzung die Interzeptionsverdunstung und die Transpiration. Die höhere Transpirationsleistung der Aufforstungsflächen drückt sich in der Änderung der Bodenfeuchte und der Verringerung der Abflussmenge flussabwärts aus. Ein verminderter Bestandsniederschlag und eine geringere Bodenvorfeuchte reduzieren die Oberflächenabflussbildung und auch die Hochwasserscheitel. Die infiltrationsfördernden Terrassen und Erdwälle erhöhen lokal die Wasserverfügbarkeit und verringern sowohl den

Oberflächenabfluss als auch die Abflussmaxima. Das im Boden gespeicherte Wasser wird aber aufgrund der hohen potentiellen Evapotranspirationsraten nicht abflusswirksam, sondern verdunstet oder transpiriert.

Die Ergebnisse zeigen, dass landwirtschaftlich genutzte Böden im Einzugsgebiet des Ronquillo nicht geeignet sind, Wasser über längere Zeiträume zwischen zu speichern, um die Wasserverfügbarkeit in den Trockenperioden zu erhöhen. Desweiteren zeigt sich, dass Terrassen und Erdwälle den Oberflächenabfluss effizienter reduzieren als Aufforstungen, insofern als dass sie die Wasserverfügbarkeit flussabwärts nur in vergleichsweise geringerem Maße reduzieren.

Das Forschungsvorhaben verdeutlicht, dass die Implementierung der untersuchten Maßnahmen in der Fläche (Terrassen, Erdwälle und Aufforstung) eine Umverteilung der Wasserströme innerhalb des Einzugsgebietes des Ronquillo bewirkt. Daher sollte die Umsetzung dieser Maßnahmen von einem integrierten Einzugsgebietsmanagement begleitet werden. Ein integrierter Ansatz ermöglicht es, Ober- und Unterlieger betreffende Auswirkungen auf die Ressourcen Wasser und Boden zu betrachten, zu bewerten und gegebenenfalls durch entsprechende Maßnahmen abzumildern.

1. Introduction

Mountain areas are an important source of freshwater for adjacent lowlands (Viviroli and Weingartner 2004; Viviroli et al. 2007). In the Andean region most of the population centers are located in the arid and semi-arid regions along the Pacific coast and depend on water supply from the Andean highlands (Tovar-Pacheco et al. 2006; Viviroli et al. 2011; Lavado-Casimiro et al. 2012). In addition, some other important Andean population centers, such as Bogotá in Colombia, Quito in Ecuador, Cajamarca in northern Peru, and La Paz in Bolivia, are located in the Andean highlands. The availability of water resources to these high-altitude urban agglomerations depends almost exclusively on the water yield of nearby mountain ranges (Mulligan et al. 2010; Buytaert and De Bièvre 2012). In the Andean region the headwaters are known to be water source areas and water recharge areas (Buytaert et al. 2006a). The Andean headwaters, including wetlands and glaciers, act as buffer systems against seasonal precipitation and ensure water provision during the dry season. They are thus crucial for the citizens of the Andean countries (Vuille et al. 2008; Buytaert et al. 2011).

The mountainous region of the northern Andes is characterized by an absence of glaciers, and thus the main source of freshwater is precipitation. The allocation of water resources strongly depends on the hydrological function (collection, storage and discharge) of the watersheds (Black 1997). In respect to water security, defined as the “availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies” (Grey and Sadoff 2007), soil erosion is a severe issue, for in the non-glaciated areas of the northern Andes soils are of major relevance to the base flow generation (Buytaert et al. 2006a; Célleri and Feyen 2009). Land degradation is attributable to inappropriate land use and insufficient conservation practices, and is defined as a temporary or permanent decline in the productive capacity of an ecosystem (Scherr and Yadav 1996; Eswaran et al. 2001). Land degradation deteriorates the hydrological function of watersheds, and thus poses a fundamental threat to water security. However, land degradation does not have to be an irreversible process, as soil and water conservation (SWC) can mitigate land degradation, and thus secure water resources and land productivity (Nyssen et al. 2009).

A vast number of SWC measures, techniques and practices have been implemented in nearly all semi-arid landscapes around the world (Bruins et al. 1986; Prinz 1996). These measures are sustainable (Denevan 1995) and have been shown to enhance water productivity (Tian et al. 2003; Oweis and Hachum 2006; Kahinda et al. 2007; Makurira et al. 2009) and reduce surface runoff and soil erosion (Dehn 1995; Alegre and Rao 1996; Gardner and Gerrard 2003; Hammad et al. 2004; Al-Seekh and Mohammad 2009). Nevertheless, the success of initiatives promoting SWC is far from guaranteed (Hudson 1991) and the SWC adoption rates often remain very low (Mekdaschi Studer and Liniger 2013). The variables that influence the adoption of a particular SWC measure are context and site dependent. However, the literature points to several key factors that influence the adoption of resource conservation measures: (i) inputs and materials, (ii) incentives and credits, (iii) training and education, (iv) land and water use rights, (v) access to markets for inputs and outputs, (vi) research, monitoring and assessment, (vii) genuine participation of land users and professionals, (viii) profitability of the SWC measures and long-term financial benefits (e.g. increased production, reduced labor input, higher off-farm income, etc.) and (ix) adaption and fine-tuning of standard designs of a particular technology to the local natural, socio-economic and cultural environment (de Graaff et al. 2008; Liniger et al. 2011; Mekdaschi Studer and Liniger 2013).

In order to promote SWC as a tool for resource conservation and sustainable development, and to provide decision-making support to planers, decision-makers and local land users, it is essential to make use of sound science-based procedures for assessing the environmental and socio-economic impact of SWC at different spatial and temporal scales. The overarching question is as follows: What will be the environmental and socio-economic impacts of SWC? This question must be answered regardless of the scale of the project – from small-scale isolated plots to projects covering a whole watershed or landscape – and must also take temporal consideration into account – i.e. what are the impacts from project start up to the distant future.

Against this backdrop, the present thesis assesses the impact of selected SWC measures on the hydrology of the Ronquillo watershed in northern Peru. The research was undertaken as part of the research project *The conservation of water and soil resources in the Chetillano and Ronquillo basins in the Northern Sierra of Peru (CASCUS)* [in Spanish: *Conservación del agua y suelo en las cuencas de los ríos Chetillano y Ronquillo en la Sierra norte del Perú*]. The project aims to develop a science-based integrated soil and water resource management strategy for the region under investigation. The present thesis contributes to the overall aim of the research initiative by strengthening the knowledge base on the hydro-meteorological boundary conditions in the research area, and by quantifying the impact of selected resource conservation measures on the hydrology of the Ronquillo watershed.

1.1 The research project CASCUS

1.1.1 CASCUS – project development and project progression

In 2006, Professor Achim Schulte, the head of the working group Applied Geography, Environmental Hydrology and Resource Management at the Institute of Geographical Sciences at Freie Universität Berlin, was invited to Cajamarca, Peru by Dr. Alonso Moreno, then head of the Cajamarca branch of the Deutsche Geschellschaft für Internationale Zusammenarbeit (GIZ). Professor Schulte, an expert in flood risk management, with a special focus on decentralized flood protection (DFP), was asked to develop a project to apply the DFP concept to the Andean environment. In 2008 the research project *The conservation of water and soil resources in the Chetillano and Ronquillo basins in the Northern Sierra of Peru (CASCUS)* was initiated. It sought to implement decentralized resource conservation measures in order to improve water availability and reduce overland flow, thus hindering soil erosion and land degradation. The research project was kindly funded by the Hans Sauer Stiftung, a German foundation, during 2008–2012.

The catchments of the Chetillano River (approx. 182 km^2) and the Ronquillo River (approx. 42 km^2) were picked as key research areas. Their borders constitute the South American Continental Water Divide (SACWD) in the region of Cajamarca. The watersheds are thus considered as Andean headwaters, which are known to be crucial for water resource availability in the Andean region (Buytaert et al. 2006a). The eastward draining Ronquillo watershed is of special interest for the city of Cajamarca, as its water resources contribute to the urban water supply (EPS SEDACAJ S.A. 2006). The westward draining Chetillano watershed is of interest, as the downstream Gallito Ciego reservoir is rapidly filled with sediments due to erosion processes (Loayza 1999; Walter et al. 2012). As a result, the operational life of Gallito Ciego reservoir, completed in 1988, has been reduced to 33 years, instead of the originally calculated 50 years (Chavez et al. 2013).

The research within CASCUS is conducted in cooperation with several Peruvian governmental and non-governmental organizations – namely, El Centro Ecuménico y Acción Social Norte (CEDEPAS Norte), the Cajamarca branch of the Deutsche Geschellschaft für Internationale Zusammenarbeit (GIZ), Instituto Cuencas, Consorcio Interinstitucional para el Desarrollo Regional (CIPDER), Asociacion para el Desarrollo Rural de Cajamarca (ASPADERUC), Universidad Nacional de Cajamarca (UNC), Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), Empresa Prestadora de Servicios de Saneamiento de Cajamarca S.A. (EPS SEDACAJ S.A.), the provincial capital of Cajamarca, and the district capitals of Chetilla and Magdalena.

From 2008 to 2012 five long-term field campaigns were conducted. In February 2008 the research area was explored in order to gain a geographical overview and to find representative sampling-taking sites and appropriate locations for the installation of measurement equipment. In July and August 2008, three weather stations (Davis Vantage Pro II) and two pressure transducers (Orpheus Mini, OTT Hydrometrics) were installed in order to extend the existing hydro-meteorological monitoring network in the region (Figure 1–1). Additional field campaigns were conducted in February to March 2009 and in August to September 2009. During the latter period, a group of German students from the Department of Earth Sciences at Freie Universität Berlin joined the research team. Together with Peruvian students at UNC, field measurements were undertaken in the Ronquillo region. Since then several papers have been completed by German students, which are listed in Table 1–1. In September 2012 the preliminary results of the CASCUS research project were presented at two symposia in Peru – one held in Lima at the Universidad Nacional Agraria La Molina (UNALM) and the other held in Cajamarca at the UNC.

Figure 1–1: During the CASCUS research project, three Davis Vantage Pro II weather stations and two pressure transducers (OTT Orpheus Mini) were installed in the area under investigation. Left: Installation of the Alto Chetilla rain gauge at 3422 m asl. Right: Installation of the pressure transducer at the Ronquillo water intake at an altitude of 2838 m asl. To view sites composing the hydro-meteorological monitoring network, refer to the maps in Figure 2–1 and Figure 5–1 (Photos: Krois 2009).

From 2012 to present, research activities have continued, thanks to the funding of the Hans Sauer Stiftung and the German Federal Ministry of Education and Research (BMBF). A follow-up research initiative is currently in preparation, preliminarily titled CASCUS II, in which even more German and Peruvian research institutions, such as Technische Universität Kaiserslautern, Universidad Nacional Mayor de San Marcos (UNMSM), and UNALM, among others, will take a part.

Table 1–1: Bibliographical list of finalized and ongoing Bachelor and Master theses related to the research project CASCUS (2008 to 2015)

Year	Author	Title/working title	Academic degree
2010	Jens Hartwich	Hydrologische Charakterisierung des Río Ronquillo in der nördlichen Sierra Perus: Faktoren – Monitoring – Hydraulische Modellierung (Hydrological Characterization of the Ronquillo River in the Northern Sierra of Peru: Factors, Monitoring, Hydraulic Modeling) [in German]	MSc Environmental Hydrology
	Kerstin Furchner	Qualitative und semiquantitative Charakterisierung der Bodenerosionsformen im Einzugsgebiet des Río Manzana in der Region Cajamarca, nördliche Sierra Peru (Quantitative and semi-quantitative characterization of soil erosion forms in the Manzana catchment in the region of Cajamarca) [in German]	BSc Geographical Sciences
	Samuel Stettner	Landnutzungsveränderungen im Einzugsgebiet des Río Manzana in der nördlichen Sierra Perus. Eine Untersuchung anhand eines historischen Luftbildes und Quickbird-Satelliten-Daten (Land use changes in the Manzana River watershed in the northern Sierra of Peru: An investigation on the basis of historical aerial images and Quickbird data sets) [in German]	BSc Geographical Sciences
2011	Sven Abendroth	Hydrogeologische Untersuchung im Einzugsgebiet des Río Ronquillo in der nördlichen Sierra Perus (Hydrogeological investigation in the catchment of the Ronquillo River in the northern Sierra of Peru) [in German]	MSc Hydrogeology

Table 1–1: (continued)

Year	Author	Title/working title	Academic degree
2011	Soraya Kaiser	Charakterisierung der Niederschlagsverteilung von 2005 bis 2010 in der Region Cajamarca, nördliche Sierra Perus (Characterization of rainfall patterns from 2005 to 2010 in the region of Cajamarca, northern Sierra of Peru) [in German]	BSc Geographical Sciences
2012	Sophia Rohde	Landnutzungsänderungen und ihr Einfluss auf die Wasserverfügbarkeit im Einzugsgebiet des Ronquillo – eine hydrologische Modellierung (Land use change and its impact on the water availability in the Ronquillo watershed – a hydrological modeling approach) [in German]	MSc Environmental Hydrology
to be finished in 2015	Christina Hofmann	Quantifizierung und Bewertung der Bodenerosion im Einzugsgebiet des Río Ronquillo in den nördlichen Anden Perus (Quantification and assessment of soil erosion in the Ronquillo River watershed in the northern Andes of Peru) [in German]	MSc Environmental Hydrology
	Hanna Krüger	Untersuchung der Höhenstufe Jalca im EZG des Río Ronquillo im Hinblick auf ihre Retentionsfunktion (Investigation of the altitudinal belt Jalca in the Ronquillo watershed with a view to water retention) [in German]	MSc Environmental Hydrology
	Sonja Taheri Rizi	Klassifikation von Landnutzung und Landbedeckung zur Ermittlung des Wasserbedarfs im Einzugsgebiet des Río Mashcón in den nördlichen Anden Perus (Land use and land cover classification in order to identify water demand in the Mashcón River in the northern Andes of Peru) [in German]	MSc Environmental Hydrology

1.1.2 Methodological framework of the CASCUS research project

In the CASCUS research project, large-scale water related problems are addressed with adaptive, small-scale measures for managing water and soil resources. The project is informed by an integrated and holistic approach. The resource management strategy promoted within the CASCUS research project aims to optimize water availability in the watershed as well as downstream, and simultaneously to optimize the protection of soil resources. The small-scale and low-cost conservation measures aim to locally enhance water availability, and thus support land productivity (Tian et al. 2003; Oweis and Hachum 2006; Kahinda et al. 2007; Makurira et al. 2009). Once a critical level of adaptation is achieved throughout the watershed, the hydrological functions of the watershed will be affected, thus impacting the water availability downstream and affecting the livelihood and the economic development of the urban centers further downstream.

The outlined resource management strategy is consistent with the concepts of DFP or decentralized water retention (DWR), which are based on the idea that measures of protection or conservation can be distributed throughout a drainage area instead of – or in addition to – the development of large technical constructions downstream (Reinhardt et al. 2011). In the German literature DFP (or DWR) and its principles are well established (Assmann et al. 1998; Marenbach and Koehler 2003; Röttcher et al. 2007; Schulte et al. 2009; Reinhardt 2010; Bölscher et al. 2013). In order to adapt the concept of DFP/DWR to the Andean environment, the catalogue of potential conservation measures (for an overview see Reinhardt 2010) was extended with the supplemental adoption of SWC measures (Hudson 1987; Critchley and Siegert 1991; Critchley et al. 1994; Prinz 1996; Oweis et al. 1999; FAO 2000; Unger and Howell 2000; Lancaster 2006; Oweis and Hachum 2006; Lesschen 2007; Lancaster 2008). In addition, the strong heterogeneity of the Andean landscape was taken into account through the development of a tailored set of promising conservation measures for each landscape type.

Figure 1–2 illustrates the adapted DFP/DWR concept for a typical northern Andean watershed, void of snow-dominated areas. Within such a watershed, distinct ecoregions (Pulgar-Vidal 1996) or altitudinal belts (Stadel 1991) emerge, each of them characterized by different land cover due to differing meteorological and hydrological boundary conditions. The figure illustrates that the lower parts of the watershed are characterized by scare vegetation, owing to arid and semi-arid climatic conditions, whereas in the middle part of the watershed, a patchy pattern of land cover emerges, owing to more favorable hydro-climatic conditions. Depending on site-specific environmental boundary conditions, widespread agricultural and pastoral activities alternate with shrubland and herb cultivation. In the upper part of the watershed, low temperatures constrain agriculture, and higher rainfall favors the expansion of natural grasslands.

In line with the principles the DFP/DWR concept, the CASCUS research project intends to manage the outlined “starting conditions” by promoting an “aspired state,” in which different conservation measures are distributed throughout the drainage area. As Figure 1–2 makes clear, the type of conservation measure employed needs to correspond to the environmental boundary conditions. Check dams, for example, are appropriate for mitigating gully erosion, and mechanical structures such as terraces and bund systems or small-scaled reservoirs (micro reservoirs) can mitigate soil erosion and improve land productivity, and/or enhance water availability. As a supplemental measure, one should promote land use changes, conservation agriculture and the temporary storage of floodwater in reservoirs (water retention basins). In the relevant literature, many more techniques and measures for soil and water conservation are described than illustrated in Figure 1–2. For a review of different SWC techniques and measures see Morgan (1986), Hudson (1987), Young (1989), Critchley and Siegert (1991), Oweis et al. (1999), FAO (2000), Lancaster (2006), Lesschen (2007), Zeh (2007), Bekele et al. (2009), Blanco-Canqui and Lal (2008), Lancaster (2008), Schwilch et al. (2010), Liniger et al. (2011), and Mekdaschi Studer and Liniger (2013).

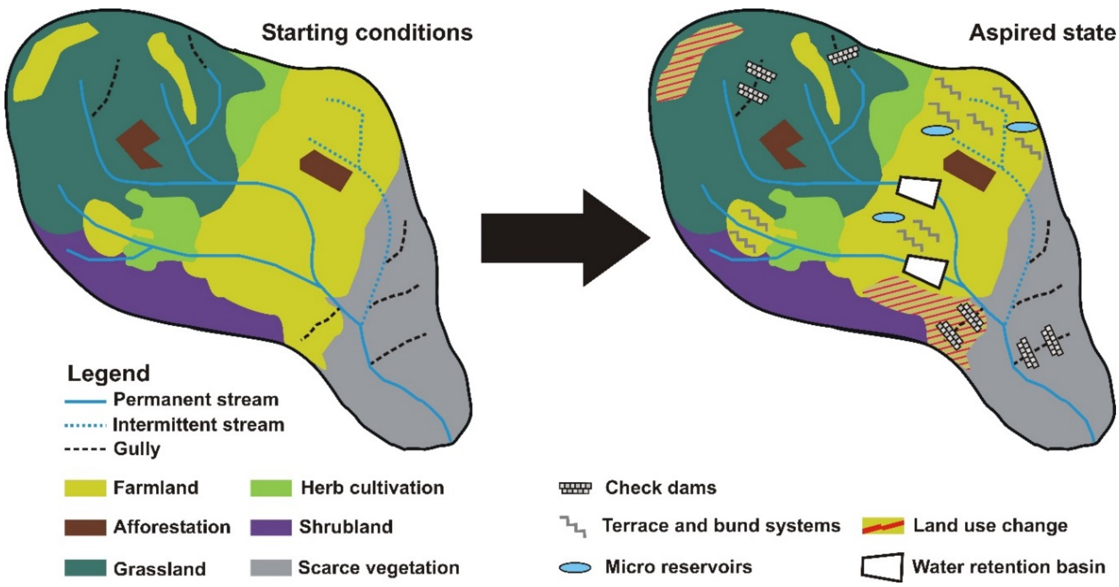

Figure 1–2: Concept for the implementation of soil and water conservation measures in an Andean watershed. The map is more representative of watersheds draining the western escarpment of the Andes, where rainfall increases with altitude. It is not as representative for the eastern slopes of the Andes, where the highest amount of rainfall is observed below 1500 m asl (Espinoza-Villar et al. 2009), or for glaciered watersheds, where hydrology is strongly related to glacier fluxes (Ribstein et al. 1995; Kaser et al. 2003; Mark and Seltzer 2003; Mark et al. 2005).

1.2 Study area and related environmental problems

The study area is the Ronquillo watershed, located in the vicinity of the city of Cajamarca, in the northern Andes of Peru (Figure 1–3). The catchment of the Ronquillo River, which is a key research area in the CASCUS project, extends from the SACWD at an altitude of approx. 4000 m asl to the Ronquillo gauging station (2838 m asl) at the urban fringe of the city of Cajamarca. The above-ground catchment area encompasses approximately 42 km^2 and drains into the Amazon via the Cajamarca, the Crisnejas and Marañón rivers. Thus, the Ronquillo watershed is a headwater basin of the Amazon River.

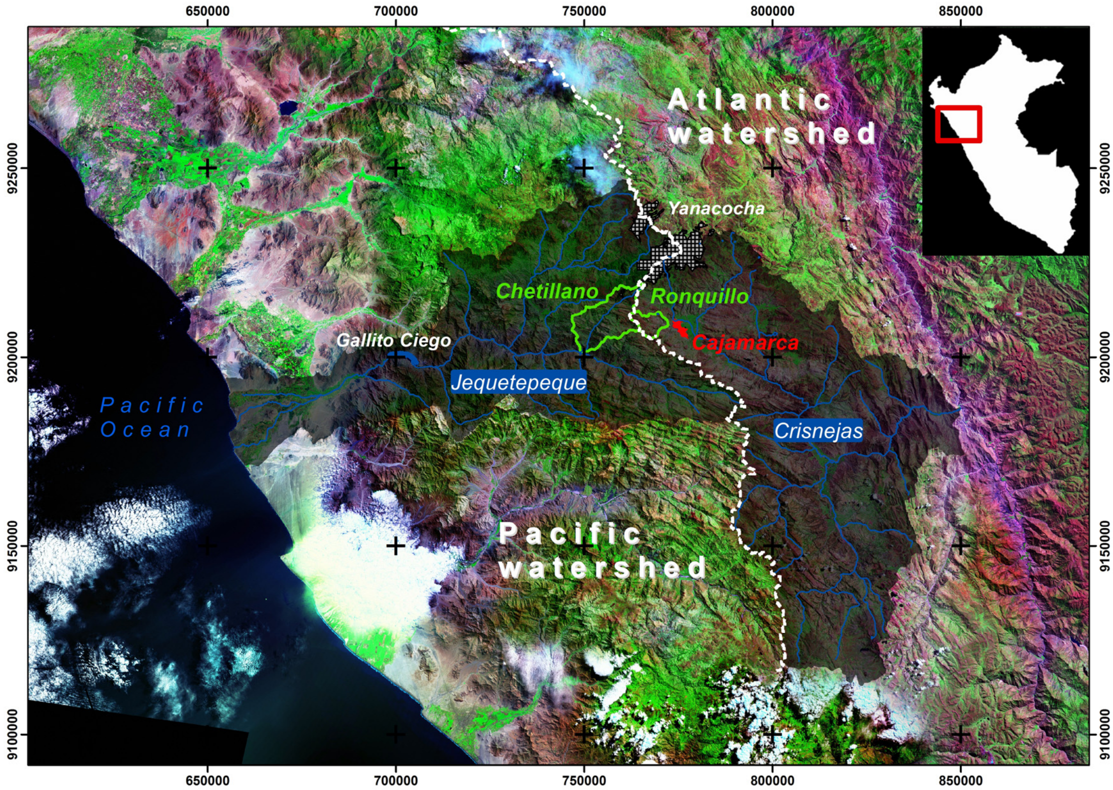

Figure 1–3: Overview of the area of interest based on satellite imagery. In the region of Cajamarca, the SACWD (white dotted line) divides the watersheds (black shaded areas) of the westward draining Jequetepeque River and the eastward draining Crisnejas River, constituting the Pacific and the Atlantic watersheds, respectively. The Jequetepeque River drains directly into the Pacific Ocean, whereas the Crisnejas River is a headwater basin of the Amazon River. The Chetillano and the Ronquillo watersheds (green line) are the key research areas within the CASCUS project. The city of Cajamarca is located southeast of the outlet of the Ronquillo River. North of the city of Cajamarca, the Yanacocha gold mine covers a large area, extending on both sides of the SACWD (black and grey checked area; spatial extent in 2006). The Gallito Ciego reservoir, located in the Jequetepeque watershed, produces electricity and supplies water for the irrigation of the coastal plains. (Data source: Landsat 7 ETM 7-4-2, WGS84 UTM Zone 17 South, and SRTM 90m digital elevation model, and Gobierno Regional de Cajamarca).

Orogenes such as the Andes are characterized by varying vertically arranged landforms, emerging as altitudinal belts (Blüthgen and Weischet 1980; Stadel 1991). To account for the hypsometric changes of the Peruvian landscape, the Peruvian geographer Javier Pulgar-Vidal defined in his magnum opus *Las ocho regiones naturales del Perú*, first published in 1941, eight different regions, which differ from each another by altitudinal range as well as climatological, geomorphological and biotic features. Following the landscape classification scheme proposed by Pulgar-Vidal (1996), two distinct ecoregions, the Quechua (2300–3500 m asl) and the Jalca (3500–4000 m asl), can be identified within the Ronquillo watershed (see Figure 1–4 and Figure 1–5). The Quechua is characterized by widespread agricultural activities (wheat, corn, potatoes), whereas grassland is predominant in the Jalca, as cultivation is impaired by lower temperatures and wet atmospheric conditions (Pulgar-Vidal 1996; Sánchez-Vega and Dillon 2006).

Figure 1–4: Photo of the Ronquillo River taken on September 7, 2009. The photo shows the deeply incised Ronquillo River in the lower watershed, corresponding to the Quechua altitudinal belt. In the lower part of the Ronquillo River there is an alluvial valley bottom, which is mainly used for grazing or irrigation farming. The less steep terrain of the lower watershed area is characterized by widespread agricultural activities; in some areas the cultivation extends up to the hilltops. The severely degraded steep flanks are dominated by shrubs, whereas trees, mainly Eucalyptus globulus, are planted along the riverside (Photo: Krois 2009).

The area under investigation is located in a region of overlapping cold humid and moderate sub-humid climates (ONERN 1975). Mean temperature is 11–16°C in the Quechua and 7–10°C in the Jalca (ONERN 1975, 1977). Mean annual rainfall in the Quechua varies from approx. 500–1200 mm, according to rain gauges used in the present study (see section 2). The high variability in the numbers indicates that generalization of mean annual rainfall in the Andean environment is a difficult task, as spatial rainfall patterns are affected by local topography, rain shadowing effects, and local wind fields (Buytaert et al. 2006b; Rollenbeck and Bendix 2011). Information on rainfall in the Jalca is scarce, though ONERN (1975, 1977) reports that mean annual rainfall exceeds 1100 mm. The rainfall regime is characterized by a distinct dry season from May to September and a major rainfall period from October to April. The pronounced seasonal rainfall regime is a response to the seasonal displacement of the Intertropical Convergence Zone and the South Atlantic and South Pacific anticyclones. Consequently, in terms of water resource management, water appears to be an abundant commodity during rainy seasons, whereas during dry seasons water is scarce (Figure 1–6).

Figure 1–5: Photo of the upper Cushunga watershed, a subwatershed of the Ronquillo River, taken on September 2, 2009. The photo shows the characteristic landscape of the Jalca altitudinal belt. An alpine grassland ecosystem extends over gently sloping Mesozoic sediments and outcrops of Paleogene volcanic rocks. The bedrock is overlain by organic, black colored soils, typically covered by bunch grass vegetation (Luteyn 1992; Sánchez-Vega and Dillon 2006). The high water retention capacity of the soils constrains farming to the slopes, as these areas drain more quickly. Plain areas are preferentially used for pasture. Owing to afforestation initiatives during the last decades, mainly pine species (e.g. Pinus radiata and Pinus patula) have been introduced in the Jalca orobiome (Sánchez-Gómez and Gillis 1982; van den Abeele 1995; Sánchez-Zevallos 1998, 2000) (Photo: Krois 2009).

Corresponding to the seasonality in rainfall, high discharges during rainy seasons endanger the urban and rural infrastructure and result in the loss of water resources, as the water rapidly drains from the catchments. Moreover, owing to surface runoff generation and related fluvial and erosive processes, the watersheds suffer soil erosion and degradation (De la Cruz et al. 1999). Consequently, the negative effect exerted by pronounced rainfall seasonality on water availability is reinforced by the fact that the water retarding capacity of river basins is undermined in a self-reinforcing process in which continued soil erosion causes degradation of the absorptive function of the topsoil, which reduces water infiltration rates and thus enhances the generation of surface runoff, which causes even more soil erosion (Martinez-Mena et al. 1998; Römkens et al. 2002; Carrillo-Rivera et al. 2008). Owing to this self-reinforcing process, the natural water retarding and water storage capacity and also the groundwater recharge of the watersheds decline. As a result, the generated base flow does not provide sufficient discharge to meet the human demand for water resources during the dry season. Additionally, inappropriate land use and a lack of conservation practices enhance land degradation and the deterioration of the hydrological functions of the watersheds.

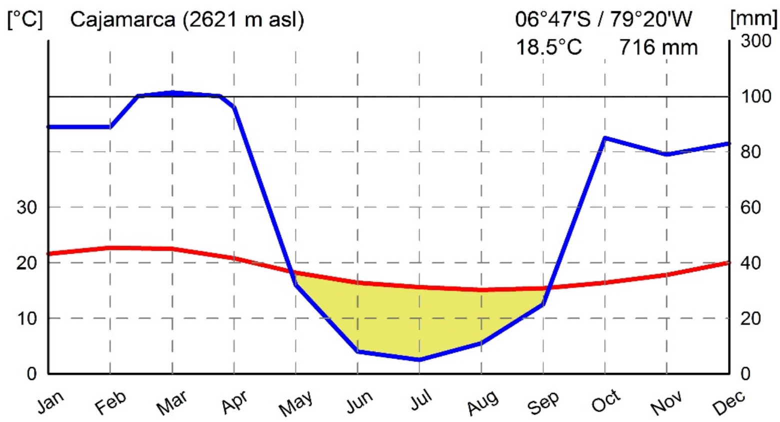

Figure 1–6: Walter Lieth climate diagram for the city of Cajamarca. The temperature axis on the left side refers to monthly mean temperature and the precipitation axis on the right side refers to average monthly precipitation. The diagram distinguishes between dry (yellow shaded area), wet (blue shaded area) and humid (blank area) conditions (Walter and Lieth 1960). The figure indicates that the dry period extends from May to September (data source: Müller 1996).

The water resources of the Ronquillo River are of special interest to the city of Cajamarca, as about one third of the total urban water supply is provided by discharge from the Ronquillo River (Atkins et al. 2005; EPS SEDACAJ S.A. 2006). However, in recent decades, a growing urban population (CENAGRO 2012) accompanied by an increase in water demand (EPS SEDACAJ S.A. 2006), has resulted in severe water shortages. The interruption of water services in the city for several hours a day during the dry season is now common, underscoring the magnitude of the problem (CES 2010). By 2035 water demand will double compared to 2005 (Table 1–2).

Accordingly, residents of the Cajamarca region attach great importance to water resource issues, not only because of restricted water availability, but also because of a rapidly growing mining industry. Since the 1990s, transnational mining companies have greatly expanded their presence in Peru (Bury 2002). The mining activities in the headwaters are perceived as affecting downstream water quantity and quality (Bury 2004, 2005; Barenys et al. 2014) and are a trigger of severe social unrest (Gifford et al. 2010; Triscritti 2013). Against the backdrop of such social tensions, it becomes even more important to assess the hydrological functions of headwater basins and to develop strategies for water resource management and soil protection.

Table 1–2: Projected increase in population and water use in the city of Cajamarca (EPS SEDACAJ S.A. 2006)

Year	2005	2006	2010	2015	2020	2025	2030	2035
Inhabitants	115,116	119,350	136,287	157,458	178,629	199,800	220,970	242,141
Increase (%)	0	4	18	37	55	74	92	110
Water use (ls^{-1})	222	231	261	309	359	404	449	494

1.3 Aims, objectives and outline of this study

The aim of the present thesis is to contribute to the CASCUS project by (1) strengthening the knowledge base on hydro-meteorological boundary conditions in the research area, and (2) advancing the envisioned integrated resource management strategy by quantifying the impact of selected resource conservation measures on the hydrology of the Ronquillo watershed. In order to achieve the above stated aim, research was undertaken in several stages (Figure 1–7). Specifically, these stages were: (1) the exploration of the meteorological and hydrological boundary conditions, (2) the development of scenarios for the implementation of resource conservation measures, and (3) the assessment of the hydrological impact of resource conservation measures on the catchment using hydrological modeling.

In light of the foregoing, the specific technical goals of the present study are as follows:

i. To fill the knowledge gap related to spatial and temporal rainfall characteristics in the region under investigation.

ii. To contribute to a better understanding of the hydrology of the Ronquillo by quantifying its base flow and its natural water storage capacity, and by relating them to the existing natural water storage entities, with an emphasis on low flow conditions during the dry season.

iii. To develop a GIS-based multi-criteria evaluation process in order to conduct a site assessment of resource conservation measures in the Ronquillo watershed.

iv. To assess and quantify the impact of selected resource conservation measures on Ronquillo River water yield, overland flow generation, and high flows using a hydrological model.

The thesis is organized based on the multi-stage research approach presented in Figure 1–7. Sections 2 and 3 focus on the meteorological and hydrological boundary conditions. Section 4 presents the site assessment procedure for resource conservation measures in the Ronquillo watershed. Section 5 elaborates the hydrological modeling used to assess and quantify the impact of resource conservation measures on the hydrology of the Ronquillo watershed.

The main scientific results, presented in sections 2 to 5, are prefaced by section 1, which gives an introduction to the overall research program, the study area and the related environmental problems. Section 1 outlines the main research questions, as well as the aim and the main objectives of the present study. Sections 6 to 7 offer a synthesis of the research findings and the conclusions.

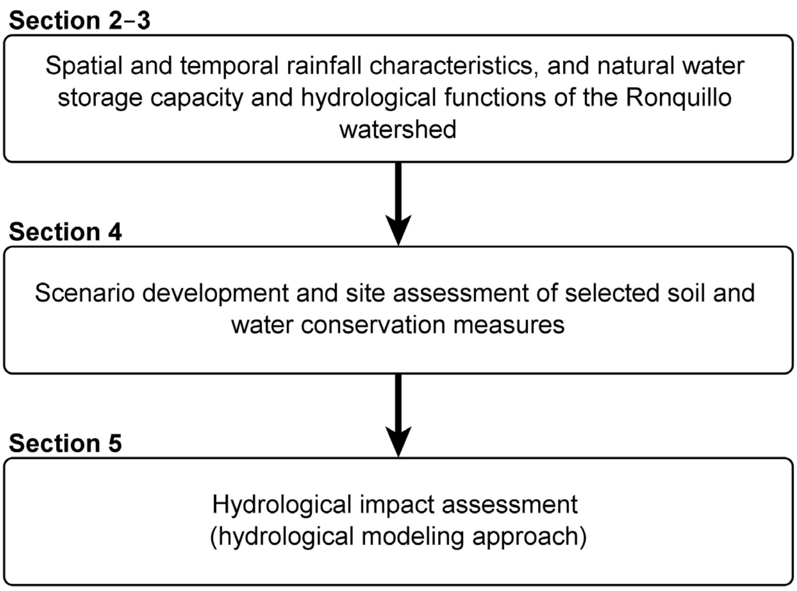

Figure 1–7: Flow chart detailing the multi-stage research approach of the present thesis

Sections 2 to 5 consist of papers that were published in international peer-reviewed journals or conference proceedings (Table 1–3). All of the papers included in these sections were entirely structured and prepared by the author of the present composition. Additionally, the author carried out all changes based on feedback received from anonymous reviewers during the peer-review process. The hydro-metrological raw data analyzed in section 2 and section 3 was gathered and transmitted to the author by Carlos Cerdán. Edwin Pajares supported the installation of the monitoring network by networking and negotiation. The manuscript in section 3 is inspired by the thesis of Sven Abendroth (Abendroth 2011).

To improve readability of the present compilation, the original published manuscripts have been adapted to fit the overall text layout.

Table 1–3: Bibliographical information on the manuscripts contained in the present thesis

Section	Authors, title and publication details
2	Krois, J., Schulte, A., Pajares-Vigo, E., Cerdán-Moreno, C. (2013): Temporal and spatial characteristics of rainfall patterns in the northern Sierra of Peru – a case study for La Niña to El Niño transition from 2005 to 2010. Espacio y Desarrollo, 25: 23–48 http://revistas.pucp.edu.pe/index.php/espacioydesarrollo/article/view/10621
3	Krois, J., Abendroth, S., Schulte, A., Schneider, M. (2013): Dry season runoff and hydrological buffer systems in the high Andean catchment of Río Ronquillo in the northern Sierra of Peru. Journal of Latin American Geography, 12 (3): 59–89 http://muse.jhu.edu/journals/journal_of_latin_american_geography/v012/12.3.krois.html
4	Krois, J. & Schulte, A. (2014): GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques in the Ronquillo watershed, northern Peru. Applied Geography, 51: 131–142 http://www.sciencedirect.com/science/article/pii/S0143622814000769
5	Krois, J. & Schulte, A. (2013): Modeling the Hydrological Response of Soil and Water Conservation Measures in the Ronquillo watershed in the Northern Andes of Peru. Proceedings of the 6th ICWRER Conference, Koblenz, Germany, June 3–7 2013, Water & Environmental Dynamics: 147–184 http://www.water-environment.org/proceedings.html

2. Temporal and spatial characteristics of rainfall patterns in the northern Sierra of Peru – a case study for La Niña to El Niño transition from 2005 to 2010

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Abstract

The climatic conditions of the northern Sierra of Peru are marked by the interaction of different macro- to mesoscale climatic features such as the El Niño Southern Oscillation (ENSO) or Mesoscale Convective Complexes and the seasonally shifting Intertropical Convergence Zone, but also by local scale climatic features such as inhomogeneous topography and local wind fields. The region under investigation, located in the vicinity of the South America Continental Water Divide (SACWD), provides the opportunity to study interactions of western and eastern disturbances in a high mountain environment and their effects on rainfall variability. In general, rainfall variability is related to diurnal convection patterns, enhanced by valley breeze systems and modulated by local scale wind anomalies. Spillover of low-level air masses of Pacific origin passing over the Andean ridges is frequent. Although direct effects of ENSO on high Andean rainfall variability are in debate, the findings show that the majority of rain gauges used in this study follow an El Niño/dry and a La Niña/wet signal. However, high elevation areas on the western escarpment of the Andes benefit from abundant nocturnal rainfall that partly offsets the rainfall deficits during El Niño. Our data suggest that the spatial extent of this easterly wet pulse is limited to areas located above 3000 m asl. ENSO cycles contribute to rainfall variability near the SACWD in the northern Sierra of Peru by modulating the seasonal rainfall regime and causing a positive temperature anomaly.

This section has already been published. Please see below for corresponding information.

Krois, J., Schulte, A., Pajares-Vigo, E., Cerdán-Moreno, C. (2013): Temporal and spatial characteristics of rainfall patterns in the northern Sierra of Peru – a case study for La Niña to El Niño transition from 2005 to 2010. Espacio y Desarrollo, 25: 23–48

Link: http://revistas.pucp.edu.pe/index.php/espacioydesarrollo/article/view/10621

3. Dry season runoff and hydrological buffer systems in the high Andean catchment of Río Ronquillo in the northern Sierra of Peru

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Abstract

In the northern Sierra of Peru, water scarcity issues arise owing to the seasonal rainfall distribution and the lack of appropriate natural water storage capacity of river basins. The present study assesses the base flow and water storage volume of the Ronquillo watershed, an important rivulet for water abstraction for the city of Cajamarca. Mean base flow is 184 ls^{-1}, thus representing 44% of total stream flow. Flow recession curve analysis yields a mean catchment water storage volume of $3.57 \times 10^6 m^3$, which corresponds to a runoff depth of 85 mm. The gravitational water storage volume of Andosols, a soil type known to be a very important water reservoir in the Andes, corresponds to a runoff depth of 33 mm. Moreover, the study shows that the geological environment is of major relevance. Springs (18 mm) and an effluent flow regime (20 mm) contribute significantly to dry seasonal runoff. The findings imply that water conservation in the Ronquillo watershed should place emphasis not only on the preservation of soils, but also on subsurface water flow paths, as water availability is affected by processes operating beyond topographically derived catchment boundaries.

This section has already been published. Please see below for corresponding information.

Krois, J., Abendroth, S., Schulte, A., Schneider, M. (2013): Dry season runoff and hydrological buffer systems in the high Andean catchment of Río Ronquillo in the northern Sierra of Peru. Journal of Latin American Geography, 12 (3): 59–89

Link: http://muse.jhu.edu/journals/journal_of_latin_american_geography/v012/12.3.krois.html

DOI: http://dx.doi.org/10.1353/lag.2013.0042

4. GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques

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Abstract

This study presents a method to identify and rank potential sites for soil and water conservation techniques. The method takes into account environmental site assessment criteria and a decision-making method known as the Analytic Hierarchy Process. Spatial data is processed by applying a geographic information system and potential sites are ranked by a multi-criteria evaluation based on meteorologic, hydrologic, topographic, agronomic and pedologic criteria. The method is applied to identify potential sites for terraces and bund systems in the Ronquillo watershed, located in the northern Andes of Peru. The analysis indicates that 44% of the catchment area of the Ronquillo River is highly suited for the implementation of terraces, and 24% of the catchment area is highly suited for the implementation of bund systems. The preliminary identification of potential sites for soil and water conservation techniques may be a useful tool in the execution of resource conservation programs.

This section has already been published. Please see below for corresponding information.

Krois, J. & Schulte, A. (2014): GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques in the Ronquillo watershed, northern Peru. Applied Geography, 51: 131–142

Link: http://www.sciencedirect.com/science/article/pii/S0143622814000769

DOI: http://dx.doi.org/10.1016/j.apgeog.2014.04.006

5. Modeling the hydrological response of soil and water conservation measures in the Ronquillo watershed in the northern Andes of Peru

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Abstract

The present study assesses the impact of soil and water conservation techniques on the hydrology of the Ronquillo watershed (42 km²) in the northern Andes of Peru. The hydrological model NASIM is applied to evaluate the scenario-based implementation of four different measures of soil and water conservation (terraces, bunds, afforestation, and check dams) with respect to its impact on catchment hydrology. The modeling results indicate that earthworks and afforestation significantly affect flow volume, overland flow generation, and high flows. The impact of check dams on the stream flow characteristics of the Ronquillo River is small. Earthworks such as terraces and/or bund structures reduce surface runoff by 12–28%; however, flow volume diminishes by 6–14% as well. A loss of water for downstream usage of 1242–1643 $m^3ha^{-1}yr^{-1}$ is observed. Afforestation with eucalyptus and pine species reduces surface runoff by 9–11% and flow volume by 6–8%. Water loss due to enhanced interception and transpiration rates of plantations compared to native species or crops amounts to 1062–2586 $m^3ha^{-1}yr^{-1}$. On average, high flow discharge is reduced by 2–31%. For a single runoff event of the peak over threshold time series, a maximum reduction of 48% in peak flow is observed. With respect to the appropriateness of SWC practices for water resource management in the Ronquillo watershed, earthworks are more recommendable than afforestation because downstream water availability is less affected.

This section has already been published. Please see below for corresponding information.

Krois, J. & Schulte, A. (2013): Modeling the Hydrological Response of Soil and Water Conservation Measures in the Ronquillo watershed in the Northern Andes of Peru. Proceedings of the 6th ICWRER Conference, Koblenz, Germany, June 3–7 2013, Water & Environmental Dynamics: 147–184

Link: http://www.water-environment.org/proceedings.html

DOI: http://dx.doi.org/10.5675/ICWRER_2013

6. Synthesis

This thesis assesses the hydro-meteorological boundary conditions in the Cajamarca region in the northern Andes of Peru and quantifies the impact of selected resource conservation measures on the hydrology of the Ronquillo watershed. The research was undertaken as part of the CASCUS research project, which seeks to enhance water availability, and to reduce overland flow, thus dampening soil erosion and land degradation in the Cajamarca region. The CASCUS initiative promotes the modification of the watershed's hydrological functions through the implementation of small-scaled soil and water conservation measures, distributed throughout the drainage area. For decision-making with respect to resource allocation it is essential to have a sound knowledge base concerning temporal and spatial rainfall and runoff characteristics, as well as concerning the catchment's hydrological response to the implementation of soil and water conservation techniques (SWCTs).

The objectives of this thesis are as follows: to fill the knowledge gap related to spatial and temporal rainfall characteristics in the region under investigation; to contribute to a better understanding of the hydrology of the Ronquillo River; to conduct a site assessment for resource conservation measures in the Ronquillo watershed; and, finally, to assess and quantify the impact of selected resource conservation measures on the hydrology of the Ronquillo River by applying a rainfall-runoff model. Each particular research objective was discussed in the foregoing chapters 2–5. In this section, the main outcomes will be summarized and discussed from a broader perspective.

6.1 Hydro-meteorological boundary conditions

6.1.1 Meteorological boundary conditions

The rainfall regime in the northern Peruvian Andes is governed by the seasonal displacement of the Intertropical Convergence Zone. The region under investigation is characterized by a mono- to bimodal rainy season, and annual precipitation varies from 437 mm to 1555 mm, depending on elevation and locality (see Table 2–1). At the Cajamarca rain gauge (2621 m asl) with a mean annual rainfall of 716 mm, approx. 88% of annual rainfall occurs during the rainy season (Oct.–Apr.) (Müller 1996). While seasonality in rainfall generally decreases with altitude, a unique relationship between rainfall and elevation could not be established for the region under investigation due to the multifarious factors influencing spatial and temporal rainfall patterns, acting on different scales in space and time. Previous research has shown that it is difficult to define unique relationships between rainfall and elevation in the Andean region (Ronchail and Gallaire 2006; Celleri et al. 2007; Espinoza-Villar et al. 2009).

Topography is an important factor influencing rainfall throughout the area, as it determines the main trajectories of air masses by canalizing valley wind systems. In the Jequetepeque watershed, which drains the western escarpment of the Andes and is characterized by steep valley morphology, a pronounced valley breeze system emerges. Rainfall in the Jequetepeque watershed is mainly associated with up-slope breezes that evolve during the forenoon and finally meet, oppose and gradually overcome the prevailing easterly winds near the South American Continental Water Divide (SACWD).

In the inter-Andean valley of Cajamarca rainfall patterns are more complex. Rainfall variability is related to easterly air flow dynamics, thermally induced diurnal wind systems and frequent spillover of Pacific air masses, resulting in a reorganization of local wind fields and the strengthening of convective activity.

Spillover of Pacific air masses across the Andean ridges had been noted before by López and Howell (1967), who report that in the west-east oriented Cauca valley of Columbia, daytime sea/valley breeze circulation penetrates deeply inland at low levels, and passes across north-south oriented mountain barriers. This initiates katabatic winds on the eastern slopes of the mountain barrier. An associated hydraulic jump triggers vigorous and localized late afternoon and evening convection (López and Howell 1967) – a fine-scale feature of mountain climatology that has been confirmed by applying a mesoscale atmospheric circulation model to Northwestern South America (Warner et al. 2003).

In the region under investigation diurnal rainfall patterns are characterized by an afternoon/early evening maximum and less pronounced nocturnal peaks around midnight and predawn. The late afternoon rainfall maximum is in good accordance with the diurnal cycle of convective activity observed over the subtropical Andes (Garreaud and Wallace 1997). Furthermore, the secondary nocturnal rainfall peaks point to nocturnal convective activity due to up-scaling of storm size through the night (Mapes et al. 2003; Poveda et al. 2005; Bendix et al. 2009).

Superimposed on the meteorological features outlined above is El Niño Southern Oscillation (ENSO), with its extreme phases of El Niño (EN) and La Niña (LN). Although direct effects of ENSO on rainfall variability in the Northern and Central Andes are under debate (Kane 2000; Celleri et al. 2007; Rossel and Cadier 2009), it appears that in the area under investigation lower than normal rainfall occurs during EN episodes, whereas normal to above-normal rainfall occurs during LN. Other observed anomalies related to ENSO are the temporal shift of maximum monthly rainfall, the shift in the diurnal rainfall pattern and a positive temperature anomaly. During EN, above-normal rainfall is observed in December, whereas rainfall tends to be lower in January and February. In contrast, during LN rainfall tends to be below normal in December and higher in January and February. Similar observations of rainfall pattern change have been made by Kane (2000), who investigated rainfall anomalies due to ENSO in the central Peruvian Andes. Moreover, during EN, maximum diurnal rainfall is delayed compared to LN (see Figure 2–7) and a positive temperature anomaly of 0.9°–1.5°C is observed. This is a phenomenon that has been noticed elsewhere in the Andean highlands (Aceituno 1988; Vuille et al. 2000; Francou et al. 2004).

In summary, the complex pattern of spatial and temporal rainfall variability in tropical and subtropical Andes results from a combination of orographic rainout of moist air being transported by tropical easterlies (Vuille et al. 2000; Garreaud et al. 2009), rain-bearing mesoscale cloud systems (Laing and Fritsch 1997; Houze 2004; Bendix et al. 2009), ENSO (Kane 2000), katabatic drainage flow (López and Howell 1967; Trachte et al. 2010), rotor flow in the lee of mountain ridges (Kuettner 1959), and local convection (López and Howell 1967; Warner et al. 2003). Accordingly, rainfall patterns are nearly impossible to determine on the basis of the monitoring networks existing in many parts of the Andes (Buytaert et al. 2006b; Rollenbeck and Bendix 2011).

In order to gain better understanding of the interlinked hydro-meteorological processes in the Andean region, data collection systems must be improved. For instance, the combination of a network of high-resolution rain gauges and a rain radar in the high Andean region of Loja, southern Ecuador, revealed the complexity of temporal and spatial rainfall patterns in that region (Bendix et al. 2006; Rollenbeck and Bendix 2011). This complexity illustrates the infeasibility of using standard point data measurements and spatial interpolation methods to map spatial and temporal rainfall dynamics in such high mountainous terrain.

An alternative source for areal precipitation data are satellite based regional precipitation estimates such as the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Prescription Analysis (TMPA). Several studies on the accuracy and applicability of TMPA data have been conducted for South America and the Andes (e.g. Rozante et al. 2010; Scheel et al. 2011; Ochoa et al. 2014). Arias-Hidalgo et al. (2013) highlighted the potential of TMPA data sets as input variables for hydrological modeling studies. Recently, Mantas et al. (2015) validated the most recent TMPA products against observational data in the Peruvian Andes and concluded that for daily time steps TMPA data performs poorly but through temporal aggregation the agreement with gauge values increases significantly.

Another just recently discussed approach to expand our understanding of the hydro-meteorological boundary conditions in remote and difficult to assess regions such as the Andes is subsumed under the term *citizen science*. The basic idea is that the general public participates in the generation of scientific knowledge (Silvertown 2009; Wiggins and

Crowston 2011). Although advanced technology is needed for monitoring the water cycle, the development of more robust, cheaper and lower maintenance sensing equipment creates new opportunities for hydro-meteorological data collection in a *citizen science* context (Buytaert et al. 2014). However, the *citizen science* approach with respect to water sciences still faces major challenges such as the processing, interpretation, and use of heterogenic datasets, as well as the quantification of uncertainties, their role in decision support and the web-based dissemination of data for end-users (Buytaert et al. 2014; Vitolo et al. 2015).

6.1.2 Hydrological boundary conditions

In correspondence to the regional meteorological boundary conditions, the Ronquillo watershed is characterized by seasonality in discharge. Mean annual runoff depth at the Ronquillo gauging station is about 310 mm; however, runoff depth during the rainy season is approx. 3.7 times higher than during dry season, or in other words, about 78% of the annual discharge drains the Ronquillo watershed during the rainy season (Oct.–Apr.). In the rain-bearing months discharge dynamics are primarily controlled by surface runoff and fast interflow, whereas during the dry season discharge constitutes primarily of base flow.

In this thesis flood formation areas and direct runoff generation are delineated by applying the Soil Conservation Service curve number method (SCS-CN) to the Ronquillo watershed. Highest runoff coefficients (the ratio of runoff and rainfall) are observed for the middle parts of the catchment (see Figure 4–4B), where the combination of rainfall volumes and soil and land coverage is most prone to generate surface runoff. The upper parts of the catchment area are less prone to surface runoff generation, which is related to the fact that a large area of the upper watershed is covered by Andosols, often referred to as “Páramo soils” (Buytaert et al. 2005a; Cabaneiro et al. 2008), which are well known for high infiltration capacities (Buytaert et al. 2005b; Buytaert et al. 2006a; Célleri and Feyen 2009). In the Páramo grasslands of southern Ecuador, for example, infiltration excess overland flow is nearly absent (Buytaert et al. 2006a; Buytaert et al. 2007).

The Andosols in the Ronquillo watershed are characterized by highly permeable topsoil underlain by a dense clay-type subsoil or a rock layer of low impermeability. However, in contrast to the Páramo grasslands in Ecuador, overland flow is widespread, as witnessed in soil erosion, and rill and gully development in the headwaters of the Ronquillo basin (Figure 6–1). Rill and gully development is enforced by the presence of man-made linear structures that collect and guide runoff, such as tracks, paths and roads, as well as furrows, ditches and farm banks (Wemple et al. 1996; Desmet and Govers 1997; Souchere et al. 1998; Takken et al. 2001; Moussa et al. 2002; Croke et al. 2005; Callow and Smettem 2009). Furchner (2010) mapped features of soil erosion in the Manzana catchment, the most north-eastern sub-catchment of the Ronquillo watershed, and found that rill and gully formation is closely coupled with the presence of the footpath and dirt road network. Linear features and compacted surfaces such as roads enhance runoff connectivity through the physical integration of the road and stream network (Wemple et al. 1996; Croke et al. 2005); an issue frequently discussed under the framework of *hydrological* or *catchment connectivity* (Bracken and Croke 2007; Bracken et al. 2013).

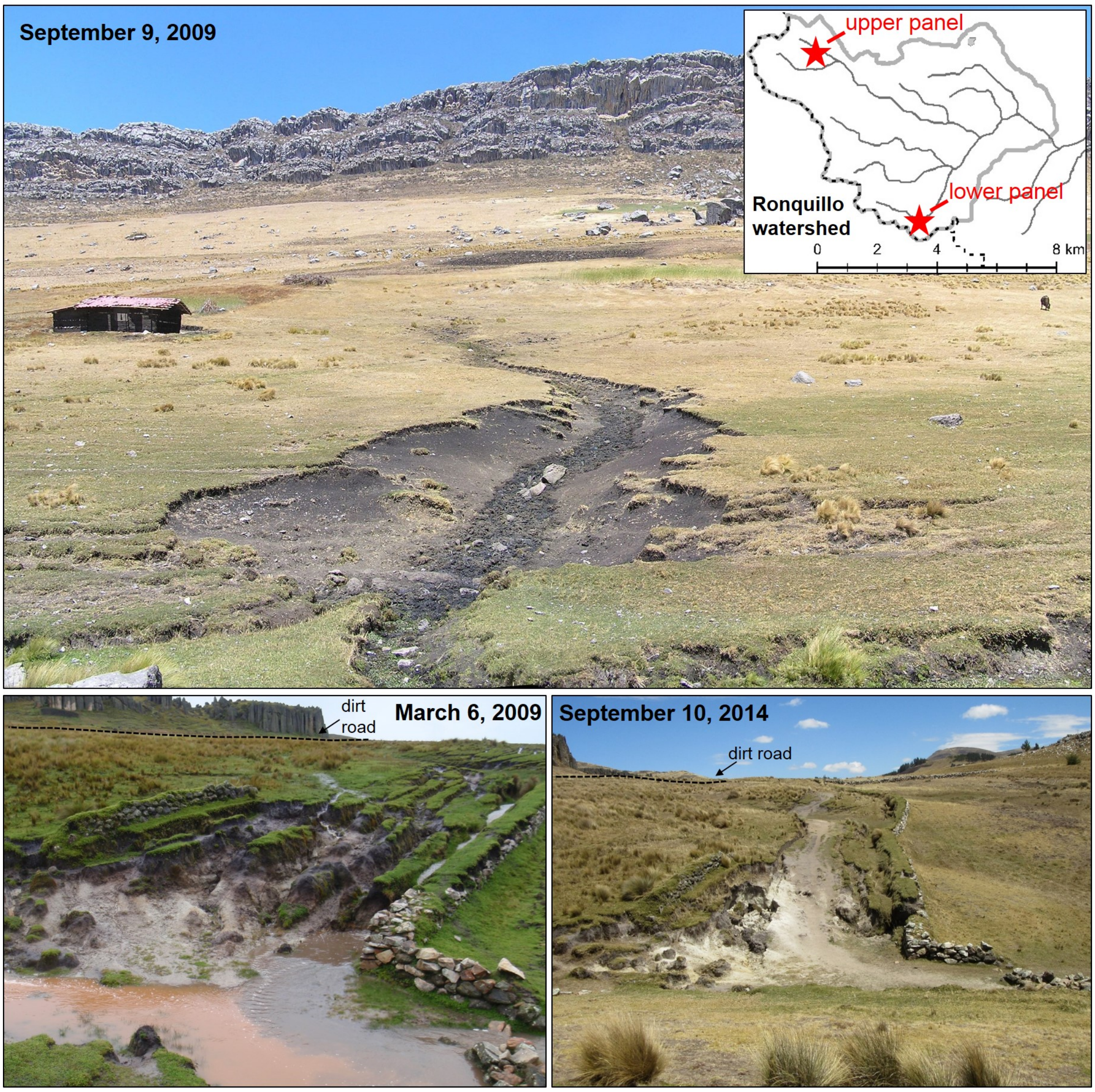

Figure 6–1: Rill and gully formation in the upper Ronquillo watershed. Upper panel: A gully located in the upper Cushunga valley at about 3650 m asl. The gully has a length of approx. 44 m, a maximum width of 14 m and a maximum depth of 1.5 m. The volume of soil loss corresponds to approx. 247 m^3. Lower panel: The two photos show the same location in the southern part of the Ronquillo watershed (approx. 3550 m asl) in March 2009 and September 2014. In 2009 severe soil erosion is already evident, as seen by rill formation (note that the brownish sediments originate from the dirt road, not from the soil layer). The construction of the dirt road in the back facilitates surface runoff channelization, as the draining water from upslope bypasses the dirt road through pipes or over fords. It is not known for what purpose the double-sided stone embankment was constructed; however, in combination with the channelized flow owing to the road construction, water erosion is vigorously enhanced so that by 2014 almost all of the topsoil within the double-sided stone embankment is irreversible lost (Photos: Krois 2009 and 2014).

In contrast to the rainy season, in which surface runoff and flood generation are of major relevance, base flow becomes most important during the dry season (June to September). On the basis of discharge data collected at the water intake of the Ronquillo River, mean annual base flow is estimated by applying the methods provided by Wundt (1953), Kille (1970), Lillich (1970) and United Kingdom Institute of Hydrology (Institute of Hydrology 1980). The resulting mean base flow rates of 0.200, 0.130, 0.192, and 0.202 m^3s^{-1}, respectively are combined with a non-linear storage-discharge approach (Wittenberg 1994, 1999), in order to calculate the water storage volume of the Ronquillo watershed (see section 3.3). Assuming that recharge is negligible during the recession period the water storage volume of the Ronquillo watershed is quantified as 3.13 to $3.75 \times 10^6\,m^3$, corresponding to a mean annual runoff depth of 74 to 89 mm, with an arithmetic mean of 85 mm.

The calculated water storage volume of the Ronquillo watershed is further related to the existing natural water storage entities, such as the soil layer and the bedrock. The quantification of the gravitational water storage volume of the Andosols, which are a major source of dry seasonal discharge, results in a volume of $1.4 \times 10^6\,m^3$, corresponding to an annual runoff depth of 33 mm (see section 3.4.4.1). Based on documented pouring rates of 107 springs (Benavides-Ferreyros et al. 2007), an annual runoff depth of 18 mm could be attributed to spring discharge (see section 3.4.4.2.1). In addition, an effluence was discovered in the lower part of the Ronquillo River during the field campaigns in September 2009 and September 2012. The effluence may be attributed to a stratigraphic boundary, intersected by the Ronquillo's stream channel, where a stratum of less permeable claystone underlies strata of marls and carbonate rocks (Peña and Vargas 2006). On the basis of discharge measurements taken along the longitudinal section of the Ronquillo River in 2009 and 2012 a regression model is fitted to the discharge-area relation in order to estimate the effluent flow to the Ronquillo River. As a result approximately 26 ls^{-1} – corresponding to an annual runoff depth of 20 mm – may be attributed the effluent flow (see section 3.4.4.2.2).

It is broadly accepted that the Jalca grasslands are a main groundwater recharge area. Therefore it is interesting to note that for the Ronquillo basin, groundwater effluence and spring discharge are additional important sources for dry seasonal discharge. However, the numbers are prone to methodological and data uncertainties and therefore must be considered with caution. The lack of reliable data and long term observation requires simplification and a number of assumptions to be made. For instance, knowledge about the spatial extension and soil depth of the Andosols covering large parts of the upper catchment area is fairly vague. In addition, no continuous data on the effluence in the lower part of the Ronquillo is available and data of spring discharge is restricted to one season. Though, by summing up the estimates for each particular water storage entity and relating them to the estimated mean water storage volume of the Ronquillo basin, approximately 83% of the mean water storage capacity can be accounted for; the residual, approx. 17%, may be attributed to methodological and data uncertainties (Figure 6–2).

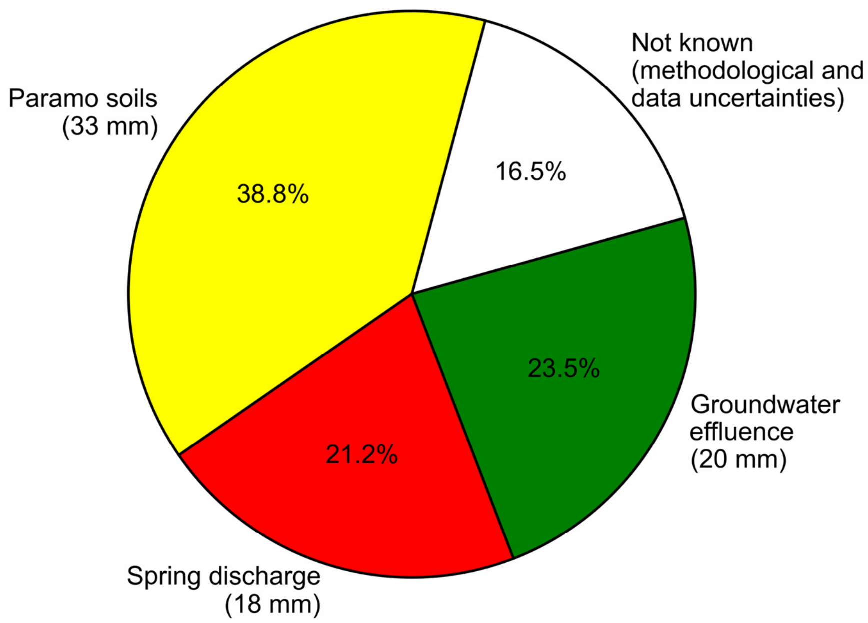

Figure 6–2: Quantification of natural water storage entities in the Ronquillo watershed. The estimates for each particular water storage entity, based on the different methods described in the text, are related to the mean water storage capacity of 85 mm, obtained by the fitting of non-linear storage-discharge relations (Wittenberg 1994, 1999) to the recession curves of the Ronquillo River. The numbers for each particular water storage entity in sum account for about 83% of the mean water storage capacity. The residual, however, of approx. 17%, may be attributed to methodological and data uncertainties.

Despite the critical importance of water resources to society, there is a conspicuous paucity of hydrological data in both the spatial and temporal domains. This problem is not restricted to the Andean region (Hannah et al. 2011). Indeed, in remote and complex environments such as the tropical Andes, lack of data and the difficulty in implementing and maintaining observation networks is a key obstacle to advancing hydrological knowledge (Celleri 2011). The Peruvian weather authority SENAMHI (http://www.senamhi.gob.pe), maintains a monitoring network of considerable scope; however, the monitoring network nodes are biased towards more accessible locations, often located close to population centers or roads. To a much lesser extent the monitoring network extends to the headwaters, which are crucial for understanding hydrological processes for sustainable water resource management and the assessment of ecosystem services.

In order to address the lack of hydrological data for the Andean region the collaborative initiative *Iniciativa Regional de Monitoreo Hidrológico de Ecosistemas Andinos* (iMHEA, http://imhea.condesan.org/) was founded in 2010. This initiative provides a common framework for network design, station maintenance, instrument selection and installation, data downloading and processing, storage and distribution, and the generation of reports for distribution among the communities (Celleri 2011). While iMHEA has not been active in the Cajamarca region to date, initiatives such as iMHEA should be considered as partners for future hydro-meteorological research projects in the region of Cajamarca or elsewhere in the Andean region. Such locally based initiatives may substantially contribute to monitoring-network maintenance and data management in future field projects. In addition such residential initiatives may be entrusted with sustaining monitoring networks beyond the scope of dedicated research projects.

6.1.3 Conceptual water balance model for the Ronquillo watershed

A conceptual water balance model for the Ronquillo watershed is developed by combining actual measurements for the period from 2008 to 2012, best available estimates, and rainfall-runoff model output (Figure 6–3). The estimations for areal precipitation (P_{areal}) of 1158 mm yr^{-1}, and for potential and actual evapotranspiration rates (*ETp, ETa*) of 1023 mm yr^{-1} and 675 mm yr^{-1}, respectively, are rainfall-runoff model outputs, based on data from the Alto Chetilla, Chamis, and Ronquillo rain gauges. Potential evapotranspiration rates are calculated by applying the modified Hargreaves equation given by Droogers and Allen (2002, see Equation 5–1). The numbers for evapotranspiration are in good agreement with data published by SENAMHI (2011) and by other available sources (González and Picard 1986; Benavides-Ferreyros et al. 2007; Fernández-Rubio et al. 2012).

The quantification of the Ronquillo watershed's water storage volume has been discussed before (see section 3.4.3). The Ronquillo's water storage volume corresponds to a runoff depth of approximately 85 mm. Analysis of the hydrological entities constituting base flow indicate that, of this amount, gravitational water accounts for 33 mm, spring discharge for 18 mm, and groundwater effluence for 20 mm. However, approximately 14 mm could not be accounted for, suggesting methodological and data uncertainties. It should be noted that the estimation of the Andosol's water storage volume in the Ronquillo watershed corresponds to a runoff depth of approx. 100 mm (see Table 3–5); however, approx. 67 mm of this amount correspond to capillary and hygroscopic water, which however do not contribute to the Ronquillo's discharge.

Computation of the discharge time series from the Ronquillo gauging station yields a mean annual runoff depth of 310 mm. The base flow index (the ratio of base flow to total flow) is computed as 0.44 (see section 3.4.2), thus indicating that 44% of discharge corresponds to base flow, whereas 56% corresponds to direct runoff, constituted by overland flow and fast interflow.

However, according to the common equation for water balance ($Q = P - E$), where Q is discharge, P is precipitation and E is evaporation, the Ronquillo's runoff depth ought to be about 483 mm yr^{-1}, which is higher than the measured runoff depth of 310 mm yr^{-1}. However, a water storage term, including capillary and hydroscopic water, and a water loss term, including deep percolation losses, were not taken into account. Furthermore, there are uncertainties related to the estimation of the precipitation and the evaporation term, including uncertainties due to data quality and data availability, spatial extrapolation of point data measurements, methodological simplifications, and the lack of knowledge on subterraneous flow paths. Accordingly, the figure of measured discharge appears reasonable.

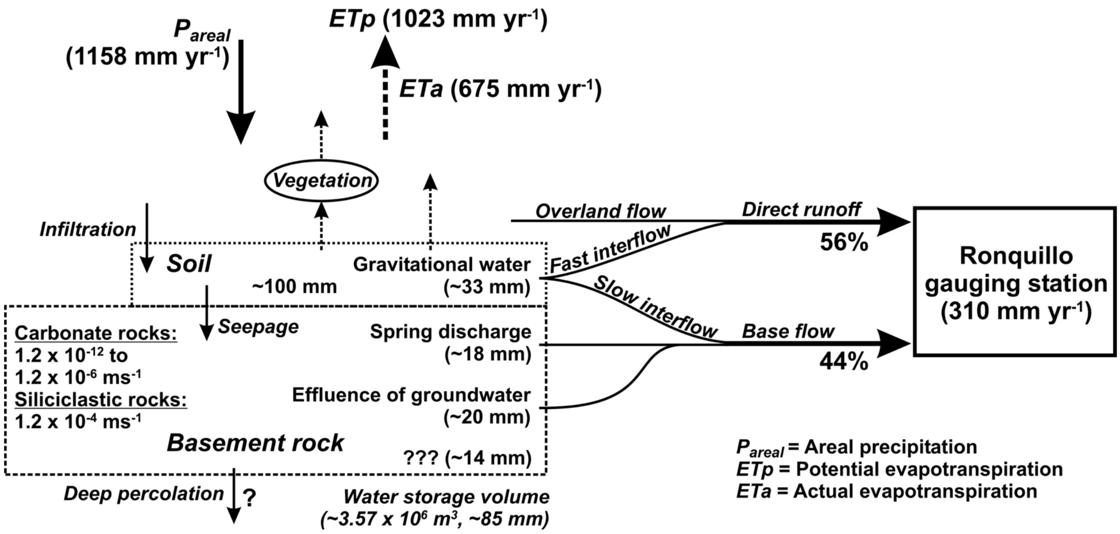

Figure 6–3: Conceptual water balance model for the Ronquillo watershed. The figure combines data of actual measurements for the period from 2008 to 2012 (see section 3.4.1), best available estimates (see section 3.4.3 and 3.4.4), and rainfall-runoff model output (see section 5.3.2). Numbers for the hydraulic conductivity of carbonate rocks and siliciclastic rocks are derived from Fernández-Rubio et al. (2012) and Peña and Vargas (2006), respectively.

6.2 Decision making and scenario development

It is widely acknowledged that soil and water conservation (SWC) measures enhance water productivity (Tian et al. 2003; Oweis and Hachum 2006; Kahinda et al. 2007; Makurira et al. 2009) and reduce surface runoff and soil erosion (Dehn 1995; Alegre and Rao 1996; Gardner and Gerrard 2003; Hammad et al. 2004; Al-Seekh and Mohammad 2009). However, implementing and sustaining SWC measures on the ground is a difficult and multistage task (Hudson 1991; de Graaff et al. 2008; Mekdaschi Studer and Liniger 2013). A number of variables influence the adoption of SWC measures. Accordingly, diverse options based on various objectives and criteria need to be evaluated when designing an implementation scheme (Schwilch et al. 2012).

Crucial factors for the adoption of a SWC measure are, first, the selection of the appropriate SWC measure, and, second, the geographical site selection to implement the measure (de Graaff et al. 2008; Liniger et al. 2011; Mekdaschi Studer and Liniger 2013). There are many publications and handbooks dedicated to measures, techniques and technologies for soil and water conservation (e.g. Morgan 1986; Hudson 1987; Young 1989; Critchley and Siegert 1991; Oweis et al. 1999; FAO 2000; Lancaster 2006; Lesschen 2007; Zeh 2007; Lancaster 2008; Bekele et al. 2009; Schwilch et al. 2010; Liniger et al. 2011; Mekdaschi Studer and Liniger 2013). However, it remains a challenging task to consider and select an appropriate SWC measure for a given location based on a literature survey. A promising approach to overcome this obstacle is provided by the *World Overview of Conservation Approaches and Technologies initiative* (WOACT; http://www.wocat.net), which provides tools that allow knowledge sharing, assistance in searching for appropriate SWC technologies and approaches, and support in decision-making and planning (Liniger and Schwilch 2002). The WOCAT methodology was successfully applied in the EU-funded project *Desertification mitigation and remediation of land – A global approach for local solutions* (DESIRE, 2007–2012, http://www.desire-project.eu), a global research initiative aimed at mitigating desertification and remediating degraded land, and at providing decision support for the selection of appropriate resource conservation measures for a number of dryland study sites in the Mediterranean and around the world (Schwilch et al. 2012).

In this thesis SWC measures were taken into consideration, which have already been applied, at least at some locations in the region under investigation (Figure 6–4). Thus, an emphasis is placed on earthworks (terraces and bunds), on check dams, and on afforestation of pine and eucalyptus species, for which the region of Cajamarca is well known (Sánchez-Zevallos 1998, 2000). Noteworthy, the catalogue of feasible SWC measures taken into considerations for the CASCUS research initiative is much broader, including water retention basins, micro reservoirs and conservation agriculture, among others. However, a scientific evaluation of these measures is slated for publication elsewhere.

Figure 6–4: Measures of soil and water conservation in the region of Cajamarca. Upper left: Terraces at the demonstration site "Parcela Pablo Sanchez," west of the city of Cajamarca (Photo: Schulte 2006). Upper right: Check dam in Choromayo, a headwater area of the Ronquillo basin (Photo: Krois 2009). Lower panel: Afforestation area in the Jalca orobiome, north-west of the city of Cajamarca (Photo: Krois 2009).

Once a set of SWC measures has been determined, different scenarios for geographical site selection need to be developed, each of them representing a possible future state of implementation. Scenario development in support of decision-making may be conceptualized as a process of progressive stages, including feedback loops (Figure 6–5) (Aspinall and Pearson 2000; Peterson et al. 2003; Mahmoud et al. 2009). In the following sections, the process of scenario development in support of decision-making is discussed under the framework of the CASCUS research initiative.

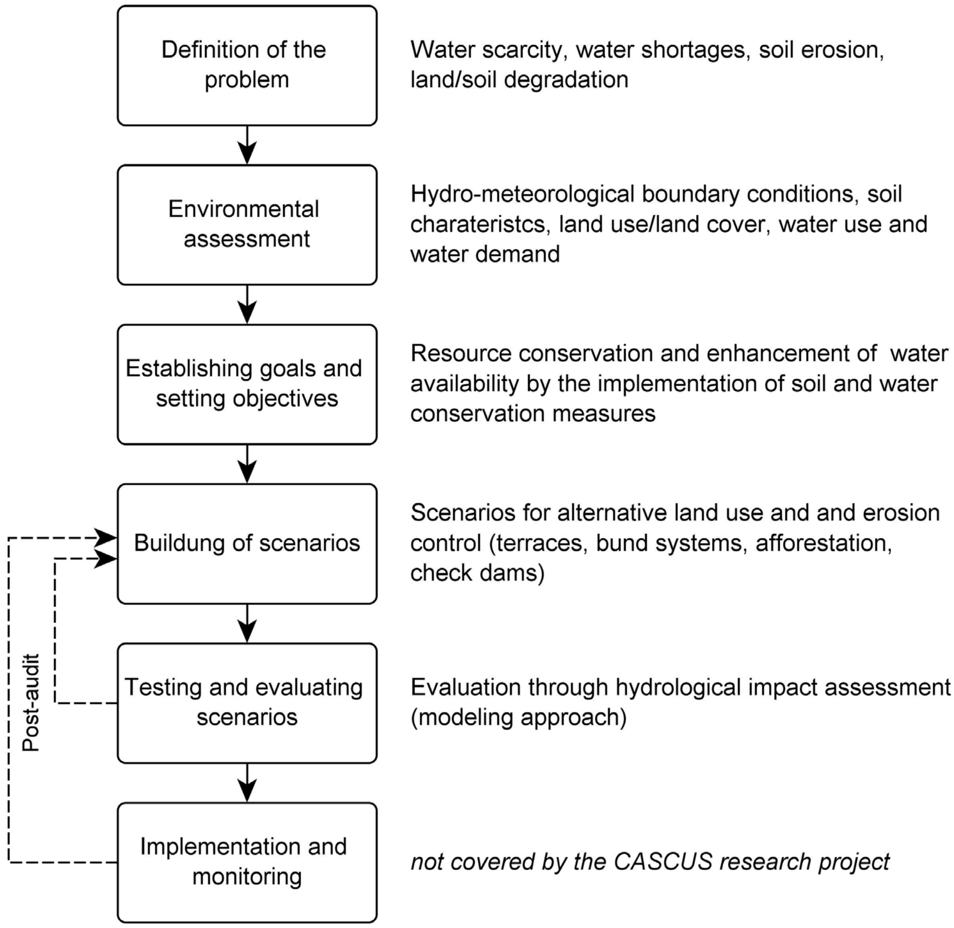

Figure 6–5: Schematic illustration of scenario development in support of decision-making (modified from Aspinall and Pearson 2000; Peterson et al. 2003). For each stage, keywords and main ideas are given related to the CASCUS research project.

6.2.1 Definition of the problem

Water resources are a very sensitive issue in the Cajamarca region. Water scarcity arises due to seasonal rainfall distribution (Krois et al. 2013b), a lack of adequate water retarding capacity in the watershed (Krois et al. 2013a), and increasing water demand (EPS SEDACAJ S.A. 2006) attributable to the region's economic development (CENAGRO 2012), which has been boosted by a fast-growing mining industry (Bury 2004, 2005). Water demand already surpasses water availability during the dry season, such that the water supply for end-users is interrupted regularly in the city of Cajamarca (CES 2010), and by 2035 water demand is projected to double over 2005 levels (EPS SEDACAJ S.A. 2006). Competition for water resources and a knowledge gap regarding the impact of mining on water resources (Bury 2004, 2005) have been triggering conflicts and social unrest (Gifford et al. 2010; Triscritti 2013).

The water resources of the Ronquillo River are of special interest for the city of Cajamarca, as about one-third of the total urban water supply is provided by the discharge of the Ronquillo River (Atkins et al. 2005; EPS SEDACAJ S.A. 2006). In addition, the Ronquillo watershed is the only watershed providing drinking water for the city of Cajamarca, where mining operations have not been conducted to date, however, mining concessions have already been awarded in the area of the Ronquillo basin (INGEMMET 2014).

As shown by Krois et al. (2013a) the organic rich soils of the Jalca grasslands contribute significantly to base flow generation. However, the favorable characteristics of these soils develop under cool and wet climatic conditions (Buytaert et al. 2006a), and, in addition, the favorable water retention potential of the Jalca grasslands may irreversibly be lost owing to inappropriate land use, including agricultural activities or afforestation (Poulenard et al. 2001; Farley and Kelly 2004; Buytaert et al. 2005b; Harden 2006; Buytaert et al. 2007). Recently the Intergovernmental Panel on Climate Change (IPCC) confirmed warming since the mid-1970s of 0.7°C to 1°C throughout South America, and projects warming of +1.7°C to +6.7°C for Representative Concentration Pathways (RCPs) 4.5 and 8.5 by the year 2100 (Magrin et al. 2014). A biome modeling approach, which assesses the impact of climate change on the expansion of tropical Andean biomes, indicates that high Andean grasslands are most at risk due to the lack of upslope area for migration. These grasslands are projected to lose about 30% of their present day area in 2040–2069 (Tovar et al. 2013a). In a land cover change analysis for the region of Cajamarca, Tovar et al. (2013b) found that the area covered by the Jalca grasslands has been decreasing at a rate of 1.5% per year due to displacement by agriculture, mining and afforestation. These findings are corroborated by the anecdotal perceptions of the local population, who note that agricultural activities have spread across the Jalca grasslands up to altitudes where farming was prevented some decades ago by low temperatures (Florindez, A. 2014, pers. com.). Thus, it is reasonable to assume that climate change and human activities are considerably impacting the hydrological function of the Jalca grasslands and, by extension, the water regulation function of the Ronquillo basin. However, if the water retention potential of the Jalca grasslands diminishes, higher peak discharges are to be expected during the rainy season, as the soil layer will fill up more rapidly, and thus enhance the potential of saturation excess overland flow generation. In contrast, during the dry season the reduced storage capacity of the soil layer will cause less base flow to be released.

Moreover, the lower and middle catchment areas surrounding the city of Cajamarca are severely affected by land degradation and soil erosion (De la Cruz et al. 1999). Continued degradation and erosion of the topsoil reduces infiltration rates and water storage capacity, which in turn increases surface runoff and, correspondingly, soil erosion and further degradation (Martinez-Mena et al. 1998; Römkens et al. 2002; Carrillo-Rivera et al. 2008). Owing to this self-reinforcing process, the natural water retarding and water storage capacity – and, by extension, the water regulation capacity – of the watersheds is in continuous decline. Taking into account the projected increase in water consumption owing to population growth and economic development (EPS SEDACAJ S.A. 2006; CENAGRO 2012), socio-economic conflicts owing to water resource allocation will be even more likely in the future (Figure 6–6).

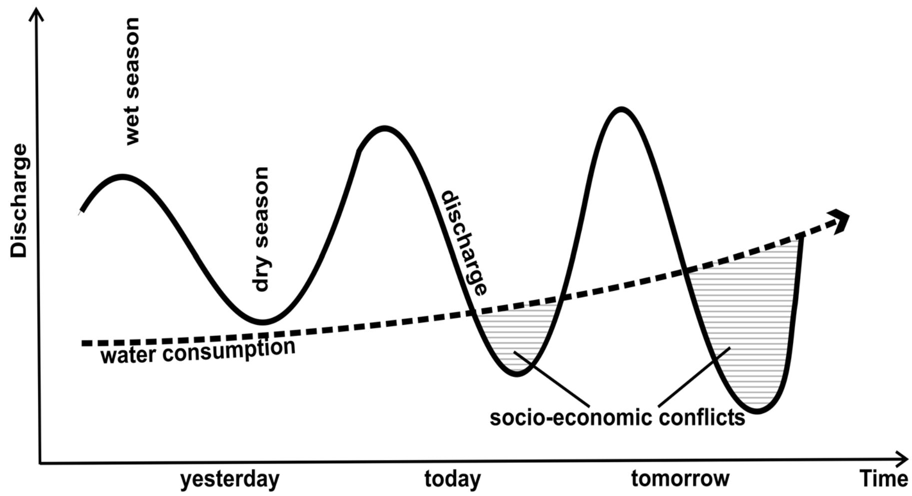

Figure 6–6: Deterioration of the watershed's water retention capacity results in higher seasonal discharge variability. Growing demand may exceed water supply during the dry season and lead to socioeconomic conflicts unless measures are taken to adapt to the new situation (modified based on Vergara 2009).

6.2.2 Environmental assessment

The environmental assessment conducted within the framework of the CASCUS research project focuses on the key aspects of the hydrological system, such as the hydro-meteorological boundary conditions, land use/land cover, and soil characteristics. Detailed studies concerning hydro-meteorological boundary conditions are presented in section 2 and section 3. The hydrology and hydrogeology of the Ronquillo basin have been previously discussed in thesis papers by Hartwich (2010) and Abendroth (2011).

Within the CASCUS initiative, Rohde (2012) investigated land cover and land use while drawing on Quickbird data sets from 2003, 2004 and 2007 to obtain a land use map of the Ronquillo catchment. In an ongoing master thesis, a land use and land cover classification approach is being elaborated, based on RapidEye remote sensing data for the Mashcón River basin (306 km²), which hosts the Ronquillo watershed (Taheri-Rizi, in prep.). The main aim of that study is to quantify the green water cycle in the Mashcón watershed by applying CROPWAT 8.0, a model for the calculation of crop water requirements provided by the FAO (Smith 1992).

Within the CASCUS initiative a number of soil samples, gathered during the field campaigns of 2008, 2009 and 2012 have been analyzed in respect to soil texture, organic content, and chemical and mineralogical composition. Until now, however, there hasn't been a systematic survey of spatial soil patterns and the physiochemical composition of the soils in the Ronquillo watershed. Information on the spatial distribution and the physical characteristics of the soils occurring in the watershed of the Ronquillo is primarily available in the literature (ONERN 1975; Landa-E. et al. 1978; Poma-Rojas 1989; Poma-Miranda and Poma-Miranda 2001; Poma-Rojas and Alcántara-Boñón 2010). More recently, a study on the San Lucas River basin, which hosts the Ronquillo basin, revises the state of knowledge concerning soils in the San Lucas basin and presents several representative soil profiles within the Ronquillo watershed, including physiochemical soil parameters for each of them (Poma-Rojas 2013).

In addition, several Master and Bachelor theses related to the CASCUS research project have substantially widened the knowledge base about the environmental boundary conditions of the region of Cajamarca and the Ronquillo watershed (refer to Table 1–1 for bibliographic information).

6.2.3 Establishing goals and setting objectives

The goals and objectives of the CASCUS research project have informed scenario development and the decision making process of the present thesis. The main idea of the CASCUS research project is to improve water availability and to reduce overland flow, thus dampening soil erosion and land degradation, by implementing decentralized measures for resource conservation. Large scale water related problems are encountered by adaptive small scale measures in the management of water and soil resources; a conceptual approach that is in line with the concepts of decentralized flood protection or decentralized water retention (Assmann et al. 1998; Marenbach and Koehler 2003; Röttcher et al. 2007; Schulte et al. 2009; Reinhardt 2010; Bölscher et al. 2013). Consequently, the main objective of the scenario development process is to provide implementation scenarios for selected SWCTs in the Ronquillo watershed, in order to evaluate their impact on catchment hydrology using a hydrological modeling approach.

6.2.4 Building of alternative scenarios

The scenario development stage aims to model different states of SWCT implementation and associated land use changes. The present study evaluates SWCTs that fall under three categories: (A) earthworks, (B) afforestation, and (C) the construction of check dams. These categorical clusters are subdivided into different representations, each of them accounting for a particular technique and a different level of spatial implementation (see Table 6–1).

Table 6–1: Type and description of the scenarios and methods applied for scenario development

Type	Description	Method for scenario development
Earthworks (A)	Terraces (A_T) Bunds (A_B) Combined bunds and terraces (A_{BT})	Multi-criteria evaluation (MCE), Analytical Hierarchy Process (AHP), Weighted overlay process (WOP)
Afforestation (B)	Expansion of existing afforestation (B_{Buffer}) Afforestation of areas of scarce vegetation (B_{sVeg})	Land cover map and Geographical Information System (GIS)
Check dams (C)	Implementation in all stream channels (C_{all}) Implementation in intermittent streams only (C_{int})	River channel network and field assessment

The earthworks scenarios (A) are developed on the basis of a decision support model (DSM), which assess potential sites for the implementation of earthworks in the Ronquillo basin (Krois and Schulte 2014). The DSM implements a GIS-based multi-criteria evaluation (MCE) procedure, taking into account several environmental site assessment criteria such as meteorology, hydrology, topography, land use, and soil properties. To assess the relative weight of each environmental site assessment criterion, a pair-wise comparison matrix method, known as the Analytical Hierarchy Process, is applied. Suitability maps for each particular SWCT are obtained by applying the weighted overlay process, a routine for multi-criteria evaluation implemented in ArcGIS (for details, see section 4). The suitability maps show that approximately 44% of the catchment area is highly suited for the implementation of terraces, and 24% of the catchment area is highly suited for the implementation of bund systems.

The site assessment, however, is of a preliminary nature, as validation of the decision support model is lacking. Validation may be achieved by applying the promoted GIS-based MCE approach to a region, where earthworks are already in place, and by comparing the results of the suitably mapping with the existing spatial pattern of earthworks in order to validate the choice of the environmental site assessment criteria and its relative weighting. However, terraced landscapes are landscapes of great intricacy and highly complex systems that have emerged from the outcome of multiple small-scale decisions by multiple people, iterated over many generations (Bevan and Conolly 2011). Consequently predictive modeling of terraced landscapes is very challenging, for, in addition to environmental criteria, cultural and socio-economic criteria have to be taken into account (Antle et al. 2005; Posthumus and de Graaff 2005; Tenge and Hella 2005; Countryman et al. 2011; Teshome et al. 2013).

Afforestation (B) scenarios are developed for the planting of pine and eucalyptus species. This scenario development stage is based on two underlying hypotheses. The first is that the existing forest areas will build the nucleus of future afforestation. The second is based on the common idea that for soil and water conservation and erosion control, degraded areas will be subject to afforestation. The spatial extent of each scenario is delineated on the basis of a land cover map of the Ronquillo watershed provided by Rohde (2012) within a GIS environment (ArcGIS).

For the implementation of check dams (C), two scenarios are developed. In the first, check dams are implemented in all stream channels. In the second, check dams are implemented in intermittent stream channels only. The selection procedure is based on a river channel network map delineated from a digital elevation model (ASTER-DEM).

6.2.5 Testing and evaluation of the scenarios

Within the framework of the CASCUS research project the different scenarios were evaluated using a hydrological modeling approach. The rainfall-runoff model NASIM 3.7 (Hydrotec 2009) was applied to quantify the impact of different SWCT implementation scenarios on the hydrological stage variables discharge, overland flow, and high flow of the Ronquillo River. The hydrological modeling approach is presented in section 5.

6.2.6 Implementation and monitoring

The implementation and the subsequent monitoring of the promoted SWC measures is not covered by the CASCUS research project. However, decision-making in the context of land use management and planning is most successful as an iterative process of consultation, evaluation and revision (Aspinall and Pearson 2000; Mahmoud et al. 2009).

6.3 The impact SWCTs on catchment hydrology and water availability

6.3.1 Modeling approach

The positive effect of SWCTs on soil and water retention is well established on the scale of small plots (Maetens et al. 2012). However, owing to the non-linearity and scale dependency of runoff processes, the extrapolation of plot measurements to the catchment scale is of limited value (Lesschen et al. 2009). Accordingly, hydrological models are used to up-scale the impact of SWC practices on soil and water fluxes to the catchment scale (e.g. Al-Weshah and El-Khoury 1999; Ngigi 2003; Ngigi et al. 2007; Hessel and Tenge 2008; Andersson et al. 2009; Lesschen et al. 2009; Ouessar et al. 2009). However, depending on the model structure SWCTs may not be incorporated directly into a hydrological model, but by changing the model input parameters (e.g. infiltration rates, surface roughness or saturated conductivity) their hydrological effects may be reproduced in an indirect way (Hessel and Tenge 2008).

The modifications that are most appropriate for replicating the hydrological impact of a particular SWCT depend on the type of model applied, and its conceptual specifications and limitations. Ouessar et al. (2009), for example, modified the code of the Soil and Water Assessment Tool (SWAT) to simulate the collection of runoff from water-harvesting structures by bringing the runoff generated in a sub-catchment back to the water-harvesting Hydrological Response Units (HRUs) in the sub-catchment. Yang et al. (2009) applied SWAT to assess the effect of flow diversion terraces systems on stream water and sediment yield in the Black Brook watershed in northwestern New Brunswick, Canada. In order to simulate the impacts of flow diversion terraces on abating water and sediment yields, the authors modified infiltration-related parameters and the support practice factor (P-factor), which is one of the factors in the Modified Universal Soil Loss Equation (MUSLE) used in SWAT (Wischmeier and Smith 1978). Al-Weshah and El-Khoury (1999) applied the Hydrologic Engineering Center model (HEC-1) to compute the effect of afforestation, terracing and check dams on the hydrology of the Petra watershed in Jordan, by adapting CN-values and the time of concentration. Hessel and Tenge (2008) applied the process-based Limburg Soil Erosion Model (LISEM) to assess the effectives of SWC measures on soil loss and runoff in the Gikuuri catchment in Kenya. The authors used data obtained by in-field measurements and by a literature survey to modify model input variables, such as soil moisture, cohesion, aggregate stability and roughness, among others. Lesschen et al. (2009) used the LAPSUS (Landscape Process Modelling at Multi-Dimensions and Scales) model to simulate runoff and sediment dynamics of the Carcavo basin, a terraced landscape in southeast Spain. Terraces were modeled by assigning them an additional storage and infiltration capacity. Callow and Smettem (2009) analyze the influence of water collection infrastructure on the hydrologic connectivity of hillslopes in dryland agricultural areas in the Kent River catchment in southwestern Australia. The authors edited a DEM to replicate hydrologic flow paths of small-scale water diversion (earth banks) and collection (farm dams) infrastructure. Gatot et al. (2001) applied a geomorphologic-unit-hydrograph based model (H2U) to simulate the discharge of the Kali Garang river in Indonesia. The authors compute the outflow of terraced areas by a hydraulic model, based on the theoretical assumption that cascaded irrigated terraces are analogous to a series of linear reservoirs.

6.3.2 The rainfall-runoff model NASIM

In this thesis, the rainfall-runoff model NASIM version 3.7 is applied to assess the impact of selected SWCTs on the catchment hydrology of the Ronquillo basin. NASIM is a deterministic and semi-distributed rainfall-runoff model, which calculates the water balance for user-defined sub-catchments. Each sub-catchment is assigned a time series with data on temperature, rainfall and potential evaporation. In addition each sub-catchment is assigned a representative stream channel, characterized by channel geometry and Strickler roughness values. Each sub-catchment is composed of elementary units, corresponding to the concept of Hydrological Response Units (Beven 2012). In NASIM elementary units are characterized by a particular land cover and a particular soil type. In order to reduce computation time, elementary units distributed throughout a sub-catchment but with identical land cover/soil type combinations are aggregated to simulation units (Hydrotec 2009). In NASIM surface runoff is generated either as infiltration- or as saturation-excess overland flow on the basis of a soil moisture simulation approach developed by Ostrowski (1982). Via soil moisture accounting actual infiltration, evapotranspiration and seepage are computed by piecewise linearization of the nonlinear relationships for infiltration and seepage in line with Holtan (1961) and Bear (1972), respectively (Ostrowski 1992). Surface runoff is routed based on the time-are technique derived by Clark (1945), coupled to a linear reservoir. Clark’s unit hydrograph approach describes the translation of flow through the watershed by runoff isochrones and a corresponding histogram of contributing area versus time (Nicklow et al. 2006). Interflow and base flow are modeled by a linear reservoir approach and channel flood wave propagation is modeled according to the Kalinin-Miljukov approach (Ostrowski et al. 1988). In NASIM the runoff components are not routed between elementary units within the sub-catchments, but each runoff component is added directly to the outlet of the sub-catchment. The outlet of a particular sub-catchment corresponds to the inflow of sub-catchment downstream.

6.3.3 Implementation of SWCTs in the NASIM rainfall-runoff model

In this thesis three different types of SWCTs (earthworks, afforestation and check dams) are implemented in the NASIM model. Each type of SWCTs is further subdivided into different implementation scenarios (see Table 5–2).

For the development of earthworks scenarios, potential sites for earthworks are delineated on the basis of a GIS-based multi-criteria evaluation procedure (Krois and Schulte 2014). Three different implementation scenarios are realized, each of them accounting for a particular technique and/or a particular level of spatial implementation (see Figure 5–4). These are terraces (scenario A_T), bund systems (scenario A_B) and a combination of both (scenario A_{BT}), covering 16%, 12% and 26% of the Ronquillo watershed, respectively. Earthworks are parameterized by modifying the input parameters of the hydrological model with respect to surface runoff generation and runoff concentration. In order to model the encouraging effect of earthworks on infiltration (Dehn 1995; Inbar and Llerena 2000) the maximum soil infiltration rates are modified by setting the index of surface-connected porosity (*av*) in Equation 5–6 to 0.8 for bunds and to 0.6 for terraces (Holtan and Lopez 1971; Hydrology Handbook 1996; Hydrotec 2009). In order to model the impact of earthworks on runoff concentration, the Strickler roughness value (k_{st}) is modified for areas covered with terraces and bunds. Corresponding Strickler roughness values are estimated by a step-wise additive/weighted roughness estimation method (Engman 1986; Arcement and Schneider 1989; Phillips 1989). According to this roughness estimation method k_{st} for terraces and bunds is set to 3 and 5, respectively. In addition, to account for the reduced slope steepness of terraces the DEM is leveled within a GIS environment in order to obtain stepped terrain morphology (Callow and Smettem 2009).

With respect to the implementation of afforestation measures, two scenarios are developed, based on the underlying hypothesizes that the existing forested areas will build the nucleus of forthcoming afforestation (B_{Buffer}), and that for soil conservation and erosion control degraded areas are afforested primarily (B_{sVeg}). To represent the afforestation scenarios in the NASIM model, the forest land use classes of pine and eucalyptus are expanded. According to the climax in growth rate for *Pinus radiata* and *Eucalyptus globulus* (Sánchez-Gómez and Gillis 1982; Villar-C et al. 1982; van den Abeele 1995) all plantations above a elevation threshold value of 3300 m asl are modeled as pine species, whereas all plantations below the threshold elevation are modeled as eucalyptus species. Vegetation parameters required for the NASIM model are obtained from the literature (Burgy and Pomeroy 1958; Hoyningen-Huene 1983; Leuschner 1986; Valente et al. 1997; Allen et al. 1998; Domingo et al. 1998; LUBW 2002; Breuer et al. 2003; Hydrotec 2009; Descheemaeker et al. 2011).

For the implementation of check dams in the hydrological model, two scenarios are development. In one scenario (C_{all}) check dams are implemented in all stream channels, whereas in the other (C_{int}) check dams are implemented only in the intermittent stream channel of Manzana River and Rosapata River (see Figure 5–1). Check dams are parameterized by adjusting the values of river bed roughness. Strickler roughness values (k_{st}) for channel sections are set to 16, corresponding to the values reported by Wang and Yu (2007) for step-pool systems, as check dams resemble the longitudinal profile of step-pool reaches (Lenzi 2002).

6.3.4 Model performance

The NASIM hydrological model, run on a daily time step, is capable of reproducing the seasonal runoff characteristics and cumulative runoff over the three-year monitoring period (see Figure 5–6 and 5–7). The statistical model performance evaluation confirms that the model is capable of capturing the hydrology of the Ronquillo basin. However, the model performs better in modeling the hygrograph's rising and recessional limps, whereas it fails to predict the magnitude of peak flows. The statistical model evaluation for the calibration period results in a model performance of NSE = 0.71, RSR = 0.54 and PBIAS = 9.04%. As common in hydrological modeling studies the model performance is not as good for the validation period, with NSE, RSR and PBIAS being 0.57, 0.65 and 1.48%, respectively. According to Moriasi et al. (2007) the numbers for NSE and RSR correspond to a rating of "good" and "satisfactory" for the calibration and the validation period, respectively (see Table 5–3). It is relevant to note that the model performance rating given by Moriasi et al. (2007) is for a monthly time step. Less strict model performance rating is warranted for a daily time-step. In contrast to the moderate rating of NSE and RSR, PBIAS is rated as "very good" for the calibration and validation period.

It should be noted that NSE and RSR evaluation is based on the sum of squared errors and thus provides a measurement of the overall error. Such performance measures are known to be very sensitive to extreme values (Legates and McCabe 1999). This has led to significant criticism of NSE as a performance measure in hydrological modeling (Beven 2012). More recently Cheng at al. (2014) show that a hydrological model that is calibrated to maximize NSE may mimic observed major flood events well, but fails to mimic the base flow. Consequently, a combination of various performance measures is warranted for the assessment of hydrological model performance (Moriasi et al. 2007).

6.3.5 Model uncertainty

Uncertainty in hydrological modeling is related to the fact that no rainfall-runoff model is a true reflection of all the processes involved. To overcome the limitations in model structure and data available to model parameter values, initial conditions and boundary conditions in hydrological models are calibrated against observational data. However, the optimum parameter set for one period of observations may not be the optimum set for another period (Beven 2012) and different performance measures usually give different results in terms of the optimum parameter values (Cheng et al. 2014). In the early 1990s Keith Beven proposed the concept of *equifinality* to be applied to hydrological modeling (Beven 1993). The concept originates from system theory (Bertalanffy 1950) and was adapted to geomorphology (Culling 1957; Culling 1987) in order to describe the multiplicity of potential explanations for the evolution of landforms when their true initial conditions and developmental history are unknowable (Beven 2012). *Equifinality* in hydrological modeling implies that there are different model representations of a catchment that may be equally valid in terms of their ability to reproduce acceptable simulations of the available data (Beven 2006; Beven 2012). This in turn indicates that there is no single model configuration but a number of acceptable model configurations that can provide useful predictions and that, consequently, all model calibrations and subsequent predictions are subject to uncertainty. The main sources of uncertainty in the application of hydrological modeling may be categorized as uncertainties in the initial and boundary conditions, uncertainties in model structure, uncertainties in parameter estimation, and overlooked uncertainties (Figure 6–7).

The following paragraphs outline the limitations and uncertainties of the rainfall-runoff modeling approach applied in the present study. Overlooked uncertainties are not further discussed.

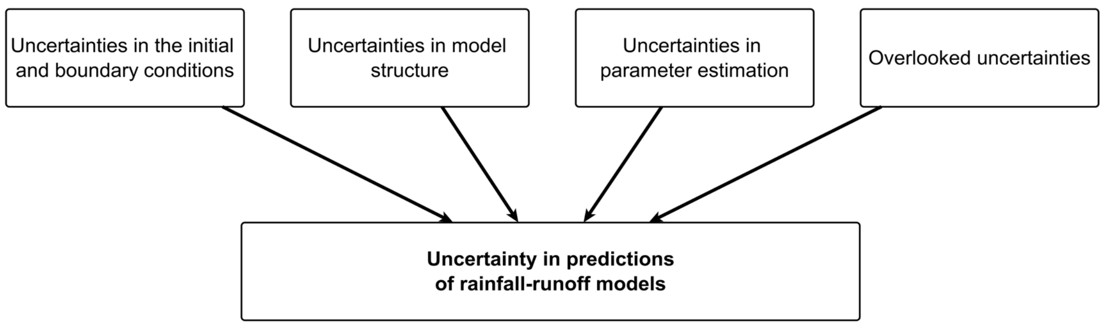

Figure 6–7: Main sources of uncertainty in the application of rainfall-runoff models (after Beven 2012).

6.3.5.1 Uncertainties in the initial and boundary conditions

Uncertainties in the initial and boundary conditions are mainly related to the data that are used to set up and run a rainfall-runoff model. This includes all model inputs, either meteorological time series (temperature, rainfall, evaporation, etc.) or spatial data describing topography, soil and vegetation cover, etc., as well as any empirical data used to calibrate the model output, such as discharge and soil moisture measurements, among others.

The success of a hydrological model depends critically on the data available to set it up and to run it. No rainfall-runoff model produces accurate runoff predictions if fed with inaccurate rainfall data (e.g. Beven 2012). Uncertainty in rainfall data arises from (i) an inadequate representation of the areal precipitation field delineated by a set of point-scale measurement and (ii) the interpolation of rain rates between these gauges (McMillan et al. 2011). In addition, the measurement process is prone to errors arising from mechanical limitations, wind effects and evaporation losses (Sevruk et al. 2009).

Another source of uncertainty is the spatial representation of soil and vegetation cover. In heterogeneous landscapes the value of soil sampling is limited, as values obtained by one sample may not be representative for a larger area, nor for the effective element value needed as an input parameter for the hydrological model. In addition, parameters accounting for soil moisture in time and space are difficult to measure. Accordingly, pedotransfer functions, which provide estimates of the parameters based on soil texture variables, are widely applied (Beven 2012).

The soil maps and representative soil profiles available to set up the NASIM model are only a very rough representation of the heterogeneity observed in the field. More recently, a revised soil map had been made available (Poma-Rojas 2013). A land use and land cover map is provided by Rohde (2012), who used Quickbird remote sensing data from 2003, 2004 and 2007. Although the land cover map is very detailed, field observations reveal considerable land use diversity in the Ronquillo watershed. There is a high temporal fluctuation in the areas that are used for agriculture and farmland that lies fallow. In addition, a clear increase in urban infrastructure and housing can be observed. During the period of investigation (2008–2014) several dirt roads along with power supply lines were constructed and a considerable number of new houses were built, both indicating dynamic population growth and economic development. It remains a challenge to update land cover mapping to accurately reflect changing land cover.

Another specific problem encountered with respect to data quality is related to the discharge time series of the Ronquillo gauging station, which is used for model calibration. At the beginning of the CASCUS research project a pressure transducer that measures water stages was installed close to a weir at the water intake facility of the Ronquillo River. The water stage record is transformed into a discharge time series by applying Poleni's equation (Patt and Jüpner 2013). However, from time to time, but most likely during the high river stage, the staff at the water intake facility open a gated spillway in order to flush out accumulated sediments or to prevent flooding of the facility. The opening of the additional spillway during high river stages, however, biases the stage-discharge relation and ultimately causes data loss. Unfortunately, there is no documentation of the maintenance schedule. Accordingly, the discharge time series is subject to uncertainties, particularly with regard to peak flow discharge.

6.3.5.2 Uncertainties in model structure

A model is only an approximate representation of the complexity of the processes occurring in a catchment (Beven 2012). Uncertainty in model structure relates to the internal computation of hydrological processes and to the spatial simulation scale. Some studies assess model structure uncertainty by comparing different rainfall-runoff models with a particular model structure (e.g. Refsgaard and Knudsen 1996; Perrin et al. 2001). A quantitative assessment of uncertainty related to internal computation of hydrological processes in NASIM is beyond the scope of this thesis. However, some of the simplifications that the NASIM model relies on to model the hydrological processes within a watershed are listed below.

i. In NASIM computed runoff components of each elementary/simulation unit are not routed between elementary units within a sub-catchment, but are added directly to the outlet of the sub-catchments. This, however, permits the modeling of processes such as return flow and the re-infiltration of surface runoff.
ii. The NASIM model is limited to account for high spatial rainfall variability. Each user-defined sub-catchment is assigned a unique rainfall time series. Thus, all elementary units within a particular sub-catchment are modeled using the same meteorological input data. Ultimately, the modeler needs to decide on an appropriate size for the sub-catchments to account for spatial rainfall variability. However, catchment geometry is barely suited to mimic the spatial variability of rain fields.
iii. In NASIM the modeling of surface runoff generation via soil moisture accounting is governed by empirically derived equations. The advantage to this approach is that only a few parameters are needed for modeling. However, it is not guaranteed that this modeling approach yields reasonable results in terms of partitioning between surface runoff due to infiltration excess and due to saturation excess. This is of special interest for the Jalca area, where overland flow generation due to saturation excess is a

common phenomena. Unfortunately, there are no observational data on runoff generation in the Jalca to allow for validation of the model output.

iv. In the model, each user-defined sub-catchment is assigned a representative stream channel geometry. This, however, is very difficult to achieve in mountainous watersheds, where stream channel geometry is constantly changing. Again, the modeler is challenged to properly design the size of sub-catchments to account for natural variability.

6.3.5.3 Uncertainties in parameter estimation

The rainfall-runoff model calibration process seeks to overcome limitations in model structure and data availability when setting up and running the model. However, many hydrological processes are nonlinear and variable in time and space, such that point measurements yield only limited insight into their hydrological behavior and importance at larger catchment scales (Buytaert and Beven 2011; Beven 2012). As a consequence, the calibration process may be viewed as a process for transforming model input values that are usually obtained by small scaled laboratory or field measurements into effective model values for representing the model's elementary scale (Beven 2012). However, there is not one optimal model parameter configuration. Rather, a number of model parameter combinations may acceptably reproduce the observational data (in line with the concept of *equifinality*) (Beven 2006; Beven 2012).

The estimation of hydrological model parameters is difficult, owing to the non-linear nature of hydrological processes and the fact that changes in some parameters might be compensated by others. Moreover, different parameters may have the same effect on discharge (Bárdossy and Singh 2008). In the NASIM model parameters are adjusted manually by a "trial-and-error" model calibration procedure. Goodness-of-fit is judged by visual comparison of the simulated responses with the observed variables. Manual calibration approaches are widely applied in hydrological modeling studies and their key advantage is the incorporation of the user's experience in parameter estimation (Boyle et al. 2000; Efstratiadis and Koutsoyiannis 2010). However, the manual approach is criticized as being an overly subjective method for adjusting parameter values and for judging the goodness-of-fit of the model simulation (Blasone et al. 2007). In more recent rainfall-runoff model applications, however, the process of manual calibration is replaced by computer-based automated calibration methods. The main advantages of automatic techniques are the speeding up of the calibration process and the reduced subjectivity involved in the calibration processes, as for most of the techniques only the parameter range needs to be specified by the modeler (Blasone et al. 2007). In addition, automated calibration methods allow one to quantify the uncertainty of model prediction in a more comprehensive way, as quantitative measures of goodness-of-fit – i.e. objective functions, likelihood measures or possibility measures – are more easily implemented.

The NASIM 3.7 software package does not allow automated calibration. Accordingly, comprehensive parameter sensitivity and parameter uncertainty analysis is difficult to achieve. However, the NASIM software package, version 4.3, published in 2014, provides an interface with the programming language *Python*, which in principle allows the user to conduct automated parameter calibration and parameter uncertainty analysis.

6.3.6 Model results

6.3.6.1 Earthworks scenarios

The hydrological modeling results show that earthworks considerably affect the hydrology of the Ronquillo River. The implementation of terraces and bund systems affects surface runoff volume, peak flow and flow volume. The flow volume of the Ronquillo watershed is reduced by the implementation of earthworks compared to the baseline by 10.0%, 5.7% and 14.0%, corresponding to a mean annual stream flow reduction of 35, 20 and 49 ls^{-1} for the scenario A_T (solely terraces), A_B (solely bund), and A_{BT} (combination of bunds and terraces), respectively. Moreover, overland flow generation is considerably reduced in the earthworks scenarios. The scenario combining bunds and terraces (A_{BT}) results in a diminution of overland flow of 28.0% compared to the baseline. The scenarios A_T and A_B reduce overland flow by 19.2% and 11.8%, respectively. Compared to all tested SWCTs earthworks result in the highest reduction of high flows. On average, high flows are reduced by 31%, 19% and 12% for the scenarios A_{BT}, A_T and A_B, respectively.

The rainfall-runoff modeling implies that the reduction in overland flow generation and the diminution of peak flows is related to the encouraging effect of earthworks on infiltration. Higher infiltration rates cause more water to infiltrate the soil column. However, the additional soil water does not necessarily drain as base flow, but is stored in the soil layer and consequently evaporated or transpired by the crops. It appears that the implementation of earthworks in the Ronquillo basin reduces surface runoff generation, and thus dampens the self-reinforcing process of surface runoff generation and subsequent soil erosion; however, at the expense of a reduction in stream flow (Figure 6–8).

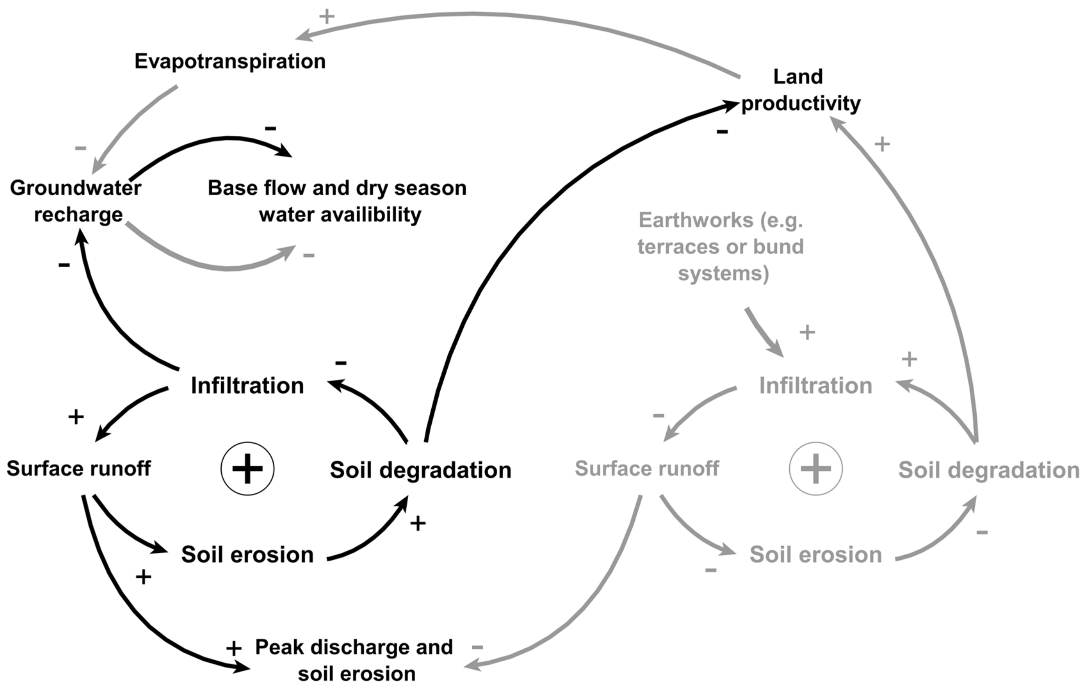

Figure 6–8: Schematic illustration of the hydrological processes affected by the implementation of earthworks. Black colored arrows indicate the hydrological cause-and-effect relationship in the Ronquillo basin without measures of soil and water conservation (actual state), whereas grey colored arrows indicate the hydrological cause-and-effect relationship if earthworks are implemented (interfered state).

6.3.6.2 Afforestation scenarios

Similar to earthworks, afforestation scenarios result in a reduction of flow volume, overland flow and high flows. Compared to the baseline, flow volume is reduced by 6.2% and 7.9% for the scenarios B_{Buffer} and B_{sVeg}, respectively, corresponding to a decrease in mean annual stream flow of 22 and 28 ls^{-1}. Overland flow is reduced by 9.2% (B_{Buffer}) and 10.8% (B_{sVeg}). On average, the high flows are reduced by 8% and 12% for the scenarios B_{Buffer} and B_{sVeg}, respectively.

The reduction in flow volume is related to the fact that the water consumption of forests and plantations is higher than that of short vegetation such as shrubland or grassland (Farley et al. 2005; Buytaert et al. 2007). In addition, afforestation enhances interception losses (Breuer et al. 2003; Benyon and Doody 2015).

Moreover, interception and transpiration interfere with the process of overland flow generation. In this connection, interception alters the amount of rain that effectively reaches the soil and thus affects directly overland flow generation. In addition, higher interception losses, as well as enhanced transpiration, reduce soil moisture content, which in turn affects the probability of saturation excess overland flow generation. This process is of high relevance in the Jalca altitudinal belt.

6.3.6.3 Check dam scenarios

The hydrological modeling implies that in contrast to the other SWCTs assessed in this thesis, the impact of check dams on the hydrology of the Ronquillo River is comparatively small. As expected, check dams do not alter overland flow generation nor flow volume. Instead, check dams influence the discharge after runoff has already concentrated in the channel. However, the impact of the modeled check dam scenarios on peak flow is very small.

It should be noted that the current modeling approach models the mature stage of check dams, when the check dam is already filled up with sediments (Xiang-zhou et al. 2004). In contrast, modeling the initial stage of check dams, characterized by the retention of sediments and the impounding of floodwater within the check dam, as small scaled water retarding basins with a corresponding storage volume assigned, would probably have had a more distinguishable impact on hydrological state variables. However, Boix-Fayos et al. (2008) argue that check dams provide only temporarily additional storage volume for flood water retention as they fill up rapidly with sediments.

6.3.6.4 Scenario inter-comparison

The model results indicate that the implementation of SWC practices such as earthworks or afforestation considerably affect the hydrology of the Ronquillo River. In contrast, the expected impact of check dams on the hydrology of the Ronquillo River is small. The implementation of terraces and/or bund structures reduces surface runoff by 12–28%; however, stream flow diminishes by 6–14% as well. Afforestation with eucalyptus and pine species results in a reduction of surface runoff and stream flow by 9–11% and 6–8%, respectively.

The computation of the *R*-index, which is a proxy for soil moisture conditions and defined as the ratio of *ETa* to *ETp* (Yao 1974), confirms that more water infiltrating the soils does not necessarily augments base flow (Figure 6–9). Applied to the climatic boundary conditions of the Ronquillo watershed, the *R*-index indicates that solely from January to April water requirement for crop growth tends to be optimal. For the rest of the year insufficient soil moisture availability limits crop growth. Thus, the additional soil water provided by the implementation of earthworks is stored in the soil layer and is consequently evaporated or transpired by the crops, but does not drain as base flow. It appears that the climatic conditions of the Ronquillo watershed do not favor long-term water storage in soils under agricultural use.

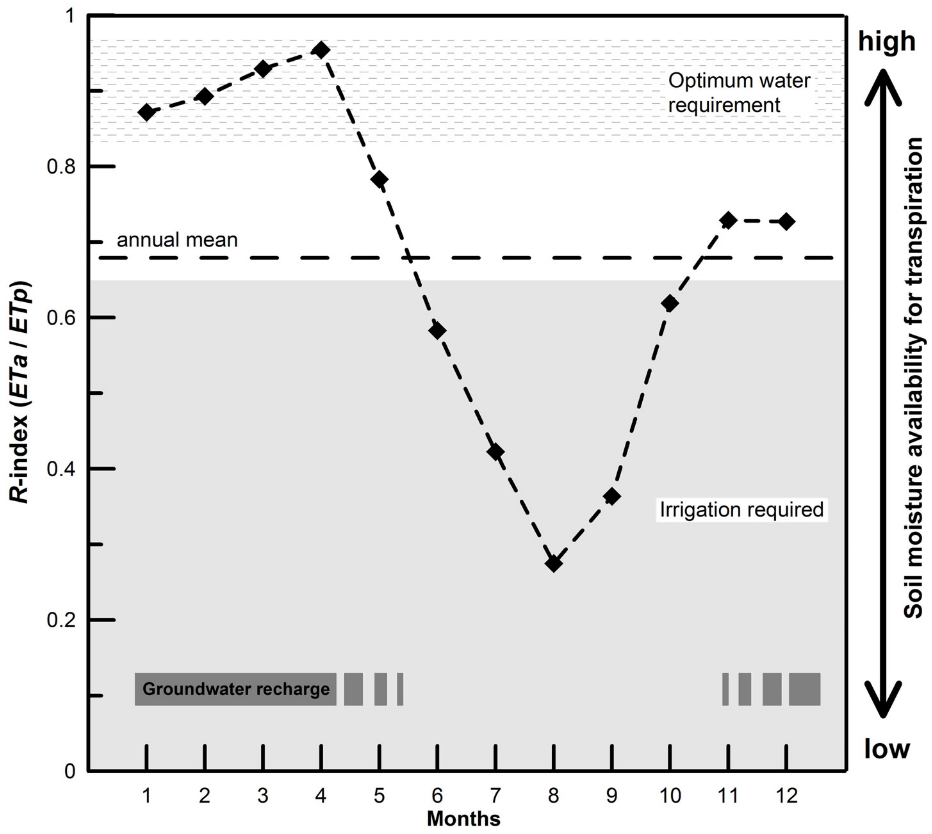

Figure 6–9: The R-*index, defined as the ratio of* ETa *to* ETp*, is a measure of plant water supply in relation to plant water demand (Yao 1974).* R-*index values close to 0.6 can be considered as requiring irrigation for crop growth, and* R-*index values close to 0.9 can be assumed to be the optimum water requirement. Evaluated under the climatic boundary conditions of the Ronquillo watershed seasonality is well documented, as values as low as 0.27 are observed in the dry season and values as high as 0.95 during the rainy season, with an annual mean of 0.68. A higher* R-*index indicates higher soil moisture availability for transpiration and favors groundwater recharge. The data is derived from the baseline run of the hydrological model NASIM 3.7 covering the period from 10-2008 to 09-2011.*

Within the framework of a water resource conservation strategy and for decision-making in respect to economic viability and sustainability it is highly relevant to know the quantities and the temporal variability of water being retained by a particular SWCT. In addition it is equally important to consider trade-offs, such as the redistribution of water resources within a catchment and the reduction of downstream water availability.

The diminution of stream flow is more pronounced during the rainy season than during the dry season. Seasonality arises owing to the cyclicality of interception, soil evaporation and transpiration, which results in augmented evapotranspiration during the rainy season compared to the dry season (Figure 6–10). Stream flow reduction is most pronounced during the rainy season, when there is plenty of water to fulfill the human demand. During dry season, stream flow reduction is comparably low, but still evident. Accordingly, it needs to be accounted for under the framework of a water resource conservation strategy.

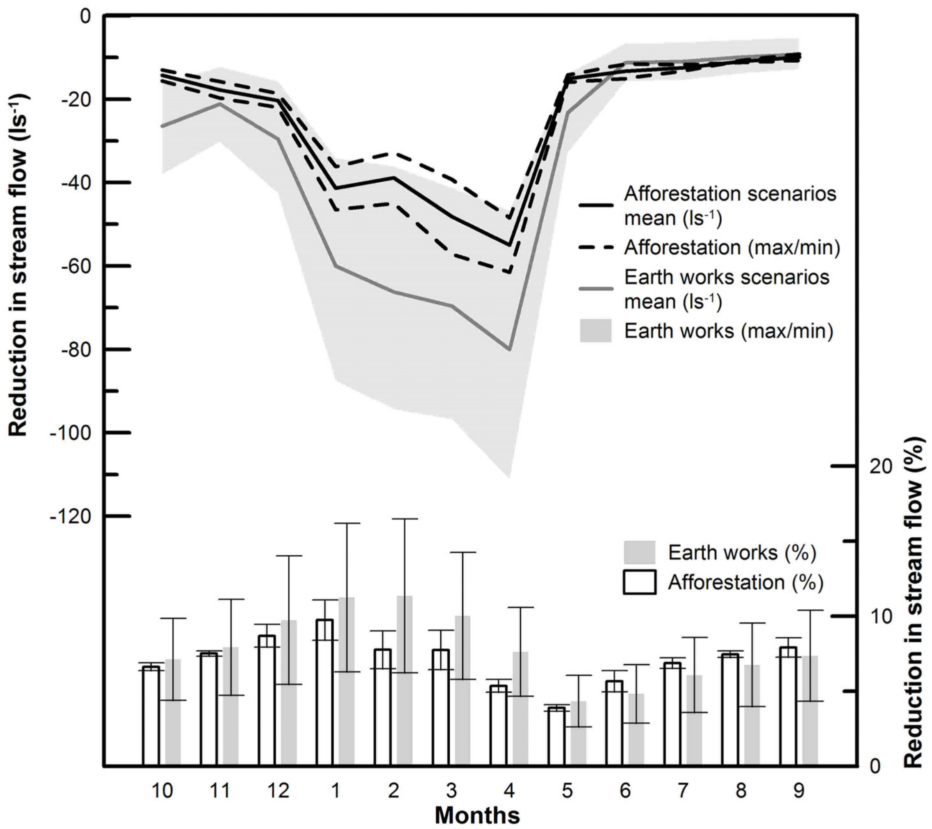

Figure 6–10: Reduction in stream flow owing the implementation of earthworks (gray colored) and afforestation scenarios (black colored). The implementation of terraces and/or bund structures, and afforestation with eucalyptus and pine species results in a reduction of stream flow. The diminution in stream flow is related to enhanced evapotranspiration. The reduction mimics the seasonal cycle of evapotranspiration, being most pronounced during the rainy season.

The quantity of water being retained within a catchment by a particular SWCT is assessed by computing the effectiveness of the SWCT. In this connection, the SWCT's impact on a hydrological state variable is estimated for the area of coverage. Calculations indicate that for the earthworks and afforestation scenarios reduction in stream flow corresponds to 1242–1643 $m^3ha^{-1}yr^{-1}$ and 1062–2586 $m^3ha^{-1}yr^{-1}$, respectively. Furthermore, SWCT effectiveness in reducing surface runoff generation corresponds to 489–603 $m^3ha^{-1}yr^{-1}$ for earthworks scenarios and to 297–676 $m^3ha^{-1}yr^{-1}$ for afforestation scenarios (Figure 6–9). The most effective scenario for water retention in the catchment is the afforestation of scarcely vegetated areas (B_{sVeg}), followed by earthworks (A_T, A_{BT}, A_B) and the augmenting of afforested areas (B_{Buffer}). The clear difference between the afforestation scenarios is due to the fact that the net change of actual evapotranspiration is much higher if areas of scarce vegetation are afforested compared to areas characterized by other types of vegetation cover.

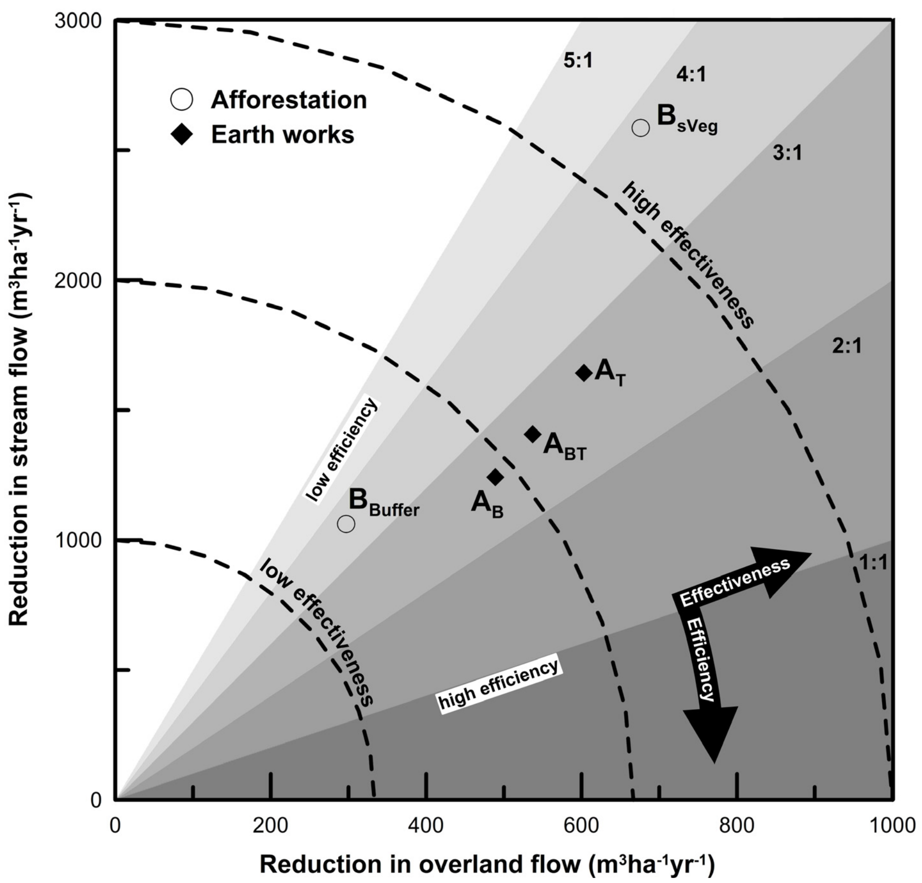

Figure 6–11: Assessment of the effectiveness and efficiency of the earthworks and afforestation scenarios. Effectiveness corresponds to the reduction in flow volume or overland flow per hectare of implemented SWCT measure. Efficiency corresponds to the amount of water being retained within the watershed and reduction in overland flow attributable to a particular SWCT.

Within the framework of the CACSUS research project, which seeks to reduce surface runoff generation, but as well to improve water availability for the city of Cajamarca, the reduction of stream flow emerges as an unintended trade-off. Therefore, in addition to the effectiveness criterion, the efficiency of a particular SWCT is introduced as an evaluation criterion. SWCT efficiency corresponds to the reduction of overland flow and the diminution of stream flow, and is defined as the ratio in the reduction of flow volume per hectare ($m^3ha^{-1}yr^{-1}$) and in the reduction of overland flow volume per hectare ($m^3ha^{-1}yr^{-1}$). The dimensionless number relates the change in overland flow to the change in flow volume. For afforestation scenarios, the reduction of 1 m^3 in overland flow corresponds to a reduction in the flow volume of approximately 3.6–3.8 m^3. By contrast, earthworks reduce flow volume by only 2.6–2.7 m^3 in order to diminish overland flow by 1 m^3. In other words, in the earthworks scenarios overland flow is reduced more efficiently because concurrent stream flow does not decrease as strongly as in the afforestation scenarios (Figure 6–11).

The findings imply that earthworks are preferable to afforestation in water resource conservation strategies that seek to enhance water availability and reduce soil erosion, However, it should be noted that both measures redistribute water resources within the catchment area: blue water is retained in the basin, enhancing so-called green water availability for plant transpiration. The investigation shows that the implementation of widespread soil and water conversation measures in the Ronquillo watershed is opposed to the water demand of the city of Cajamarca.

7. Conclusions

The foregoing study was conducted as part of the CASCUS research project, which seeks to identify opportunities for enhancing water availability and reducing soil erosion in the region of Cajamarca. In a broader sense, the project contributes to improved water security in the Ronquillo watershed, which can be defined as the "availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies" (Grey and Sadoff 2007), as soil and water conservation measures, have the additional advantage of positively impacting water quality while reducing water related risk (e.g. Blanco-Canqui and Lal 2008).

The research undertaken in this thesis was subdivided into distinct phases. In the first phase, the meteorological boundary conditions in the region of Cajamarca, and the hydrology of the Ronquillo watershed, an important water source for the city of Cajamarca, were investigated. The conducted analysis revealed a complex mountain climate marked by the interaction of a number of meteorological features, including orographic rainout, rain-bearing mesoscale cloud systems, ENSO, katabatic drainage flow and local convection, all of which act on different spatial and temporal scales.

However, it remains difficult to precisely map the spatial distribution of rainfall in the region under investigation on the basis of the existing monitoring networks. To obtain more accurate estimates of areal precipitation, improved data collection systems are needed. Furthermore, in addition to standard rain gauges measurements, other techniques, including rain radar, satellite based regional precipitation estimates, and *citizen science* approaches, are needed in order to advance our understanding of rainfall distribution and rainfall dynamics in such remote mountainous terrain. The lack of data is particularly problematic in the Jalca ecoregion, where in addition to rainfall, fog interception is thought to have a non-negligible impact on the water balance (Buytaert et al. 2005b; Buytaert et al. 2006a; Tobón and Morales 2007).

In conformance with the observed meteorological boundary conditions, the Ronquillo watershed displays strong seasonality in stream flow. During the rainy season a large portion of stream flow originates from direct runoff, which drains the watershed rapidly. The study shows that the middle part of the Ronquillo catchment, the so-called Quechua ecoregion, is most prone to direct runoff generation and subsequent soil erosion. This finding is corroborated by visual observation, as the middle parts of the Ronquillo watershed are severely degraded and rills and gullies are widespread (Furchner 2010). During the dry season a large portion of the discharge from the Ronquillo River originates from the soils covering the high altitude Jalca grasslands. However, the favorable water retention capacity of the Jalca grasslands may be irreversibly lost owing to the transformation of these grasslands into agricultural and afforestation areas (Poulenard et al. 2001; Farley and Kelly 2004; Buytaert et al. 2005b; Harden 2006; Buytaert et al. 2007), as well as the expansion of mining activities (Tovar et al. 2013b).

From a water resource conservation and management perspective that seeks to augment dry seasonal water availability, the preservation of the Jalca ecosystem as a viable water recharge area is of crucial importance. Moreover, measures for soil protection are warranted in Quechua ecoregion, in order to restore the soil layer as a medium for water storage and to mitigate soil erosion and further soil degradation. In addition, greater attention should be paid to *catchment connectivity* related to linear features and compacted surfaces, as well as to the exploration of subterraneous water flow paths. The study shows that the basement rock aquifers and spring discharge significantly contribute to dry seasonal discharge. However, knowledge of subterraneous water flow paths and their contribution to dry season runoff in the region of Cajamarca is currently quite limited. Indeed, more sophisticated monitoring techniques and hydrogeological modeling approaches are needed to evaluate the spatiotemporal variability of groundwater effluence and spring discharge.

The main objective in the second phase of research was the development of implementation scenarios for soil and water conservation techniques (SWCTs) in the Ronquillo watershed. For the earthworks scenario, a GIS-based decision support model (DSM) was used that enabled the identification of suitable sites for earthworks. To this end, a multi-criteria evaluation was conducted that included meteorologic, hydrologic, topographic, agronomic and pedologic site assessment criteria. Such a DSM provides a rational, objective and non-biased approach for the decision-making process; however, the determination of suitability levels and the development of each criteria's relative weighting were based on expert preferences and thus remained to some extent subjective. In this way, stakeholder participation is warranted in the criteria-development and criteria-weighting process. In addition, to ensure the viability and sustainably of the promoted SWCTs, cost-benefit analyses that address economic trade-offs should be incorporated in the decision-making process.

The third phase of research sought to assess how different SWCT implementation scenarios would impact the hydrology of the Ronquillo watershed. During this phase, a rainfall-runoff model was used. The hydrological modeling shows that earthworks and afforestation scenarios considerably impact the hydrology of the Ronquillo River. By contrast, the impact of check dam scenarios on the hydrological state variables under consideration is comparatively small. The rainfall-runoff model results imply that earthworks and afforestation reduce surface runoff, and thus dampen the self-reinforcing process of surface runoff generation and subsequent soil erosion. However, this comes at the expense of a reduction in stream flow. On-site effects such as the reduction of overland flow and enhanced water availability for crop growth *in situ* are counterbalanced by a reduction in water availability off-site. The results indicate that the climatic conditions of the Ronquillo watershed do not favor long-term water storage in soils under agricultural use, as additional soil water provided by the implementation SWCTs is stored in the soil layer and consequently evaporated or transpired by crops, but does not drain as base flow.

Stream flow reduction is most pronounced during the rainy season, when there is plenty of water to serve human demand. During the dry season, stream flow reduction is comparably low, but still evident. The modeling results imply that within the framework of a water resource conservation strategy, it would be preferable to implement earthworks rather than afforestation measures, as the former reduce surface runoff more efficiently compared to the latter, and thus have less impact on water availability downstream.

The findings from this research partially contradict the key aims of the CASCUS research project, which seeks to reduce soil erosion from surface runoff and simultaneously improve water availability downstream. The implementation of SWCTs redistributes the catchment's water resources by augmenting water availability in the watershed while decreasing water availability downstream. Enhancing green water availability for plant transpiration is counterbalanced by less blue water flow draining the basin. Therefore, in order to ensure optimal redistribution of water resources an integrated watershed management approach should be taken into consideration. Indeed, in the Ronquillo watershed, where water availability does not meet water demand – at least during part of the year – such an approach is crucial for reconciling upstream and downstream environmental and economic effects during SWCT implementation.

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Berlin, 15.07.2015

Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorgelegte Arbeit selbständig und ohne fremde Hilfe verfasst und andere als die angegebenen Hilfsmittel nicht benutzt habe. Die Beiträge der Co-Autoren der wissenschaftlichen Veröffentlichungen sind im Rahmen der Danksagung (Acknowledgements) und im Kapitel 1.3 (Aims, objectives and outline of this study) dargelegt. Ich erkläre, dass ich die Arbeit erstmalig und nur am Fachbereich Geowissenschaften der Freien Universität Berlin eingereicht habe und keinen entsprechenden Doktorgrad besitze.
Der Inhalt der dem Verfahren zugrunde liegenden Promotionsordnung ist mir bekannt.

Dipl.-Geogr. Krois, Joachim