FACULTY OF
BIOSCIENCE ENGINEERING

ASSESSMENT OF ECOSYSTEM SERVICES IN MINING REGIONS: A CASE STUDY IN CAJAMARCA, PERU

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Content

List of abbreviations

AMD	Acid mine drainage
ArcGIS	A GIS software with paid license
ArcSWAT	ArcGIS extension and graphical user input interface for SWAT
ARIES	ARtificial Intelligence for Ecosystem Services
CENAGRO	National Census of Agriculture of Peru
CF	Correction factor
CICES	Common International Classification of Ecosystem Services
DEM	Digital Elevation Model
DPSIR	Driver Pressure State Impact Response
EIA	Environmental Impact Assessment
ES	Ecosystem goods and services
ES ‘water use’	ES ‘Ground- and surface water for (non)-drinking’ from the CICES classification
ESA	Ecosystem services assessment
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GEOCATMIN	Sistema de Información Geológico y Catastral Minero
GIS	Geographic Information System
GRASS	Geographic Resources Analysis Support System, a free and open source GIS
GRASS-SWAT	Interface between GRASS and the SWAT model
INEI	The Peruvian National Institute of Statistics and Informatics

INGEMMET	El Instituto Geológico, Minero y Metalúrgico de Peru
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
LIDAR	Light Detection and Ranging
LUCI	Land Utilisation and Capability Indicator
LULC	Land use land cover
MEA	Millennium Ecosystem Assessment
MINAM	Peruvian Ministry of the Environment
MINEM	Ministry of Energy and Mines
MYSRL	Minera *Yanacocha* S.R.L
PI	Productivity Index
QGIS	Quantum GIS, a free and open source GIS
QSWAT	Quantum SWAT is a QGIS interface for SWAT
RGC	Regional Government of *Cajamarca*
SEA	*Sector de Enumeración Agropecuario.* It is the research unit of the CENAGRO census
SENAMHI	Servicio Nacional de Meteorología e Hidrología del Perú
SolVES	Social Values for Ecosystem Services
SU	Stock unit (animal of 450 kg)
SWAT	Soil and Water Assessment Tool
TESSA	Toolkit for Ecosystem Service Site-based Assessment
USDA	United States Department of Agriculture
ZEE	Zonificación Ecológica y Económica

Summary

Mining will continue to increase in the future due to population growth and green energy technology development. The counterpart of this economic development is its serious environmental and social impacts. Mandatory Environmental Impact Assessments have been introduced to identify these impacts. However, the former often fail to identify the impact on livelihood.

The assessment of ecosystem services can address some of the shortcomings of Environmental Impact Assessments by identifying human dependence on ecosystems. In this thesis, ecosystem services are assessed in the *Mashcón* catchment, situated near the *Yanacocha* gold mine in *Cajamarca*, Peru. Simplified site-specific methods are used to assess the supply and the demand of three of the ecosystems services, namely ‘water use’, ‘cultivated crops’ and ‘reared animals’.

The results suggest a mismatch between areas of high water supply and areas of high demand. Animal and crop production show a higher water demand than the mining company and *Cajamarca*-city, but their water demand per hectare is way lower. It was found that the demand of the ecosystem service ‘cultivated crops’ is adapted to the low supply, while the demand of the ecosystem service ‘reared animals’ is five times higher than the supply, indicating a potential shortage.

The results strengthen the existing evidence of the impact of the *Yanacocha* mine on water resources. *Cajamarca*-city and rural livelihoods are dependent on the groundwater discharges from the mine. The closure of the mine, scheduled for 2020, could strongly impact the supply of the ecosystem service ‘water use, thus impacting ‘cultivated crops’ and ‘reared animals’ that rely on water.

The conclusion of this thesis is that the assessment of ecosystem services is useful to analyse potential impacts of mining on livelihood and that their inclusion in Environmental Impact Assessment could identify impacts more effectively.

Samenvatting

Mijnbouw zal blijven toenemen in de toekomst zowel door de bevolkingsgroei als door de ontwikkeling van technologie voor groene energie. Met deze economische ontwikkeling gaan echter serieuze mileu- en sociale effecten gepaard. De verplichte Milieueffectrapportages zijn geïntroduceerd om deze effecten te identificeren, maar falen er echter vaak in om effecten op het levensonderhoud van omwonenden te identificeren.

De beoordeling van ecosysteemdiensten kan sommige tekortkomingen van Milieueffectrapportage aanpakken door het identificeren van de menselijke afhankelijkheid van ecosysteemdiensten. In deze thesis worden de ecosysteemdiensten van het *Mashcón* stroomgebied, gelegen in de buurt van de *Yanacocha* goudmijn in *Cajamarca*, Peru, onderzocht. Vereenvoudigde en site-specifieke methoden worden gebruikt om de vraag en het aanbod van drie van de ecosysteemdiensten te bepalen, namelijk ‘watergebruik’, ‘gecultiveerde gewassen’ en ‘geteelde dieren’.

De resultaten suggereren een *mismatch* tussen gebieden van hoog water aanbod en gebieden van hoge vraag. De dierlijke- en gewasproductie vertonen een hogere water vraag dan het mijnbouw bedrijf en *Cajamarca*-stad, maar hun water vraag per hectare is veel lager. Er is gevonden dat de vraag van de ecosysteemdienst ‘gecultiveerde gewassen’ aangepast is aan het lage aanbod, terwijl de vraag van de ecosysteemdienst ‘geteelde dieren’ vijf keer hoger is dan het aanbod, wat wijst op een potentieel tekort.

De resultaten versterken de bestaande aanwijzingen van de impact van de *Yanacocha* mijn op de watervoorraden. *Cajamarca*-stad en landelijke bewoners zijn afhankelijk van de grondwaterafvoer van de mijn. De sluiting van de mijn, gepland voor 2020, zou het aanbod van de ecosysteemdienst ‘watergebruik’ sterk kunnen beïnvloeden wat op zijn beurt ‘gecultiveerde gewassen’ en ‘geteelde dieren’ zou beïnvloeden aangezien deze afhangen van water.

De conclusie van deze thesis is dat de beoordeling van ecosysteemdiensten nuttig is voor de analyse van de mogelijke effecten van mijnbouw op het levensonderhoud en dat hun opname in Milieueffectrapportage zou helpen om de effecten beter te identificeren.

Resumen

La minería seguirá creciendo a futuro debido al crecimiento poblacional y el desarrollo de tecnologías verdes. La contraparte de este desarrollo económico son los impactos severos en el medio ambiente y la sociedad. Estudios de Impacto Ambiental obligatorios han sido introducidos para identificar estos impactos. Sin embargo, hay fallas frecuentes al identificar impactos sobre el sustento de la vida.

El estudio de servicios ecosistémicos puede tratar algunas falencias de los Estudios de Impacto Ambiental, identificando la dependencia humana en los ecosistemas. En esta tesis se evalúa los servicios ecosistémicos de la cuenca del Mashcón, ubicada en las cercanías de la mina de oro Yanacocha en Cajamarca, Perú. Métodos simplificados y específicos al caso son usados para evaluar la provisión y la demanda de tres servicios ecosistémicos denominados ‘uso de agua ‘, ‘cultivos agrícolas’ y ‘animales de cría’.

Los resultados sugieren un desequilibrio entre áreas de alta provisión de agua y áreas de alta demanda. La producción de ganado y cultivares muestran una mayor demanda de agua que la empresa minera y la ciudad de Cajamarca, pero muy menor demanda de agua por hectárea. Se encontró que la demanda del servicio ecosistémico ’cultivos agrícolas’ está adaptada a un bajo suministro, mientras que la demanda del servicio ecosistémico ‘animales de cría’ es cinco veces mayor que el suministro del mismo, indicando un déficit potencial.

Estos resultados reafirman la evidencia existente sobre los impactos de la mina Yanacocha sobre los recursos hídricos. La ciudad de Cajamarca y el sustento de la vida rural dependen de la descarga de aguas subterráneas por parte de la mina. El cierre de la mina, programado para el año 2020, podría impactar el suministro del servicio ecosistémico ‘uso de agua’, consecuentemente impactando los ‘cultivos agrícolas’ y ‘animales de cría’ que dependen del agua.

La conclusión de la presente tesis es que el estudio de servicios ecosistémicos es útil para analizar impactos potenciales de actividades mineras sobre el sustento de la vida, y su inclusión en Estudios de Impacto Ambiental podría servir para identificar impactos con mayor eficiencia.

1 Introduction

The demand for minerals and metals has significantly increased during the 20th century and will continue to increase in the future due to population growth and due to the development of green energy technologies that require a wide range of minerals and metals (Briskey & Schulz, 2007; Drexhage, 2017). The consequence of this growing demand is a mining boom such as the one in Latin America, particularly in Peru in the past two decades (Gordon & Webber, 2008; Sosa & Zwarteveen, 2012).

Mining causes environmental impacts whereof the main ones are the deterioration of water quality, the alteration of water quantity, the destruction of ecosystems and biodiversity loss (ELAW, 2010). Social impacts include human displacement, pressure on subsistence resources and degradation of cultural and aesthetic resources (Bury, 2005). To identify, predict and evaluate these impacts, mining companies are obliged to carry out an Environmental Impact Assessment (EIA). However, neither long term environmental and social impacts, nor cumulative effects, nor biodiversity are correctly accounted for in EIAs. As a consequence, mine exploitation often results in serious environmental damage as well as in social conflicts due to loss of livelihood resources.

The assessment of ecosystem goods and services (ES) could improve some of the EIA shortcomings. ES are defined as “the benefits people obtain from ecosystems” (Millennium Ecosystem Assessment, 2005). ES is a useful concept to link ecosystem health with the well-being of humans (Niasse & Cherlet, 2015). It can help to communicate about the importance of a good ecological status of ecosystems and to make the advantages tangible for decision-makers and for the public (Everard, 2012). Integrating ES into EIA would result in a more inclusive and realistic assessment of the short and long-term impacts of a project, allowing protection and reinforcement of ES benefits (Landsberg et al., 2013; UNEP, 2009).

The *Yanacocha* mine, operated in the south of the *Cajamarca* region in Peru since 1993, has led to an important population growth. The *Mashcón* catchment is the most densely populated one in the influence zone of the *Yanacocha* mine. Both the mine exploitation and the surrounding population depend on natural resources. This leads to increasing competition, especially for clean water. The growing demand of natural resources puts a severe pressure on the ecosystem and its goods and services delivered to the region. This pressure was not correctly identified and predicted by the Environmental Impact Assessment of the *Yanacocha* mine, which causes the present resource competition problems. In this context, the characterization of the supply and demand of ecosystem goods and services can be useful to identify mining pressures on the environment and the related social-economic implications.

The objective of this thesis is two-fold. The first objective is to identify the ecosystem goods and services (ES) in a mining region. The second one is to map the spatial distribution of these ES. In this thesis, the *Mashcón* catchment in *Cajamarca* (Peru) and the *Yanacocha* mine are used as a case-study.

To achieve the first objective, the ecosystem goods and services in the *Mashcón* catchment are identified via literature after what the most relevant ones are selected for further assessment. Next, appropriate assessment methods are elaborated based on data availability and local features. Hereafter, the supply and the demand of the selected ecosystem services are quantified biophysically to identify regions of ES shortage and surplus. This is done using the Geographical Information Systems ArcGIS and Quantum GIS.

The thesis report is built up as follows. In the literature review (Section 2), mining in Peru and mining impacts are discussed as well as Environmental Impact Assessments, the ecosystem goods and services concept and assessment methods. In Section 3, the applied methodology is explained. In Section 4 the ES assessment results are presented. The discussion of the results is contained in Section 5. Section 6 and 7 are the conclusion and the recommendations for further research, respectively.

2 Literature review

2.1 Mining in Peru

The oldest trace of metallurgical tradition in the Andes dates back to around 1410 to 1090 B.C. (Burger & Gordon, 1998). From then on mining developed further with periods of growth, stagnation and decline (Song, 2009). In 2015, Peru was the 1st producer of zinc, lead, gold and tin in Latin America and the 2nd of silver and copper in the world (Sánchez et al., 2016). Today, mining activities take place in 23 of the 25 regions of Peru. Mining is undoubtedly at the center of the Peruvian economy.

2.1.1 Politics and economics of mining in Peru

In 1990 the new President of Peru, Alberto Fujimori, started neoliberal political and economic reforms. Two of his objectives were to boost the economic growth and to become part of the globalizing economy. These reforms favored international capitalists by allowing foreign direct investment among other advantages (Bury, 2005). The mining sector has occupied a central place in this economic policy, with a significant boom between 1999 and 2009 (Jeronimo et al., 2015; Sosa & Zwarteveen, 2012). As an example, the production of copper increased by 46% and gold by 554% between 1992 and 2000 (Quijandría et al., 2002).

Decentralisation, another neoliberal policy, started in 2002. In this process, a part of the authority is transferred from the central to the regional government. One of the measures is the transference of the authority to develop Land Use Planning from the central government to the regions. In the region of *Cajamarca* this has led to a conflictual situation between the pro-mining central government, including The Ministry of Energy and Mines (MINEM) and the regional government that has tried to defend the interests of all local stakeholders (Jeronimo et al., 2015).

When looking from an economic point of view, the following figures give an indication on the current state of the mining sector in Peru. In 2015, 7,525 million dollars were invested in mining, export from mining activities provided 21 billion dollars of income (Figure 2.1), which is equal to 62% of the total export value, and accounted for about 13% of the Gross Domestic Product. This mining activity provided an average of 195,700 direct and 1 761,300 indirect employments. By December 2015 mining rights covered 14.2% of the Peruvian territory, whereof 1.22% was effectively used for mining (Sánchez et al, 2016).

Mining is thus deeply embedded in Peruvian politics and economy.

Figure 2.1. Evolution of mining exports in Peru from 2006 until 2015 (Sánchez, 2016).

2.1.2 The mining process

Mining is the process whereby minerals, coals or other substances are extracted from the Earth's crust. The mining process discussed in this section is for mineral ore deposits. It consists of six consecutive phases: prospecting and exploration, development, actual mining, beneficiation, recuperation and refining and lastly closure and reclamation. During the prospecting and exploration phase, the surface and underground rock is searched for ore deposits via imaging after which advanced exploration can be started. If the mineral content is high enough and of an adequate ore grade the development phase can begin. In this stage access roads are built and the land to be used for mining is cleared.

Next comes the actual mining with as main types open-pit and underground mining. For open-pit mining, overburden (waste rock) is excavated to access the mineral ore deposits. The latter are then crushed and grinded into fine particles to facilitate the process called beneficiation. Beneficiation comprises physical and chemical techniques such as leaching, flotation and electro winning to extract the metal from the ore particles. For gold extraction, leaching with cyanide is applied. The concentrated solution also contains other metals and has to be recuperated and refined to obtain pure gold. During the excavation and the processing, a lot of contaminated waste is generated. This has to be treated or secured to prevent environmental impacts.

After the active mining phase, the mine is closed and reclaimed. Mine reclamation is the process of restoring land that has been mined to a condition that most resembles the pre-mining condition (ELAW, 2010). The different mining phases cause severe environmental and social impacts, which are discussed in section 2.1.3.

2.1.3 Impact of mining on socio-ecological systems

2.1.3.1 Environmental impacts

Mining causes environmental impacts whereof the main ones are the deterioration of water quality, the alteration of water quantity, the destruction of ecosystems and biodiversity loss.
During the exploration phase and the development phase, vegetation and topsoil are removed. Ecosystems are destroyed, habitat is lost and fragmented (ELAW, 2010). This leads to an on-site and long term loss of biodiversity. During the active mining, quantities of as much as 140,000 tons a day are excavated and a lot of waste, in the form of overburden and tailings, is generated and disposed. Tailings are the non-valuable fraction of materials remaining after processing the ores. They are often contaminated with chemicals such as acids or sodium cyanide used for gold processing and can contain (toxic) metals. These compounds can deteriorate the soil, the ground and surface water quality both during mine exploitation and after mine reclamation.

2.1.3.2 Impact on water resources

The impacts of mining on water resources are multiple and can persist for several centuries after mine closure (Younger & Wolkersdorfer, 2004). Acid mine drainage (AMD) is an acknowledged phenomenon that deteriorates the water quality. The drainage originates when iron sulfide minerals, contained in overburden and tailings, react with water and oxygen to form acids. AMD contains (heavy) metals, sediments and can mobilise other metals as a result of its low pH (Akcil & Koldas, 2006). The chemicals, sediments and AMD released into the water cause the water quality to deteriorate, which in turn causes the death of (sensitive) species and decreases species diversity (Gray, 1997).

Next to that, land modification causes considerable changes on water quantity and availability. The excavation disrupts surface water flow on the mining site and can disrupt hydrological pathways of groundwater flows. Also, large water quantities, up to 10,000 m^3h^{-1}, are displaced during the mine dewatering to control the water inflow, to lower the water table and to reduce the pore water pressure. This is necessary to avoid operational and stabilisation problems, the oxygenation of metallic sulfides, landslides and acid drainage (Fernandez-Rubio & Lorca, 1993; Groundwater Engineering, 2014; Sperling et al., 1992). Beside this, ore processing requires large amounts of water for dust control and for the ore separation processes (Vela-Almeida et al., 2016). Between 1.5 m^3 and 3.5 m^3 of water is used to process 1 ton of copper sulfide ore (Bleiwas, 2012).

This water extraction can lead to a decrease of the groundwater table of up to more than 100m in 10 years on the mining site (Vela-Almeida et al., 2016). On the one hand this causes a decrease of groundwater discharge from aquifers and of water bodies’ base flow, the desiccation of ponds and wells, and land subsidence (Younger & Wolkersdorfer, 2004). On the other hand the pumped water is discharged in surface flows at a rate higher than the natural flow rate. On top of that, large mining plants often build dams, which retain large water quantities, to produce hydropower or to retain the sediments that end up in the water ways due to mining activity (Atkins et al., 2005; Castello & Macedo, 2015). Mining thus affects the natural groundwater and surface water flow regimes. The hydrological system becomes partially artificial. After the mine closure and thus the end of dewatering, the aquifer level restores somewhat (called a rebound), but the hydrologic system is impacted forever. Since mines are frequently located in headwater areas of drainage basins and of rivers, the extensive water extraction in these headwaters has an impact on the water supply and thus on the functioning of the downstream ecosystems (Vela-Almeida et al., 2016).

2.1.3.3 Social impacts

The social impacts resulting from mining are controversial and complicated. The first consequence of mine exploitation is (forced) human displacement away from the mining area. The locals lose their homes, their lands and the access to certain resources such as water (ELAW, 2010). Migration towards the surrounding areas of a mining project is a second effect. This can give rise to a sudden and important population growth that is even more remarkable in remote areas. Pressure on resources and disagreement on their distribution can emerge. Third, there is a degradation of cultural and aesthetic resources. These social impacts are all sources of conflict between the indigenous people and the mine company but also between the inhabitants themselves. A positive but somewhat controversial impact is wealth creation. Mining is associated with high incomes, the creation of jobs, the development of education, the construction of infrastructure, the increase in goods and services. These benefits are, however, unequally distributed among the population. The consequence is a perception of inequality and the appearance of social tensions that lead to a deterioration of human relations (Bury, 2005).

The environmental and social impacts caused by mining have disastrous effects for the local people, for example farmers, that rely on resources provided by these ecosystems for their livelihood activities (Bury, 2005). Also, the overall trend towards urbanization together with the population growth associated with mining areas makes cities become larger water consumers. The local increase in water demand leads to water shortages and water quality degradation (Buytaert & Breuer, 2013). Because mining sites are often located in the headwaters of water basins and because they displace an important quantity of water, water shortage is stressed in the often downstream located cities.

The described social and environmental impacts show that the present mining operations are not sustainable. Vela-Almeida et al. (Vela-Almeida et al., 2015) define: “Biophysical limits to mining activities need to consider the critical capacity of the entire socio-ecological system to maintain its structure and functions over time”. For this end, involvement of all the stakeholders, the mining company, the central and regional government and the locals, is of utmost importance to better assess the impacts of mining and consider everyone’s needs. It is therefore essential to integrate the economic, social and environmental parts to a holistic solution for the problem described in this section. This approach is probably also the most sustainable one.

2.2 Environmental impact assessment

From the previous section it is clear that mining has environmental, social and livelihood impacts. To avoid or to mitigate these, first they have to be known and preferably quantified. In this section the current impact assessment method is identified.

Environmental impact assessment (EIA) is an environmental management tool that makes use of a systematic process to identify, predict and evaluate the environmental effects of major proposed actions and projects. These environmental effects also comprise social, cultural and health effects. The EIA process makes use of consultation and public participation as can be seen in the generalised EIA process flowchart (Figure 2.2). The first purpose of the EIA is to inform decision-makers and the public of the environmental consequences of a proposed project prior to approval. The second one is to promote "environmentally sound and sustainable development through the identification of appropriate enhancements and mitigation measures" (ELAW, 2010; Sadler et al., 2002). If the EIA unfolds serious environmental impact, it does not, however, ensure that the project will be modified or refused (ELAW, 2010).

2.2.1 Legal framework

The United States of America were the first to set legislation on EIA in the National Environmental Policy Act of 1970 (Alm, 1988). After that, other countries followed their example. In Peru, EIA is incorporated in the legislation in 1990 (Legislative Decree no.613 of 1990) but general EIA procedures were only approved in 2001 (SEIA Law No. 27446). Their implementation began only eight years later, when regulations to the law were accepted (Castro et al., 2014).

Nowadays, EIA is an internationally recognised, established and most commonly used tool for environmental management, also in the mining sector, even if its effectiveness in influencing the decision-making is sometimes small (Jay et al., 2007). An extensive elaboration of the EIA process for mining is to be found in the *Guidebook for Evaluating Mining Project EIAs* published by the Environmental Law Alliance Worldwide in 2010.

2.2.2 Problems related to EIA

In the ideal case, all the probable mining impacts are objectively mentioned in the EIA, but in practice this is not always the case. When the responsibility to prepare the EIA is assigned to the project proponent, which is the situation in Peru, the consultant hired by the company can be pushed to falsify some outcomes so that the company gets the approval for its EIA (ELAW, 2010; Solano, 2013). As an example in Peru, the EIA of the *Yanacocha* gold mine for the Conga Project was manipulated to facilitate the project execution (RPP Noticias, 2016). Another encountered problem is the softening or omission of environmental impacts in the executive summary, which is often the only part of the EIA that decision-makers read (ELAW, 2010; Sosa & Zwarteveen, 2012). The discovery of these manipulations caused social conflicts and the loss of EIAs' credibility in Peru.

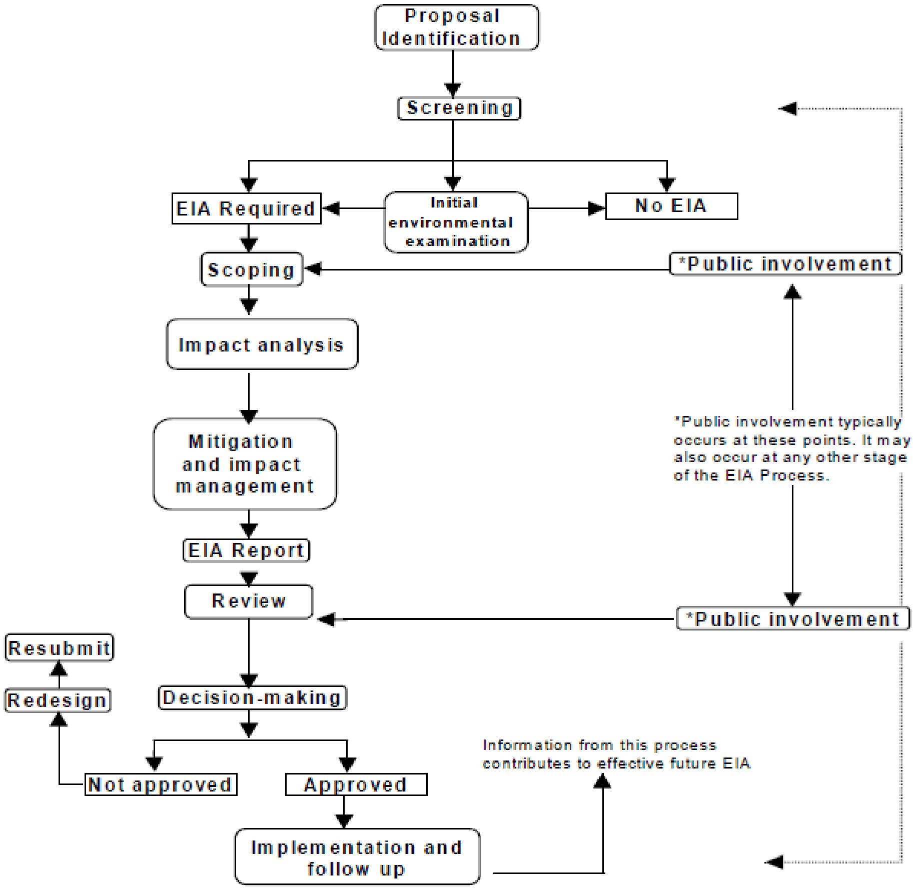

Figure 2.2. Generalised EIA process flowchart (Sadler et al., 2002).

EIA has a potential to identify probable environmental impacts of projects but the influence on decision-making is not substantial. Nowadays, next to biophysical impacts also social, health, biodiversity and economic effects should be evaluated in EIAs but their integration is by no means universal or uniform (COM (2009) 378 final; Harris et al., 2015; Sadler et al., 2002). In theory, public participation should help identify these impacts but in practice it is often limited even if it is required by legislation (The World Bank, 2012). Alongside that, certain negative effects may seem rather insignificant when considering one project, but their cumulative impact can be significant (Sadler et al., 2002). The EIA faces difficulty to address cumulative effects of a project, which can cause that important impacts are overlooked (The World Bank, 2012). Also, biodiversity, which is seen as the basis of our very existence (IAIA, 2005) is not generally included in EIAs.

In summary, neither long term environmental and social impacts, nor cumulative effects, nor biodiversity are correctly accounted for in EIAs, although they are all essential to maintain a sustainable future and they would better inform decision-makers on the potential danger of some projects.

2.3 Ecosystem Services in the Assessment of mining impact

In this section, the ecosystem service concept is explained and its potential as additional tool for the assessment of mining impact is explored.

2.3.1 General concepts

The aim of this section is to introduce the most important concepts on ecosystem goods and services (ES), generally referred to as ecosystem services. The most widely used definition is that of the Millennium Ecosystem Assessment (MEA) that defines ES as “the benefits people obtain from ecosystems” (Millennium Ecosystem Assessment, 2005). ES is a useful concept to link ecosystem health with the well-being of humans (Niasse & Cherlet, 2015). It can help to communicate about the importance of a good ecological status of ecosystems and to make the advantages tangible for decision-makers and for the public (Everard, 2012).

2.3.1.1 ES delivery cascade and classification

The link that ecosystem services make between ecosystems and human well-being is clearly visualised in the ‘ES delivery cascade’, a conceptual framework of Haines-Young and Potschin (Haines-Young & Potschin, 2009). An adapted version of this ‘cascade’ is shown in Figure 2.3. The ‘cascade’ visualises that “benefits flow from services, services from functions, functions from processes and processes from the biophysical structure of the ecosystem” (Landuyt, 2015). An ecosystem function is defined as a biophysical process that is potentially useful to people. If this function is perceived as profitable, it will be considered as a service (Landuyt, 2015). The fact whether it is profitable or not depends on the spatial, temporal and social context (Haines-Young & Potschin, 2009). The use of a good or a service provides benefits that can be valued in monetary and non-monetary terms (de Groot et al., 2010). This ‘cascade’ herein differs from the MEA definition, where ES are the benefits themselves. There are many interpretations for the ES concept, and the ‘cascade’ is a comprehensive one. An example of the cascade is the following: nutrient cycling (a process) is needed for water purification (a function) to provide clean water (a service) that contributes to health (benefit) (The Economics of Ecology and Biodiversity, 2010).

The services can be classified via different typologies. The first one, proposed by the MEA, divides ES in four categories: supporting (e.g. nutrient cycling), regulating (e.g. climate regulation), provisioning (e.g. freshwater) and cultural services (e.g. recreation) (Millennium Ecosystem Assessment, 2005). Some researchers recommend not to include the supporting services class, which represent the ecological processes that underlie the function of the ecosystem, to avoid double counting (Hein et al., 2006).

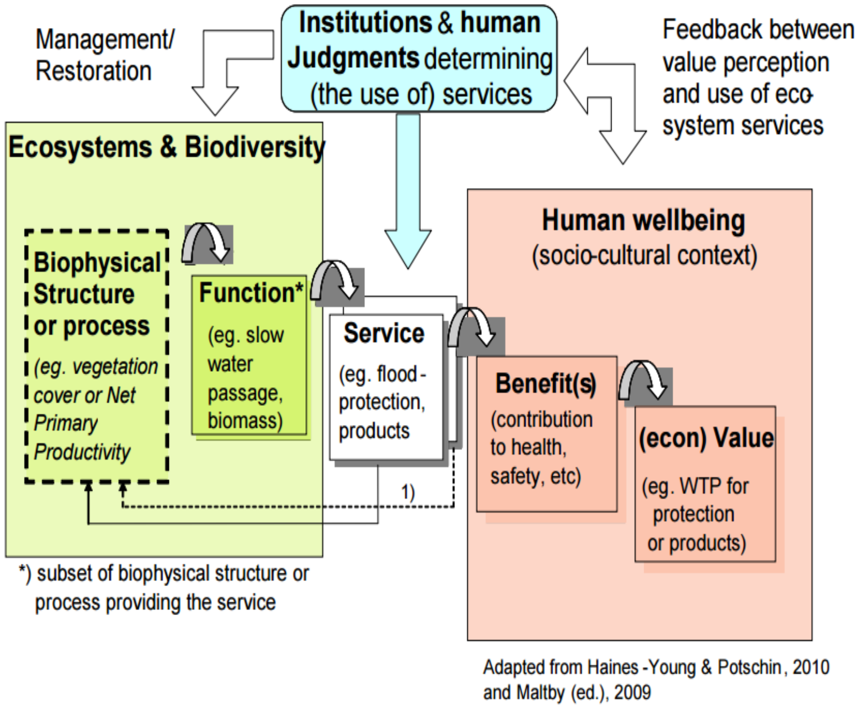

Figure 2.3. The ecosystem services 'cascade' (The Economics of Ecology and Biodiversity, 2010).

Considering this, the Common International Classification of Ecosystem Services (CICES) proposed the following main categories: regulation and maintenance, provisioning and cultural ES. In the MEA, The Economics of Ecosystems and Biodiversity, and the CICES classification version 4.3[1], abiotic ecosystem outputs (e.g. wind and minerals) are not included because ES are seen as outputs that are fundamentally reliant on living processes (Haines-Young et al., 2012; Haines-Young & Potschin, 2013). However, other scientists emphasise the importance of their integration in ES because they contribute to economic, cultural and social benefits. There is clearly much debate about definitions and classifications (van der Meulen et al., 2016). Some scientists stress the need of a single definition and a generalised classification while others say these should be case-specific and purpose-driven (Costanza, 2008; Martin-Ortega et al., 2015). What is important is to clearly define the terms whenever they are used to avoid misunderstandings.

2.3.1.2 Points of interest of the ES concept

Even if the ES concept seems promising, attention has to be paid to the following aspects. First, the many frameworks and definitions (see Section 2.2.1.1) can confuse the users. Second, ecosystem functioning as well as interactions between humans and ecosystems are very complex. A lot of these processes and interactions are not yet unraveled and the understanding of the link between processes and ES provision is poor (Bull et al., 2016).

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[1] Available from https://cices.eu/

This incomplete scientific basis leads to the use of many simplifications in ES assessments what can lead to errors in the outcome. Results of these assessments should thus be handled carefully (Costanza, 2008; Eigenbrod et al., 2010). Next to that, the ES concept is inherently anthropocentric (de Groot et al., 2002). This engenders that only processes and functions of ecosystems that are known to be useful for people are preserved and that biodiversity conservation can be lost from sight. A last point is that not all ES categories are evenly accounted for during ES assessments. Cultural and regulating ES are more difficult to assess than provisioning services and tend to be less well represented.

In summary, ES are thus a useful concept to help communicate about the link between and the importance of the good ecological status of ecosystems and human well-being. Several weaknesses of the ES concept and implementation exist, but the strengths can be used to overcome these weaknesses. Ecosystem services-based approaches should be viewed as a particular way of understanding the complex relationships between humans and nature but it is not a management tool per se (Martin-Ortega et al., 2015).

2.3.2 The added value of ecosystem services for environmental impact assessment

Even if EIA is quite well established in project licensing as evidenced by its generalized use in environmental law processes (Honrado et al., 2013; this thesis section 2.1), there are some shortcomings though. These have been cited in section 2.1.2. Apart from these, EIAs do not specifically account for the effect of a project on ecosystem service benefits. Consequently, these assessments might overlook stakeholders who are sensitive to ecosystem modification (Landsberg et al., 2013).

ES can address some of the EIA shortcomings. They help to identify and understand cumulative impacts, demonstrate the social consequences of biophysical changes and their impact on human well-being, thus facilitating communication with stakeholders and decision-makers (Rosa & Sánchez, 2016). Integrating ES into EIA results in a more inclusive and realistic assessment of the short and long-term impacts of a project and allows the protection and reinforcement of ES benefits (Landsberg et al., 2013; Sadler et al., 2002).

There is, however, little research on the impact of mining on ES. To date, only a few peer-reviewed articles deal with this subject (Castello & Macedo, 2015; Larondelle & Haase, 2012; Li et al., 2011; Rosa & Sánchez, 2016; Vela-Almeida et al., 2016). Rosa and Sánchez (Rosa & Sánchez, 2016) conducted an ecosystem services assessment (ESA) of an iron mining project in Brazil and compared it to the EIA of that project. The ESA identified several impacts not considered in the EIA. Also, the impacts described by the ESA were assessed with higher significance than the equivalent impacts assessed with the EIA (Rosa & Sánchez, 2016). The consideration of ES in EIA, and especially mining EIA, could have an added value to obtain a more comprehensive assessment of the impacts related to a project.

On the legislative level, the Peruvian Ministry of Environment (MINAM) modified the law on the National Environmental Impact Assessment System (SEIA) in 2008 by including the protection of the environmental goods and services (Article 5, DL Nº 1078). The regulation of SEIA, published in 2009, includes the requirement for the assessment, conservation and valuation of Peru's natural heritage including the environmental services that they provide (Article 25, DS Nº 019-2009-MINAM) (MINAM, 2011). In practice, the topic of ES is only vaguely addressed. As an example, the EIA executive summary of the Conga mining project in Peru, issued in 2010, only mentions the analysis of ES, but neither quantitative data nor qualitative explanations are mentioned (Knight Piésold Consultores S.A, 2010).

ES have the potential to make a more inclusive and realistic assessment of the impacts of a project and have thus an added value for EIA. The inclusion of ES assessment in the Peruvian law and the increasing literature on the integration of ES into EIA are proof of this. More in depth research is needed, however, on the impact of mining on the delivery of ecosystem goods and services.

2.3.3 Ecosystem services assessment

This part starts with the presentation of an existing methodological framework to assess ES. Then, the influence of mining on ES delivery is analysed and a selection is made of the ES that seem to be the most threatened or that are perceived as very important for the local stakeholders, according to literature. To conclude, models to assess ES are compared for several criteria.

2.3.3.1 A methodological framework

To assess ecosystem services in a methodological way, the use of a framework can be advantageous. TESSA, the Toolkit for Ecosystem Service Site-based Assessment, utilizes a methodological framework, which is presented in Figure 2.4. The framework is made up of six consecutive steps: preliminary work, rapid appraisal, identification of plausible alternative state, method selection, data acquisition and analysis and communication. From Figure 2.4 it is clear that stakeholder engagement is important during the whole process (Peh et al., 2013).

For the preliminary work, the site is defined based on biological significance and perceived dangers, the (local) policy context is explored, and stakeholders are identified. The early engagement of stakeholders and decision-makers can provide a more correct and precise insight of the economic, ecological, social and cultural importance of the site. Next, a rapid appraisal is carried out. It helps identify the most important habitats, the drivers of (land use) change, the services delivered by the site and their beneficiaries, which can be further away from the site. The ES considered in this step are based on the CICES classification version 4.3.

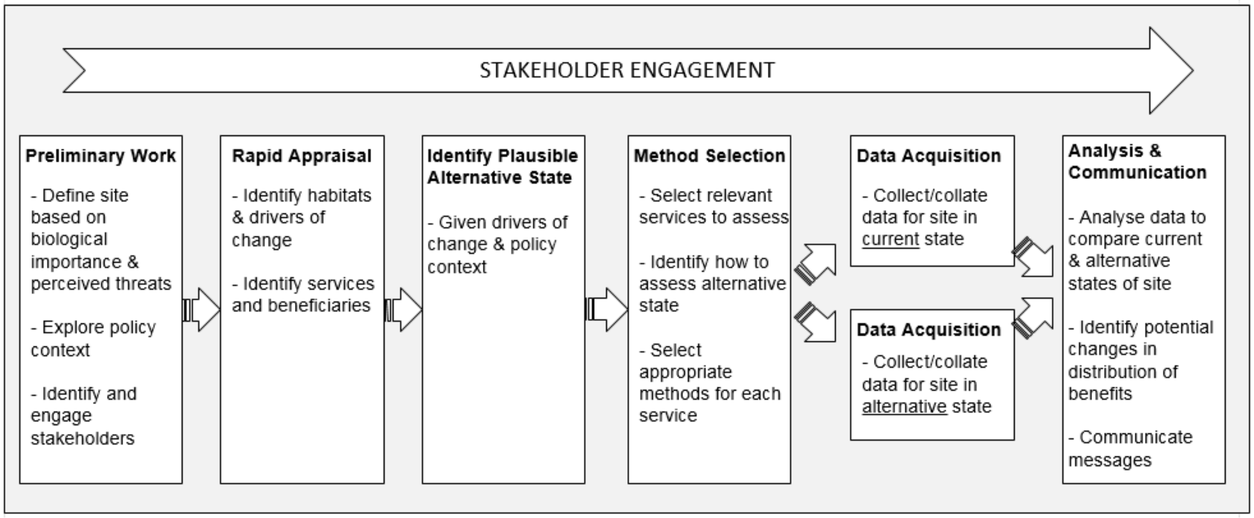

Figure 2.4. The methodological framework of TESSA (Peh et al., 2013).

The third step is the identification of the plausible alternative states, based on information gathered during the previous steps combined with knowledge of the local context. The alternative state can be a plausible state in the future (10-20 years), or how the previous state of a site evolved into the current one. Possible alternative states are the conversion, the intensive use, and the restoration of a (degraded) site. To be useful, this part of the assessment should include the important current services of a site as well as new services provided under the alternative state. If possible, data representative of the alternative state should be collected from a nearby site with the same characteristics.

The fourth step is the method selection. The most relevant services are selected prior to the use of decision trees for finding appropriate assessment methods for each service. These methods include collecting primary data through field surveys, key informant interviews, and household questionnaires; using existing databases and studies; and employing numerical models. The method, or combination of methods chosen, depends on the availability of data, time, resources and expertise. The identification of how to assess the alternative state is assessed in this part too.

The fifth step is the data acquisition, where data is collected and/or collated for the current and the alternative state of the site. The final step is the analysis and communication. The data obtained from previous steps is compared for the current and the alternative state of the site. By knowing the change in service delivery, potential changes in benefits distribution should be identified. These findings need to be communicated in an appropriate way to the decision-makers and the stakeholders (Peh et al., 2013).

This TESSA framework, a six-stage stepwise approach focused on stakeholder engagement, can serve as guidance throughout the whole ecosystem services assessment.

2.3.3.2 Ecosystem services impacted by mining

Two types of scientific articles on the mining impact on ES are available. The first type mentions explicitly which ES are impacted, the second one covers mining impacts without mentioning ES. The impacts of the latter can be translated into impacts of ES. For the first category, the following articles are analysed: Castello and Macedo (2015), Larondelle and Haase (2012), Li et al. (2011), Rosa and Sánchez (2016). For the second category, next to the impacts discussed in this thesis (section 1.3), Palmer (Palmer et al. 2010) is additionally examined. In these articles, some ES are mentioned once or twice while others are repeatedly referred to. The most recurrent ES are retained as priority ES to assess in the context of mining and are reproduced in the dotted line boxes in Figure 2.5. To stay in line with the TESSA framework, the CICES classification 4.3 from January 2013 (Appendix 1) is used.

Like mentioned in section 2.2.1 and visualized in the ES cascade (Figure 2.3), the ES concept is used to link ecosystem health with human well-being. Another commonly used organising approach to represent human-environmental connections and cause and effect relations is the DPSIR (Drivers-Pressures-State-Impact-Response) framework. In this framework, the *drivers* represent the “social, demographic and economic developments, consumption or production patterns in societies” (Müller & Burkhard, 2012) that cause certain *pressures. Pressures* are the direct anthropogenic stresses or inputs in the natural environment. This causes the *state* of environmental systems (environmental, physical, biological and chemical conditions) to change.
The *impact* is the effect of this change of state on natural and human systems. To minimize these negative impacts, society and governments can respond by taking actions (Müller & Burkhard, 2012; Pirrone et al., 2005). The merged DPSIR and ES cascade structures have already been presented in several articles (Kandziora et al., 2013; Müller & Burkhard, 2012). Based on this and on a scheme from Castello and Macedo (Castello & Macedo, 2015), Figure 2.5 integrates elements from the ES cascade and the DPSI(R) framework for mining and shows interactions between the different components. The biophysical structure and human benefits, both elements of the ES cascade, are respectively subsumed in the *state* and the *impact* part of the DPSI(R) structure. The ecosystem services are positioned in between *state* and *impact* and can be seen as the link between both elements of DSPI(R). This scheme can serve as a basis for the assessment of ES in the context of mining.

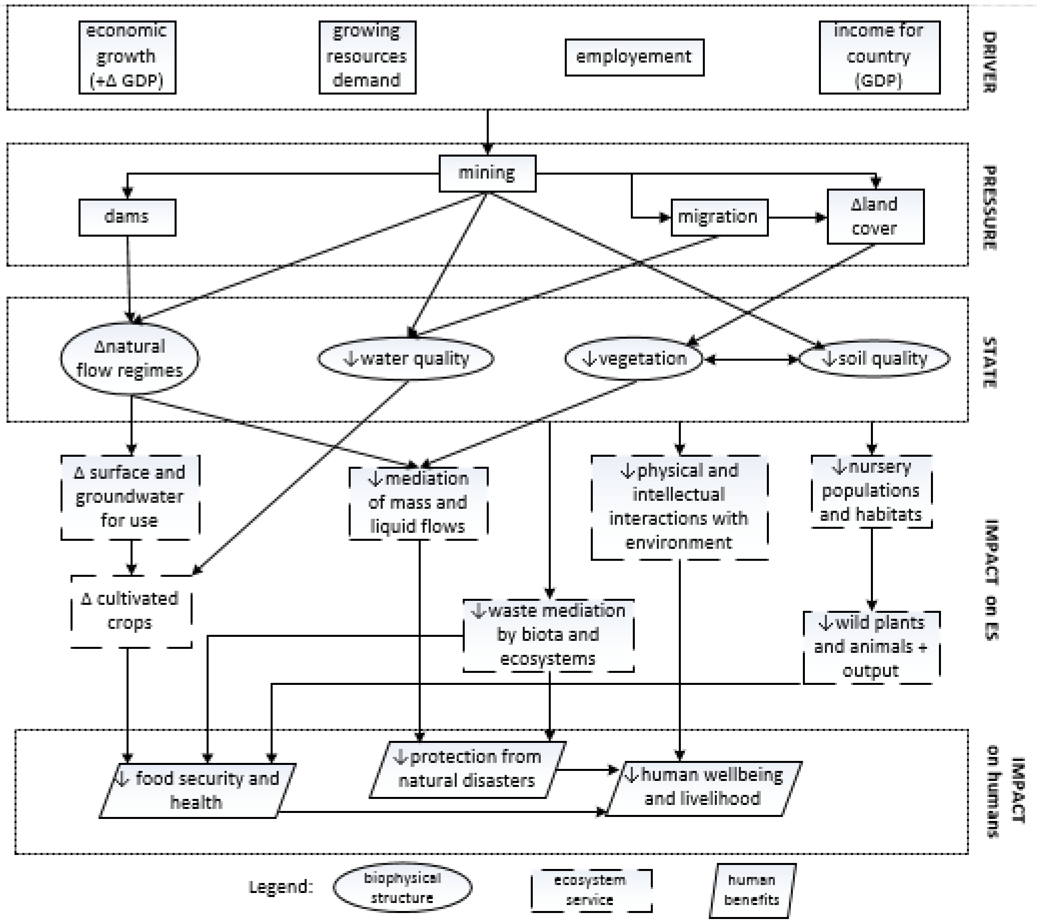

Figure 2.5. Integration of DPSI(R) and elements of the ES cascade for mining.

By retaining large quantities of water, dams alter the natural flow regimes and have thus an effect on ecosystem state (section 2.1.3). The possible chemicals' release and AMD formation during and after mine exploitation have a negative effect on soil quality (acidification, accumulation of toxic elements), next to the deterioration of water quality (section 2.1.3; Dudka & Adriano, 1997). The human migration linked with mining induces a more intensive use of the local resources, which induces land cover change and water quality deterioration if waste water is not treated. Land cover change due to mining itself and due to migration, cause a diminution of vegetated surface area. The removal of vegetation induces soil erosion and soil degradation (Albaladejo et al., 1998). A reduced soil quality due to released chemicals is also adverse for the vegetation.

The reduction of the ecosystem state causes a decline in several ES. There are less suitable habitats for flora and fauna and so less plants and animals are available for humans to harvest. Next to that, the change in water quality and flow regimes alters the available ground and surface water which has a mostly adverse effect on crop production. This negatively impacts livelihood activities. The general ecosystem state deterioration diminishes the waste mediation by biota and ecosystems. This, together with the lowering of the mediation of mass and liquid flows, negatively affects the protection from natural disasters like flooding and epidemics. The removal of vegetated areas decreases the possibilities for cultural ES such as recreation, subsumed under the ES ‘physical and intellectual interactions with the environment’ in Figure 2.5. All these changes of ES decrease human wellbeing.

Figure 2.5 presents a general scheme for mining but depending on the local context, other elements should be added, some removed or changed, and interactions could also be different. Positive economic and social impacts (section 2.1.3.3) are not taken up in this figure because they do not directly result from the change of state of ecosystems and ES. They should, however, be considered when making the balance between the positive and negative mining impacts.

2.3.3.3 Ecosystem service indicators

Once the ES selection is made, the ES have to be measured qualitatively or quantitatively. The biophysical quantification of ES is based on indicators. An indicator gives information that efficiently communicates the characteristics and trends of ES and is derived from measurements or metrics (The Economics of Ecology and Biodiversity, 2010). A measurement is a value that is quantified against a standard at a point in time. A set of these measurements or data collected and used to underpin an indicator is called a metric (UNEP-WCMC, 2011). Examples of measurements for provisioning services with direct market value are *area planted with a certain crop* or *volume of timber harvested*; for regulating services *mass of CO2 emission from deforestation* or *dissolved oxygen in water* and for cultural services *number of visitors per year* or *revenue from tourism*. Some indicators can underpin more than one ES and are addressed by metrics such as *area of vegetation cover* and *number of species per hectare*.

Sometimes, not enough information is available to quantify an indicator. In this case a proximal indicator or proxy, which is an approximation of an ES indicator, is used (Liquete et al., 2016). For example, the regulating service *erosion prevention* can use the output of erosion models, which require a lot of input data, as an indicator. But since these primary data are often not available, proxies of land cover data are more commonly used (Crossman et al., 2013). Once the appropriate method to quantify an ES is chosen, the indicator or proxies can be measured or calculated via models. A selection of tools is discussed in section 2.2.3.4.

Following the ES cascade, an indicator can be representative for the structure of the underlying ecosystem, the functioning of the ecosystem or the service itself. Structure (and composition) is easier to measure than function. For example, the size of a plant is easier measurable than its influence on soil properties. The use of structure elements as indicator is, however, only acceptable if it precisely represents the function that underlies the delivery of a service. There is still a knowledge gap of the quantitative relationship between these steps of the cascade what can result in poor indicators (de Groot et al., 2010). Also data availability plays a role in the choice and the quality of an indicator. In general, a lot of data is lacking and data collection is expensive, which means that often proximal indicators are used.

A distinction is also made between metrics of supply, demand and sustainability. Indeed, there is often a mismatch between the supply of an ES and the demand for that ES. The amount, the geographical place and the time of supply of a service often do not match with the corresponding elements of demand. Here follows an example for the ecosystem service *water supply*. Water storage in lakes is a metric of supply, water consumption by the population is a metric of demand and water scarcity, which takes into account both the supply and the demand, is a metric of sustainability. To make a useful assessment, it is important to know if the supply of certain ES can meet their demand and to understand these flows of ES. The evolution of the change of ES supply and demand over time is valuable to assess the sustainability over time. This knowledge on supply, demand and evolution over time of ES should help decision-makers to make choices with regard to environmental policy.

2.3.3.4 Ecosystem services tools

A considerable number of tools to assess ecosystems exists, as can be seen from the 183 tools that are contained in the Ecosystem-Based Management Tools database as of December 2016. It is important to consider what purpose a model is designed for and how well it fits intended applications (Vigerstol & Aukema, 2011). From previous literature exploration in this thesis, it has become clear that water-related ecosystem services are important in the context of mining areas.

Considering this and searching for generalizable, landscape-scale and open source tools, the following tools were selected to analyse their suitability in assessing mining impact: SWAT, InVEST, SolVES, ARIES and Polyscapes/LUCI. All the tools make use of Geographic Information System (GIS). Their working principle is shortly explained and they are compared in Table 2.1 for the following criteria:

ES modeled – Some tools model ES explicitly while others need post-processing to convert their non-ES output into results expressed in ES. Explicit ES tools model various ecosystem services and depending on the requirement of the study, some tools are more appropriate than others.

Input requirement – In function of the types and nature of input data required, a tool can be suitable or not depending on the available data.

Output – The tools can have different types of output going from biophysical output to ES service quantification and ES service valuation.

Model type – The tool can use deterministic models, probabilistic models or a combination of the two. Probabilistic models are useful in case of data scarcity and incomplete system knowledge whereas deterministic models are more data intensive and require better system knowledge.

Spatial and temporal scale – The spatial scale at which a tool works can vary from global to landscape, watershed and site scale. The temporal scale can range from daily to annual to decennial.

Time requirements – The time required to implement a tool can be low or high depending on the complexity of the model, the need to collect and adjust extra data or to adapt the model for a new case study.

Accessibility – Even if the selected tools are open source, some tools need specific (modeling) software that requires a license. Also the required expertise (scientific and software knowledge) to use a tool can be a limitation for its use.

Uncertainty – Every model and tool, good or bad, can make predictions and some give numbers as output. To know the degree of reliability of this outcome, the uncertainty needs to be known. Some models integrate uncertainty calculation, while others don't.

Stakeholder engagement – Certain tools require stakeholder participation, for example to fill in surveys, while other tools can run on the basis of data wherefore no stakeholder cooperation is needed.

1 SWAT (Soil and Water Assessment Tool)

SWAT is a continuous-time hydrologic tool developed to "evaluate the impact of land use changes on watershed yield, sediment, and agricultural pollutants in a river basin" (Vigerstol & Aukema, 2011). SWAT considers a watershed divided into sub-basins and hydrological response units (HRU) based on topography, soil and land use where the soil type and land use within each HRU are homogeneous (Dile et al., 2016).

Running the model requires detailed data inputs as can be seen in Table 2.1. If there is lack of daily weather data, the weather generator model can predict daily values based on monthly averages and dispersion (Arnold et al., 1998).

2 InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)

"The aim of the InVEST tool is to model and map a suite of ecosystem services across the landscape to elucidate general patterns and changes in ecosystem services" (Vigerstol & Aukema, 2011). It employs a production function[2] approach to quantify and value ecosystem services. InVEST uses a scenario comparison to investigate the effect of land cover changes on ES (Vigerstol & Aukema, 2011). The tool has a tiered approach to be able to handle different data availabilities and insights in the process (Tallis & Polasky, 2009). Tier 0

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[2] An (ecological) production function "specifies the output of ecosystem services provided by an ecosystem given its condition and processes" (Sharp et al., 2014).

works with models that give relative estimates such as indices and doesn't use a time step. Tier 1 uses simpler models and requires less data than Tier 2 (not yet released) and is thus most appropriate to apply in general scoping and planning activities (Tallis & Polasky, 2009).

3 SolVES (Social Values for Ecosystem Services)

SolVES is an ArcGIS application for mapping social values for ecosystem services, particularly cultural services, based on survey data or value transfer. "Social values are the perceived, nonmarket values the public ascribes to ecosystem services" (Sherrouse et al., 2011). SolVES uses geospatial and tabular data (see Table 2.1) as input for the three following, non-biophysical, models: the Ecosystem Services Social Values Model, the Value Mapping Model and the Value Transfer Mapping Model. The first model identifies the highest-rated social value for a specific stakeholder group as well as the corresponding location. The second model scales a selected social value relative to the maximum value and produces a 10-point scale Value Index map. In areas where survey data are not available, the Value Transfer Mapping Model predicts a Value Index map based on output from the two previous models and place-specific environmental data layers (Bagstad et al., 2013; Sherrouse & Semmens, 2015; Sherrouse et al., 2011).

4 ARIES (ARtificial Intelligence for Ecosystem Services)

ARIES builds ad-hoc, probabilistic and place-specific models of provision and usage of ES and maps the physical flows to the beneficiaries. ARIES encodes ecological production functions in these probabilistic (based on Bayesian Belief Networks) models or in existing deterministic models when the latter are widely accepted and suitable for the local context. Artificial intelligence techniques then combine source data with locally suitable ES models to quantify ES flows between source and usage location and to calculate their uncertainty (Bagstad et al., 2013; Bagstad et al., 2011; Villa et al., 2009). Each modeled ES (see Table 2.1) has a source (potential provision of ES), a sink (biophysical features that can deplete service flows), a use (human beneficiaries) and a flow model (Bagstad et al., 2011). For now, data and models are available for several western U.S. states and can sometimes be used in similar regions (Bagstad et al., 2013).

5 Polyscapes/LUCI

The Polyscape framework explores landscape capabilities and investigates the spatially explicit trade-offs amongst ES to support landscape management. The output maps use categories ranging from high actual value to high opportunity for change. The idea is to use "simple, transparent tools of appropriate complexity given data limitations and knowledge gaps" (Jackson et al., 2013). The actual tool is LUCI (Land Utilisation and Capability Indicator), an extension and accompanying software implementation of the Polyscape framework, but is not yet released for general use.

6 Comparison of the tools

Hydrological tools produce a more detailed output whereas ecosystem services tools are less detailed but generally more accessible to non-experts. The latter can provide a general picture of ecosystem services (Vigerstol & Aukema, 2011). From the above tool description, SWAT is the only solely hydrological tool. The pros of this tool are the daily time step, detailed output, focus on hydrology and uncertainty calculation. The cons are the detailed data input, the inability to model services other than hydrologic ones, the high modeling time requirement and the skills needed. Next to that, the output is not in ES terms, which implicates that output variables need to be chosen as indicators for ES (Boyanova et al., 2016).

From the other tools, which all model ecosystem services, ARIES and InVEST are most comparable. InVEST and ARIES both model water related ES like nutrient retention and freshwater supply and can model other ES like recreation but they do not output identical ecosystem services metrics (Bagstad et al., 2013b). Compared to SWAT, InVEST and ARIES need less detailed input data and hydrological knowledge. Their hydrologic models operate at an annual scale but make use of important simplifications. The InVEST hydrologic model only uses precipitation and evapotranspiration and neglects surface water – ground water interactions (Sharp et al., 2014). ARIES only considers flows of surface water, though it models the infiltration of surface water into groundwater and groundwater extraction from wells (Bagstad et al., 2011). The output of water related services should thus only be used to elucidate patterns.

Due to the use of deterministic models, InVEST is more appropriate to use in a context of good ecological knowledge and data availability. ARIES, which uses both deterministic and probabilistic models, can be more suitable in case of data scarcity. On the one hand, ARIES has a higher time requirement than InVEST for new case studies and a complex model code. On the other hand, ARIES models flows of ES from source to beneficiaries and it models uncertainty more precisely compared to InVEST (Bagstad et al., 2013b; Vigerstol & Aukema, 2011).

Polyscapes/LUCI is more designed for local scale assessment compared to the previous described tools and to work with generally available national scale datasets. It has a lower modeling difficulty compared to InVEST and ARIES but is not yet released for general use.

SolVES uses a different approach because it spatially reproduces the social values people assign to ES and does not provide qualitative biophysical outputs like ARIES, InVEST and SWAT. Environmental input data is basic but stakeholder engagement is mandatory and requires quite some time. SolVES can be useful to identify areas that people value the most and to disclose correspondent environmental metrics.

Table 2.1. Comparison of ecosystem services tools for key criteria.

Tool	Key input requirement	Key output	Ecosystem services modeled	Model type
SWAT	- daily precipitation, maximum and minimum temperature, wind speed, relative humidity and solar radiation - multi layer soil type - digital elevation model (DEM) - watershed and (sub)basin characteristics - land use land cover (LULC) - nutrient and pesticide load (optional)	- daily water yield, evapotranspiration and flows - nutrient and sediment migration and chemical transformation	no explicit modeling of ES but modeling of : -snowpack and snowmelt infiltration - soil routing of water - movement into and out of aquifer system - evapotranspiration and water diversions - plant growth	D*
inVEST	- land use land cover - DEM - soil and vegetation characteristics - annual average climate data (precipitation, evapotranspiration) - watersheds - consumptive use by LULC for ES use modeling	-spatially explicit GIS maps of intermediate modeling steps, final biophysical service levels, relative ranking, economic valuation (optional for some ES) - several output options for each ES - ES tradeoff maps	- several marine ES - water yield (hydropower) - nutrient and sediment retention - visitation: recreation and tourism - fisheries - crop pollination - others	D
ARIES	-elevation, hydrography, water extraction amounts, wells -land cover (land use), soil characteristics, precipitation, runoff, infiltration, soil loss, dams, levees -species richness, specific habitats, transportation infrastructure, population density	-spatially explicit ecosystem service trade-off, flow and uncertainty maps -maps of the location and the biophysical quantity of sources and sinks, can be monetized	- coastal and inland flood regulation - freshwater supply - sediment regulation - aesthetic view sheds and aesthetic proximity - recreation - subsistence fisheries - carbon sequestration and storage	D, P** when insufficient data
SolVES	- study area boundary - public attitude and preference surveys - minimum one environmental data layer (elevation, distance to water, land-cover type) - demographic and attitudinal information of the respondents	- social-value map - graphs comparing environmental metrics with value indices	- mainly cultural services - some provisioning services	D

Table 2.1. (continued).

Tool	Key input requirement	Key output	Ecosystem services modeled	Model type
Poly-scapes/ LUCI	- basic: national scale gridded DEM (ideally 5x5m-10x10m resolution), land use and soil data - optional: finer resolution data e.g. LIDAR, surveys, spatial coverage, species of interest	- 5-way color impact maps - trade-offs and co-benefits maps	- flood risk - erosion - habitat connectivity - carbon sequestration - agricultural productivity - extra for LUCI: water quality	D

*: deterministic, **: probabilistic

Table 2.1. (continued).

Tool	Scale	Time requirements	Accessibility	Uncertainty	Stakeholder engagement
SWAT	time: daily space: watershed, sub basin	high (model learning)	- ArcSWAT (licensed ArcGIS needed), QSWAT (free QGIS needed) or GRASS-SWAT (free GRASS needed) - GIS and hydrology knowledge	SWAT-CUP software (Calibration and Uncertainty Procedures)	No
inVEST	time: annual space: landscape - watershed – global scale	- medium for Tier 0 and 1 - high for Tier 2	- version 3: own platform to run almost all models but some need ArcGIS, any GIS tool to explore results - Tier 1: accessible, Tier 2: more knowledge needed	uncertainty through varying inputs	optional but preferred for scenario development
ARIES	time: monthly to annual space: landscape – watershed - (global) scale	High to develop new case studies, low for preexisting case studies	- user's web interface, ARIES Explorer, not yet available - modeler's k.LAB software requires intensive training -Bayesian knowledge to understand models	uncertainty through Bayesian networks and Monte Carlo simulation	not explicitly mentioned
SolVES	time: no time step considered space: watershed or landscape scale	High if primary surveys are required, low if function transfer approach is used	- ArcGIS - Maxent maximum entropy modeling software	no explicit handling of uncertainty	required via surveys
Poly-scapes/ LUCI	time: no time step or annual space: individual fields to landscape catchments of 10,000 km²	Medium	- Not yet released for general use - ArcGIS needed	no explicit handling of uncertainty	to reduce deficiencies in data

The tools compared in this section can be used in the implementation phase of spatial planning. However, using ES in the different stages of a planning process is useful for a more integrated approach of spatial planning. During the ECOPLAN (PLANning for ECOsystem Services) project, executed in Flanders during the years 2013-2016, spatially explicit information and tools were developed "for the assessment of ES and the evaluation of functional ecosystems as a cost-efficient and multi-purpose strategy to improve environmental quality" (Staes et al., 2016). The ECOPLAN tools can be used at various stages of the planning process (analysis, vision, planning and implementation) as can be seen in Figure 2.6. ECOPLAN is a good example of how to use ES in a holistic approach of spatial planning.

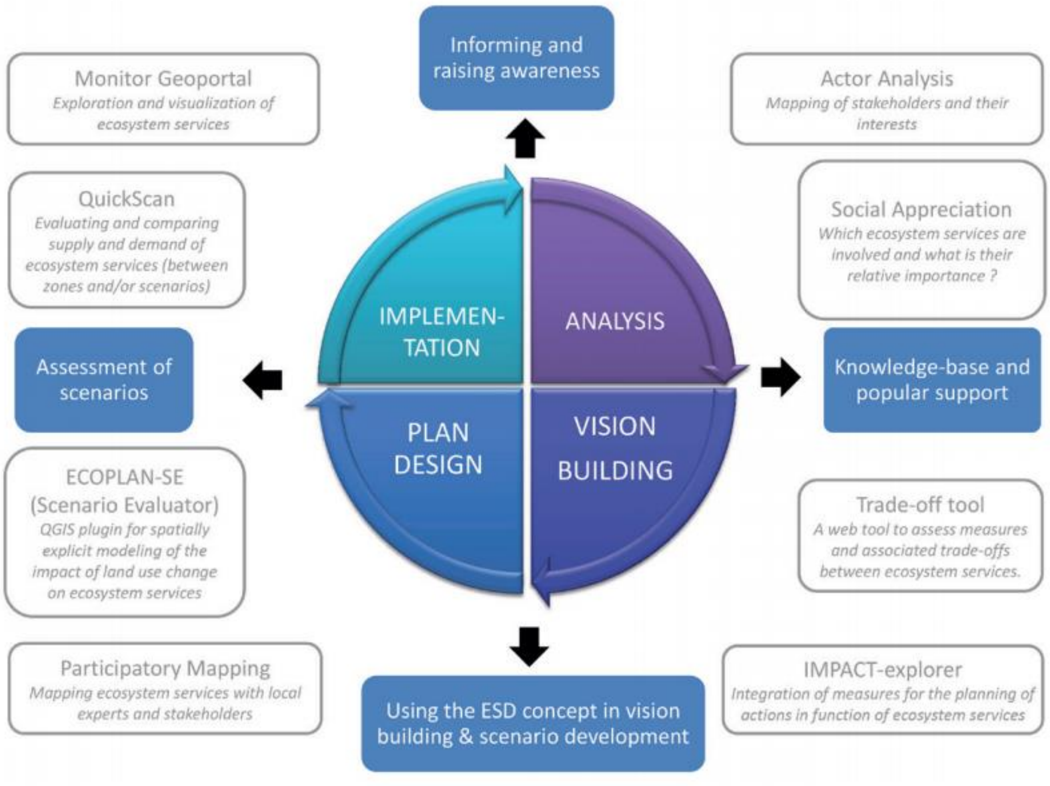

Figure 2.6 Phases in the planning processes and proposed ECOPLAN tools for each phase (Staes et al., 2016)

2.3.3.5 Geographical Information System data

Spatial data for GIS are increasingly available (Karduni et al., 2016; Kerski & Clark, 2012). A GIS is a computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface. It is used to visualise, analyse and interpret data to understand relationships, patterns, and trends. A lot of GIS data is nowadays available but attention must be paid to several characteristics of the input data.

One of them is the spatial resolution that can be defined as the dimensions of a pixel in raster data. A low or coarse resolution decreases the quality of the representation of the characteristics of an area (Baldwin et al., 2004; Cotter et al., 2004). Another characteristic is the coordinate system. Many of them exist and it is important to work with the same coordinate system for all data layers in order to be able to compare and to make calculations with the layers (ESRI, n.d.). Next to that, the quality of the input data is important. "A GIS database can contain very different types of data (e.g. raster versus vector, quantitative versus qualitative or categorical) that can also have different lineage (i.e. different primary data acquisition sources, different methods of derivation), and hence different kinds of corresponding uncertainty" (Crosetto & Tarantola, 2001). The input data can be affected by uncertainties due to measurement errors, excessively coarse scale, insufficient samples, bad digitizing of maps etc.

3 Material and methods

3.1 Study area: The *Mashcón* catchment in *Cajamarca*, Peru

The *Mashcón* catchment is located in the northern Andes of Peru. It covers an area of approximately 315 km² at an altitude between 2500 and 4100 m and is mainly situated in the districts *Cajamarca* and *Los Baños del Inca*, in the south of the department of *Cajamarca* (Figure 3.1). In the north of the catchment, the *Yanacocha* mine is operated in the mountains, while in the south the valley hosts *Cajamarca*-city. The population of *Cajamarca* (district) and *Los Baños del Inca* was estimated at 276,000 for 2013, with 180,000 inhabitants for *Cajamarca*-city (INEI).

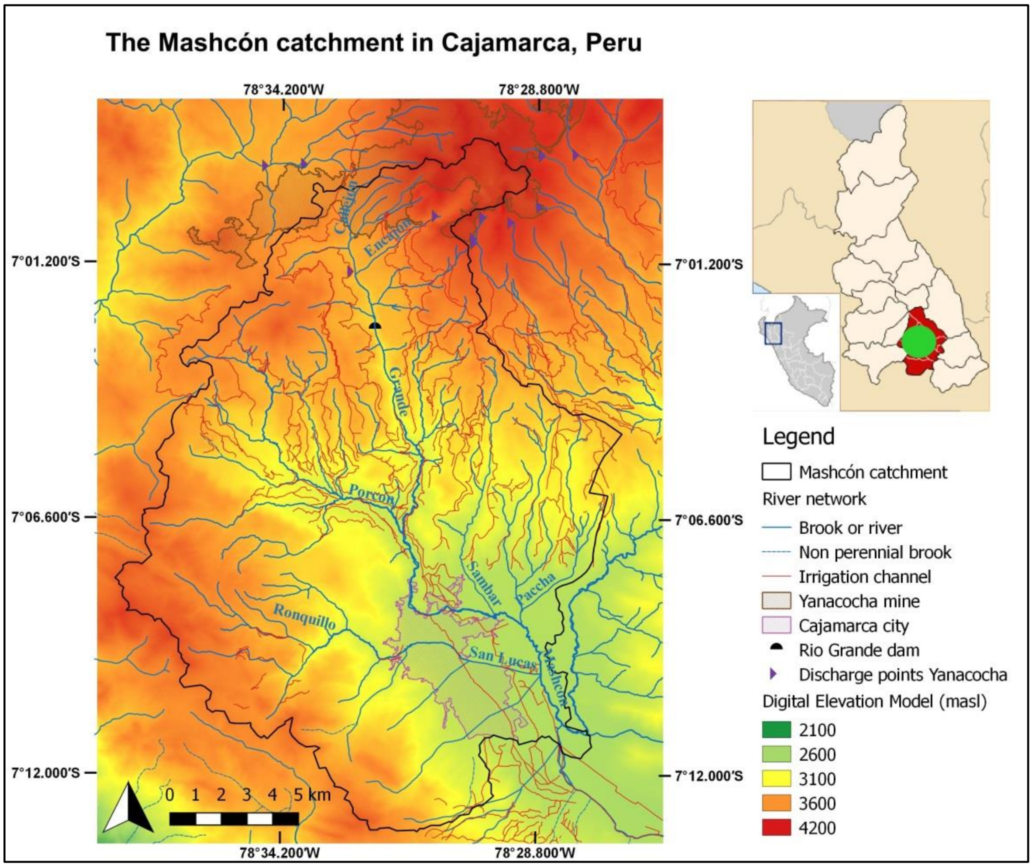

Figure 3.1. The *Mashcón* catchment in the *Cajamarca* region of Peru. The abbreviation 'masl' stands for 'meters above sea level'.

3.1.1 Climate

The *Mashcón* catchment has a cold and humid climate in general, but temperature and precipitation can vary with the altitude. The higher the altitude, the lower is the temperature and the higher the precipitation. Minimum and maximum temperatures, around 5 and 20 °C respectively, are constant throughout the year, with high daily fluctuations. The *Mashcón* catchment has a wet season from October until April and a dry season from May until September. The annual precipitation ranges between 400 and 1200 mm depending on the elevation (Ferreyros et al., 2007; Sánchez & Sánchez, 2012).

3.1.2 Hydrology

The *Mashcón* catchment is part of the *Crisnejas* river basin. The *río Mashcón* receives the water from tributaries originating in the Jalca, and leaves the catchment in the southeast of *Cajamarca* city. The headwaters of the *Mashcón* catchment are formed in the hydrological center *Cajamarca-Hualgayoc,* the largest aquifer recharge center in *Cajamarca* region. Currently, the headwaters of the *Río Grande sub-catchment,* main tributary of the *Mashcón* catchment, are mostly occupied by *Yanacocha* mine operations (Sánchez & Sánchez, 2012).

3.1.3 Ecology

The two ecosystems of the region are *Quechua* and *Jalca*. *Quecha* is at an altitude from 2300 to 3500 m.a.s.l. and is characterised by a combination of evergreen shrubs, arboreal and perennial herbaceous vegetation. Due to its temperate climate, this natural region is more suitable for human life, in comparison with the higher *Jalca*. Part of the *Quechua* is thus transformed into cultivated land and pastures for cattle raising (Figure 3.2 Left). Herbaceous vegetation covers the *Jalca* at elevations from 3500 to 4000 m.a.s.l. (Figure 3.2 Right) (Sánchez & Sánchez, 2012).

Figure 3.2. Left: Cultivated pasture for cattle in the Quechua (source: Google Street View 2017). Right: Herbaceous vegetation in the Jalca (Picture taken by Eveline Beeckman, August 2017).

3.1.4 Yanacocha mine

The *Yanacocha* mine, operated by Minera *Yanacocha* S.R.L. (MYSRL) since 1993, is situated at altitudes of 3500 to 4100 m.a.s.l. in the districts *Cajamarca, Los baños del Inca* and *Encañada* (Figure 3.3 Left). The main metals extracted in the *Yanacocha* mine are gold and silver. The current operations consist of 13 open pits whereof 7 in activity, 9 rock residue heaps and 4 cyanide leaching piles that cover an area of 37 km^3. In 2015, 26.02 tons of gold and 12.76 of silver were produced (MYSRL, 2011).

MYSRL has the permission to withdraw groundwater from the open pits at a rate of 570 $l.s^{-1}$, or 17.976 Mm^3 a year, to dry the pits to secure the working environment (MYSRL, 2011). As a consequence, the phreatic level has fallen 100 m in some areas. The major part, together with treated waste water, is discharged in brooks. The 14 authorized discharge points are shown in Figure 3.1, the discharge quantities and the receptor water bodies are detailed in Appendix 2. In total, the *Autoridad Nacional del Agua* authorised MYSRL to discharge 89.675 Mm^3 a year. From this, 22 Mm^3 can be discharged in brooks of the *Mashcón* catchment. The dried-up springs located in the mining region are replaced by a cluster of pipes, installed by MYSRL, that discharge water. The *Río Grande,* that was once formed by the confluence of the *Callejón* and *Encajon* brooks, now originates from an artificial source (Figure 3.3 Right).

Figure 3.3. Left: View on an open pit of the *Yanacocha* mine (source: Bloomberg, 2015). Right: Artificial source of the *Río Grande* (source: Celedin Libre, 2012).

Table 3.1 shows water withdrawal, discharge and reuse quantities for the year 2012. The actual water use, as MYSRL states, is the difference of the withdrawal and the discharge, which is of approximately 4.1 Mm^3 for the years 2012. They state that the major part of the water withdrawn from a catchment is returned to that same catchment (MYSRL, 2011). The extracted groundwater is, however, discharged as surface water.

Table 3.1 Water use in Mm^3 of the *Yanacocha* mine for the year 2012 (MYSRL, 2013).

Total water withdrawal	49.073 Mm^3
Surface water and precipitation	16.673 Mm^3
Ground water	32.400 Mm^3
Total water discharge	44.955 Mm^3
Recycled and reused water	89.922 Mm^3

Complaints about the high sediment load of the discharged water induced MYSRL to respond by building two dams to retain the sediments. One, built in 2004, is located on the *Río Grande* (Figure 3.1) and the other, built in 2002, on the *Río Rejo*. The latter is situated west of the *Mashcón* catchment. These dams are also used to release additional water (around 50-80 $l.s^{-1}$) during the dry season when necessary. After complaints about downstream water shortage, MYSRL agreed to maintain a minimal discharge of 500 $l.s^{-1}$. Other measures taken by MYSRL against water shortage are the building of family reservoirs and the San José reservoir, which discharges water in several irrigation channels since 2007 (MYSRL, 2011).

3.1.5 Drinking water in Cajamarca-city

The *Río Grande,* the *Río Porcón* and the *Río Ronquillo* provide 61%, 14% and 25% of the water used in *Cajamarca*-city respectively (Atkins et al., 2005). The population was estimated at 194,000 in 2015, presumably increasing to 281,000 in 2030. Considering a daily need for 120 L of water per person, the demand was of 269 $l.s^{-1}$ in 2015, and would be of 390 $l.s^{-1}$ in 2030. In dry season, the lease for water abstraction for drinking water production is of 214 $l.s^{-1}$ (ALAC, 2013). This supply-demand mismatch causes the rationing of water distribution to few hours a day in some sectors of the city (Prado, 2012). A proposed solution, investigated by MYSRL and ALAC (Asociación Los Andes de *Cajamarca*), would be the building of a new dam on the *Río Chonta* in the east of the city. Water would then be conveyed towards the city via pipelines (ALAC, 2013).

3.1.6 Economic activities

In the south of the *Cajamarca* department, *Mashcón* catchment included, cattle raising and mining are the principal economic activities. The increasing milk demand of the dairy processing sector and the secured income have made of milk production the most important agricultural activity in the region (Inga & Cosavalente, 2016; Garcia & Gomez, 2006). Large companies such as Nestlé and Gloria have settled there, procuring a continuous milk supply from the farmers. According to a study of Garcia and Gomez in 2006, 75% of this milk is produced in farms with less than a dozen of cows. Due to the climatic conditions and the limited access to irrigation water for agriculture, cattle graze on natural pastures in the *Jalca,* while in the valleys, pastures can be cultivated due to a better access to irrigation. Apart from milk production, bovine meat production is also significant in the area. Small farmers usually grow cash crops or produce forage as a second income. The predominant farming system is thus a combination of animal and crop production (Garcia & Gomez, 2006). Moreover, food crops from the catchment are used for self-sustain, rather than for commercial purposes.

Mostly, the services and trade sector develops as a result of mining activities (Inga & Cosavalente, 2016). Also, the construction sector has grown with an average of 7.2% since 2007, driven by the construction of mining infrastructure and public investment.

3.2 Data collection for ecosystem services selection in *Mashcón* catchment

In this section, the ES delivered and used in the *Mashcón* catchment and possibly impacted due to the *Yanacocha* mine were scoped via literature. Then, an overview of the data available to assess these ES was made. Knowing the ES of the study area, their importance for the inhabitants, and the data available to assess them, a choice was made on the ES to evaluate.

3.2.1 Ecosystem services in the study area

ES were implicitly mentioned in the site description. An additional source of ES is the study of the Regional Government of *Cajamarca* (RGC) on ES in 15 priority sites for biodiversity conservation, such as the *Jalca cajamarquina* (Alcántara, 2014). Supplementary ES references were found in Bebbington and Bury (2009), Atkins et al. (2005), Sosa and Zwarteveen (2012), Bernet et al. (2002), Vela-Almeida et al. (2016). Then, an ES-(D)PSI(R) scheme was built based on these references and on the general ES-DPSIR scheme from Section 2.2.3 (Figure 2.5).

Based on the importance of ES and data availability, several ES were selected for the assessment (Section 4.1.2). The relevance of the ES for the *Mashcón* catchment were derived from literature (Vela-Almeida et al., 2016; Garcia & Gomez, 2006; Sosa & Zwarteveen, 2012) and from a governmental report from the Central Reserve Bank of Peru (Inga & Cosavalente, 2016).

3.2.2 Data collection and availability

As can be seen in Table 2.1 (Section 2.3.3), the main data necessary to assess ES are precipitation, water quality, evaporation, temperature, land use and land cover (LULC), soil texture, digital elevation model (DEM) and agricultural practices. Physico-chemical and biological water quality data were available from a sampling campaign that took place during dry season (July-August) 2017 by researchers of the *Aquatic Ecology* research group from the University of Ghent. The sampling locations as well as the detailed data can be found in Beeckman (2017). The remaining data were gathered from the internet and are discussed in the next sections.

3.2.2.1 Geographical Information System data

GIS data layers were collected and used considering the spatial resolution, the coordinate system and the quality of the input data. In this thesis, EPSG projection[3] 32717 equal to WGS 84/ UTM zone 17S, which covers 84° west to 78°W and 80°S to the equator, was used.

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[3] Coordinate Reference Systems and Coordinate Transformations from the European Petroleum Survey Group

An overview of the different sources of GIS data is presented in Table 3.2 and a list of useful GIS layers is presented in Appendix 3.

Table 3.2. Sources of GIS data and their general content.

Source	Details
La Zonificación Ecológica y Económica (ZEE)	Every region in Peru has to make a ZEE study as part of the law for the sustainable use of natural resources. The RGC made available the main GIS layers they used for this project such as LULC and soil maps.
WorldClim	A set of global climate raster layers with average monthly climate data for the period 1960-1990 (Hijmans et al., 2005).
SENAMHI, the National Service for Meteorology and Hydrology of Peru	They made a model of the annual precipitation in the cajamarquino part of the Jequetepeque and Crisnejas catchment that include the *Mashcón* catchment.
GEOCATMIN (Sistema de Información Geológico y Catastral Minero)	Developed by INGEMMET (El Instituto Geológico, Minero y Metalúrgico) and contains data layers on mine concessions and geology among others.
ALOS PALSAR	PALSAR was one of three instruments on the Advanced Land Observing Satellite-1 (ALOS) and collected DEM worldwide. ALOS was a mission of the Japan Aerospace Exploration Agency (JAXA). (ASF, n.d.)
IV CENAGRO (Censo Nacional Agrocepuario)	Peruvian National Agricultural Census organised by the National Institute of Statistics and Informatics (INEI) in 2012 following the decree Nº 055 – 2011. It contains data on agricultural and animal production.

3.2.2.2 Other data

Meteorological data from SENAMHI is obtained via their website and via literature (Kuijk 2015). In the *Mashcón* catchment, *Augusto Weberbauer* is the main weather station (n°000304). MYSRL has five meteorological stations, four on the mining site and one in the north-west of the *Mashcón* catchment. The data of the MYSRL is procured by the RGC. Depending on the source, the years of measurements vary between 1934 and 2016, it are daily values or monthly sums or averages, the measured variables differ and the amount of lacking data varies. An overview table of the meteorological data is given in Appendix 4.

3.3 Assessment of ecosystem services

Having selected the main ES (‘water use’, ‘cultivated crops’ and ‘reared animals’), the following conceptual scheme was developed for the assessment of the ES in the *Mashcón* catchment (Figure 3.4).

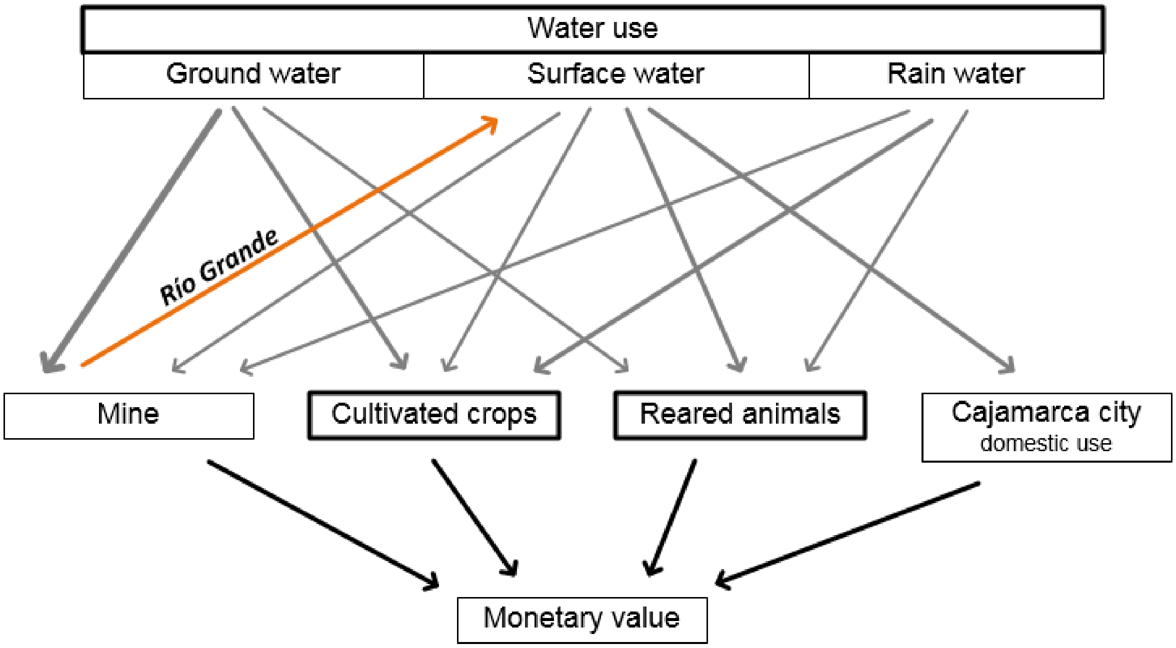

Figure 3.4. Ecosystem services assessment frame. The thick black boxes are the ES to assess. The grey arrows represent the water flow towards the major water users of the *Mashcón* catchment. The orange arrow symbolises the treated (waste) water from the *Yanacocha* mine that is fed to the *Río Grande*. The black arrows represent the monetary value of the different sectors. The thicknesses of the arrows represent the relative quantity of the flows (estimations in this case).

Water is supplied and can be used under three forms: ground, surface and rain water. The major users of this water are the *Yanacocha* mine, the farmers (crop and animal production) and the population of *Cajamarca* city. Both the supply and the demand[4] of the ES ‘water use’, ‘cultivated crops’ and ‘reared animals’ were biophysically quantified and represented as scores or biophysical values. To assess these ES, appropriate methods were elaborated based on data availability. An overview of the available data and the ES assessment methods is found in the Results (Section 4.3.1) as well as the detailed ES assessment methods. The result maps were built with ArcGIS and QGIS.

Finally, the ES ‘cultivated crops’ and ‘reared animals’ for the *Mashcón* catchment were valued with market prices as well as the domestic water use. Because the mine relies on the ES ‘water use’, the monetary value of the mine was calculated as well. The entire assessment is made with data from 2012.

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[4] The supply of an ES is the quantity of that ES that is procured by the ecosystems and available for use. The demand of an ES is the quantity of that ES that is used for human purposes.

For the monetary valuation of the agricultural and animal production, quantities of harvested crops and reared animals as well as their respective selling prices from the Regional Office for Agriculture were used. The selling price of water for domestic use was retrieved from a tariff study on Sedacaj (Sunass, 2014). Incomes and expenditure from the *Yanacocha* mine are found in the MYSRL report of 2013 and in Appendix 5.

4 Results and discussion

4.1 Ecosystem services in *Mashcón* catchment

4.1.1 Overview of ES

The scheme in Figure 4.1 is an adaptation for the *Mashcón* catchment of the ES-DPSIR scheme of Figure 2.5 taking into account information from the section on the study area and literature mentioned in Sections 3.1 and 2.1.3, 2.3.3 respectively. Only the pressure-state-impact part of DPSIR is displayed in Figure 4.1.

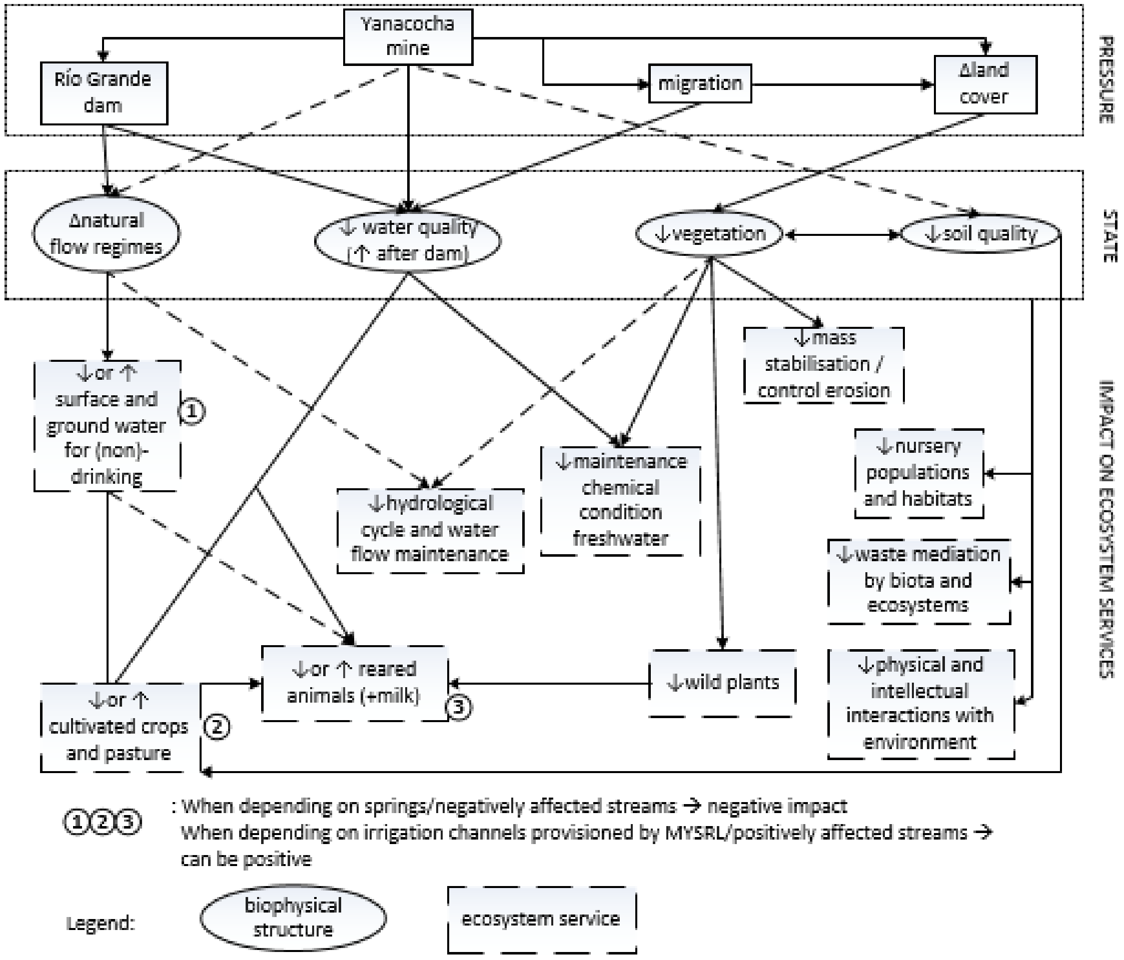

Figure 4.1. Ecosystem services and mine-related environmental stressors in the *Mashcón* catchment. The ES 'reared animals' from the CICES ES classification represents animal production like cattle raising for milk and meat production.

The settling of the *Yanacocha* mine induced large hydrological changes. Households and farmers in the influence area of the mine that depend on springs, natural brooks or rivers and irrigation channels provided by natural brooks or rivers experience a fall in water availability. For them, ES 1 is negatively impacted. Households and farmers that have access to irrigation channels or water reservoirs provisioned by MYSRL or to streams that receive treated wastewater from the mine can encounter a better water availability especially during the dry season. This water availability is better in comparison with the water availability during the period in which the mine settled but when no measures were taken to solve water shortage problems. Water availability before the mine settling is not taken into account when mentioning this positive change. In their turn, ES 2 and 3, that are both dependent on water availability, can be affected in a negative or positive way.

Part of the households using high elevation natural pastures for their cattle had to intensify their agriculture for fodder production to compensate for the loss of pastures due to the mine settling. This caused, according to farmers, a decrease in soil fertility (Bebbington & Bury, 2009) what can cause a decrease in crop production. This is represented by the link change in land cover - reduced vegetation and soil quality - reduction of crop production in Figure 4.1.

The medicinal-aromatic species *Valeriana pilosa* and *Satureja* sp. are collected by peasants in the *Jalca* and sold on markets (Alcántara, 2014). The reduction of *Jalca* due to the mine extension reduces the available area to collect these species. Next to the provisioning service, which is contained in the ES *wild plants*, collecting these herbs also has a cultural connotation that is included in the ES *physical and intellectual interactions with the environment*.

4.1.2 Choice of ES to assess

The selection of the ES to assess based on the overview of the ES in the *Mashcón* catchment and the available data are:

- ‘ground- and surface water for (non)-drinking’ (renamed as ‘water use’ for the rest of this thesis) since water is indispensable for the inhabitants’ household, for the animal and crop production and for the mine operation.

- ‘reared animals’, since milk production is the major source of income for a considerable part of the population of the catchment

- ‘cultivated crops’, since many households do agriculture for their own consumption or as a second source of income.

The remaining ES shown in Figure 4.1 are crucial too, but they are not considered here to reduce the complexity of the assessment.

4.1.3 Elaborated methods based on data availability

A concise explanation of the methods elaborated to assess the selected ES based on data availability is presented in Table 4.1.

4.2 Elaborated methods for the ES assessment

4.2.1 ES water use

Supply

The total annual precipitation in the *Mashcón* catchment was calculated based on the annual precipitation raster data. Next, rain water quantities and meteorological and soil characteristics were used to score the water supply of the study area. Since evapotranspiration (ET) determines the fraction of the rainwater that is effectively supplied to an area, evapotranspiration was chosen to score the supply of the ES 'water use'. Based on expert knowledge of Ghent University, the following variables of the *Food and Agriculture Organization of the United Nations* (*FAO) Penman-Monteith* method (Allen et al., 1998) were retained for the assessment: precipitation, temperature, wind speed and solar radiation. They are presented in Table 4.2 with their associated scores. The calculations of the characteristics are presented in Appendix 6. Land cover was chosen to take into consideration the ET from different land cover types. The score given to different land cover or plant types is given in Table 4.3 (Sharp et al., 2014).

The total score for a specific area was calculated via the formula

$$Score_{total} = S_{prec} * S_{temp} * S_{wind} * S_{rad} * S_{Kc}, \qquad (1)$$

with S_{prec}, S_{temp}, S_{wind}, S_{rad}, S_{KC} the score of the precipitation, temperature, radiation, wind speed and evapotranspiration coefficient respectively.

This score was normalised to a score ranging from 0 to 100 via min-max normalisation with the formula

$$z_i = \frac{x_i - min}{max - min} * (max_{norm} - min_{norm}) + min_{norm} , \qquad (2)$$

with x_i: original score for a specific area, *min:* minimal possible score, *max*: maximal possible score, min_{norm} and max_{norm} the chosen minimum and maximum for the normalization range (Shalabi et al., 2006).

Table 4.1. Data availability and methods for the assessment of the ES. The column 'missing data' contains data that is necessary for a better assessment. SEA stands for *Sector de Enumeración Agropecuario* and is the research unit of the CENAGRO census.

Ecosystem service	Category	Available data	Missing data	Method
Water use	Supply	- GIS raster layer with annual precipitation for the *Mashcón* catchment - Map of the radiation in the *Cajamarca* region for the months February, May, August and November - Daily precipitation, temperature, wind speed at the 5 weather stations of MYSRL and at the *Augusto Weberbauer* weather station (details see Appendix 4) - Monthly flow rate of irrigation channels at different locations, single measurements of flow rate in the rivers and sources of the catchment - LULC map	- Groundwater volumes - Repeated measurements of surface water quantities and sources - Hours of sunshine - Plant available water capacity, detailed soil texture and depth	Scoring of the supply of water based on precipitation and important characteristics for evapotranspiration namely temperature, wind speed, radiation and land cover
	Demand	- Yearly ground-, surface- and rainwater withdrawal of the *Yanacocha* mine - Number of inhabitants of *Cajamarca* city, average water use per person - Surface area of cultivated crops and pasture per SEA (spatial) - Number of reared animals per SEA (spatial)	- Exact water quantity abstracted in the *Mashcón* catchment for mine exploitation - Exact water use in the city - Real water quantity used for crop and animal production and the source	Estimation of the water use based on surface area and average crop water need for crop production , on number of animals and average water use per animal type for animal production, on the number of inhabitants and the average water use for the city and on water withdrawal and discharge for the mine
Cultivated crops	Supply	- Rough classes of soil texture, pH, stoniness, organic matter, drainage and permeability (spatial) - DEM - Climate data	- Finer classification of soil texture - Quantitative data on soil depth, pH, stoniness, organic matter, drainage and permeability	Calculation of the Productivity Index based on soil characteristics and slope
	Demand	- Total surface area of cultivated crops per SEA (spatial) - Surface area of several crop types per SEA	- Complete inventarisation of crop types and surface area per SEA	Score based on the surface area used for crop production compared to the surface area of the SEA
Reared animals	Supply	- Surface area of natural and cultivated pasture per SEA (spatial)	(-)	Score based on the available natural and cultivated pasture compared to the surface area of the SEA
	Demand	- Number of cows, sheep, alpacas, pigs and poultry per SEA - Average pasture surface need per stock unit depending on pasture type and elevation	- Feed used for pig and poultry production	Score based on the surface area of pasture needed for cows, sheep and alpacas to graze on year round compared to the surface area of the SEA

Demand

The water demand of the *Yanacocha* mine for 2012 is given in Table 3.1. The fraction of the water demand for the part of the mining site located in the *Mashcón* catchment was assumed to be the same as the fraction of allowed water discharge that flows into the catchment. This assumption was made because MYSRL claims to discharge the same amount of water in a catchment that is withdrawn in that catchment (MYSRL, 2011). The discharge points located in the *Mashcón* catchment are DCP-3 and DCP-4 with an allowed discharge of 15 and 7 Mm^3 per year, respectively (Appendix 2).

Table 4.2. Scoring of characteristics for water supply.

Characteristic		**Class 1 2600-3000 m**	**Class 2 >3000-3400 m**	**Class 3 >3400-3800 m**	**Class 4 >3800-4200 m**
Precipitation	Range (mm)	600-800	>800-1000	>1000-1200	>1200
	Score	1	2	3	4
Temperature	Value (°C)	20.8	17.4	14.0	10.6
	Score	1	2	3	4
Radiation	Value ($kWh.m^{-2}$)	5.75	5.50	5.38	5.25
	Score	1	2	3	4
Wind speed	Range (m/s)	4.2	9.5	14.7	20.0
	Score	4	3	2	1

Table 4.3. Evapotranspiration coefficient for different land cover and plant types.

Land cover/plant type	**Planted forest**	**Pasture**	**Cropland**	**Grassland**	**Bare ground**	**Urban area**
Evapotranspiration coefficient (K_c)	1	0.85	0.65	0.60	0.5	0.3
Score	1.00	1.64	2.50	2.71	3.14	4.00

The water demand of crop production was estimated per *Sector de Enumeración Agropecuario* (SEA) and for the total catchment, based on the average water need of different cultivated crop types and the cultivated surface area. A SEA, literally Sector of Agricultural Enumeration, is a surface area that covers approximately 100 agricultural units (one unit contains the land of one family) and serves as a research unit for the CENAGRO. The average water need per crop type is shown in Table 4.4 (Brouwer & Heibloem, 1986; Suquilanda, 2011). Since ryegrass is entirely used for animal production and surface areas of ryegrass production are available, its water need was added to the animal production. The average water need for all the other crops together is approximately 5500 m^3/ha.

Table 4.4. Average yearly water need per crop type (m^3/ha).

Potato	**Carrot**	**Alfalfa**	**Barley/Oats/Wheat**	**Bean**	**Mais**	**Pea**	**Quinua**	**Ryegrass**
6,000	4,500	10,000	5,000	4,000	6,500	4,000	4,000	14,000

Animal production's water demand was estimated per SEA and for the whole catchment. The number of animals was multiplied by the daily water consumption per animal. The water consumption quantities per animal type are shown in Table 4.5, including drinking water and water for the farm operation (Markwick et al., 2014; Mekonnen & Hoekstra, 2010; Ward & McKague, 2015). Ryegrass water use was added to the water use of animal production (see previous paragraph).

Table 4.5. Daily water consumption of farm animals (liters).

Milk cow	Sheep	Alpaca	Pig	Chicken	Turkey
70	7.3	11	40	0.3	0.8

Cajamarca-city is another water consumer (see Figure 3.4). Annual water consumption was calculated based on a population of 180,000 inhabitants and a water consumption of 120L/day (ALAC, 2013). The water abstraction by *Sedacaj,* the drinking water company of *Cajamarca*, is detailed in Appendix 7.

4.2.2 ES cultivated crops

Supply

The supply of the ES 'cultivated crops' was expressed in terms of suitability of the land to grow crops. The productivity index (PI) (Riquier et al., 1970) was used as primary indicator in several ecosystem service studies and was chosen as indicator for this thesis (Laterra et al., 2012; Viglizzo et al., 2004)

$$Productivity\ Index\ (PI) = H * D * P * T * S * O * A * M, \tag{3}$$

with H: moisture, D: drainage, P: effective depth, T: soil texture, S: soluble soil saturation, O: organic matter content, A: mineral exchange capacity of clay and M: mineral reserve. S can be replaced by base saturation (N). Each parameter was given a score between 0 and 100.

Data for the subsequent parameters were available: D, P, T and O. The missing data of soil moisture (H) and base saturation (N) were replaced by the number of dry months and pH data respectively (Riquier et al., 1970). Data for A, M were lacking and no replacement parameters were proposed so these parameters were not further considered. Erosion is not included in the PI but since it is a parameter included in the *United States Department of Agriculture* (USDA) land capability classification (Klingebiel & Montgomery, 1961) and the framework for land evaluation of the FAO (FAO, 1967) among others, it was included via the proxy *slope* in the PI. These adaptations were made after expert consultation at the University of Ghent.

$$Productivity\ Index_{adapted}\ (PI_{adapted}) = H * D * P * T * N * O * Sl, \tag{4}$$

Except for the slope, the data were available in qualitative classes. An overlay was made between these qualitative classes and the quantitative ones of Riquier et al. (1970) based on comparison tables of the *Booker tropical soil manual* (Landon, 1947) and *Land Evaluation Part 3 Crop requirement* (Sys et al., 1993). The scores for the parameters are detailed in Appendix 8.

Demand

The indicator used to quantify the demand side of the ES 'cultivated crops' was the surface area of grown crops. For each SEA, the score was taken as the percentage of the surface area of crops (except for ryegrass) to the total surface area of the SEA.

4.2.3 ES reared animals

The ES 'reared animals' was quantified based on the pasture supply and demand in the *Mashcón* catchment.

Supply

A score was calculated that represents the suitability of a surface area to supply pasture for grazers (cattle, sheep, alpacas). The capacity of different types of pastures to sustain grazers is given in Table 4.6 (Escurra, 2001; Garcia & Gomez, 2006). This capacity was converted to the correction factor, CF_{yield} (Table 4.6). A second correction factor, CF_{slope}, was used to score the accessibility of the pasture for the animals and was measured via the slope (see Table 4.7) (Castellaro, 2014). The CF_{slope} of alpacas was considered the same as for sheep. For the calculations, the most limiting CF_{slope} of cows was used. The formula to calculate the *reared animal ES supply* score was

$$Reared\ animals\ ES\ supply\ score = \frac{\sum_{i=1}^{2}(A_i * CF_{yield} * CF_{slope})}{A_{unit}}, \tag{5}$$

with A_{unit} : surface area of SEA

A_i : surface area of pasture type (natural or cultivated) per SEA

CF_{yield} : yield correction factor (Table 4.6)

CF_{slope} : slope correction factor (Table 4.7)

Table 4.6. Different pasture types with associated stock unit (SU) capacity and yield correction factor. A SU represents an animal of 450kg.

Type	Altitude	Capacity (SU/ha)	CF_{yield}
Cultivated pasture	2600 < Z ≤ 3500 m.a.s.l.	3	1.00
Cultivated pasture	Z > 3500 m.a.s.l.	2.5	0.83
Natural pasture	2600 < Z ≤ 3500	1	0.33
Natural pasture	Z > 3500 m.a.s.l.	0.5	0.17

Table 4.7. Slope correction factor for cattle and sheep.

Slope (degrees)	**CF_{slope}**	
	Cattle	Sheep
$0 \leq S < 6$	1.00	1.00
$6 \leq S < 19$	0.80	0.85
$19 \leq S < 25$	0.50	0.60
$25 \leq S < 33$	0.20	0.40
$33 \leq S < 44$	0.00	0.20
$S \geq 44$	0.00	0.00

Demand

The grazing need of each animal type was represented as a fraction of a stock unit (SU) (Table 4.8). For each SEA, the sum of SUs was calculated. To be able to compare it with the supply of the reared animal ES, this amount was translated into pasture surface area need. The cultivated pasture was taken as reference for the surface area needed per SU (Table 4.6). The final reared animal ES demand score for each SEA was obtained by dividing this area by A_{unit}. The score formula was:

$$Reared\ animal\ ES\ demand\ score = \frac{number\ of\ SU * A_{SU}}{A_{unit}}, \qquad (6)$$

with A_{SU}: surface area per SU (derived from Table 4.7)

This score was again normalised to obtain a final score between 0 and 100.

Table 4.8. Grazing need per animal type expressed as SU fraction.

Animal type	**SU fraction**
Holstein, Swiss cattle, others	1.00
Criolla + Gyr cattle	0.90
Sheep	0.10
Alpaca	0.15

4.3 Assessment of ecosystem services

Next follow the results from the ES assessment, presented as maps with a resolution of 500 m x 500 m. The darker the color, the higher the ES supply or demand is in that area. The color code has different associated values for every map.

4.3.1 ES water use

Supply

The total precipitation for the *Mashcón* catchment was estimated at 283.43 Mm³ a year. Depending on the climatic conditions and the land cover, the amount of precipitation that is lost by evapotranspiration varies. The normalised score for the water supply of every part of the study area, based on the ET, is shown in Figure 4.2 (Left). The score of 100 corresponds to the highest score that is encountered in the catchment.

Pixels in red have a zero value. The 500 m x 500 m raster obtained from the polygon (land cover) rasterization was slightly different than the ones derived from the DEM raster file. The zero values correspond to pixels that are part of the raster derived from the DEM but that do not exist in the raster derived from the land use polygon.

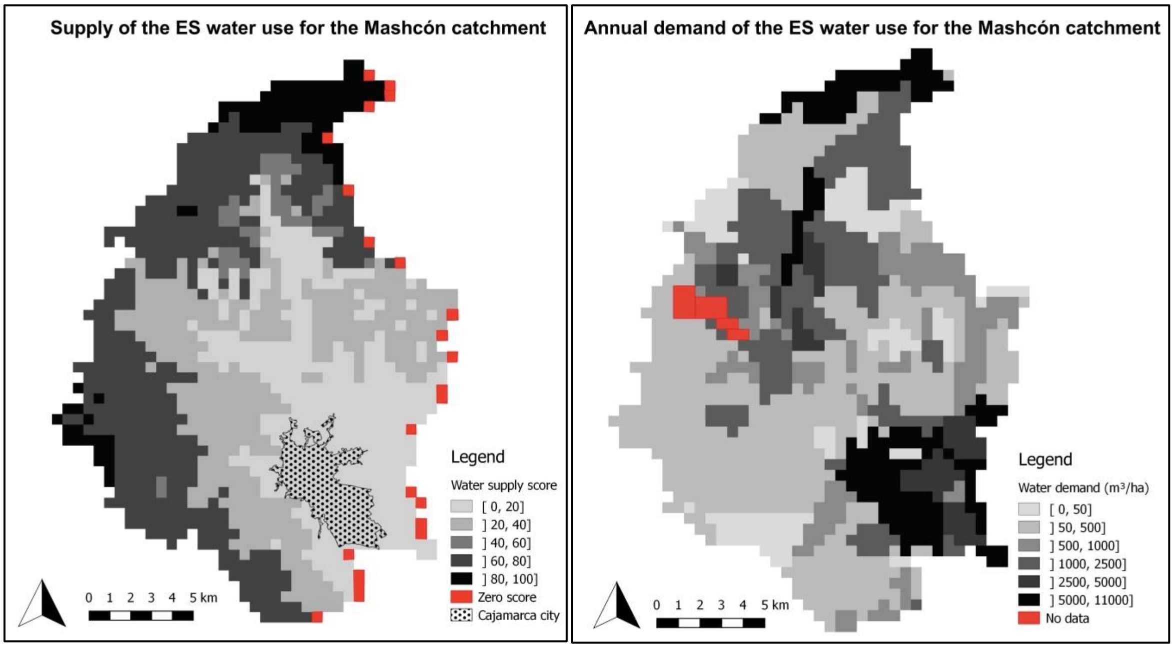

Figure 4.2. Left: Supply of the ES 'water use' for the *Mashcón* catchment. Statistics: minimum=0, maximum=100, mean=41, standard deviation=30. Right: Total annual demand for the ES 'water use' in the *Mashcón* catchment. Statistics [m³ ha^{-1}]: min=1, max=10,874, mean=1,643, SD= 2672.

The general trend is that the score rises when the elevation becomes higher (cfr. Figure 3.1 for the elevation in the catchment). *Cajamarca* city is located in the lowest score category while the *Yanacocha* mine is situated in the highest one. The mean 'water use' supply score is 41, which is lower than half of the highest score.

Demand

Figure 4.2 (Right) shows the annual demand of the ES 'water use' containing the agricultural, livestock and mining sector as well as the water consumption of the inhabitants of *Cajamarca* city. The water demand was estimated at 58.42 Mm^3. The areas corresponding with the *Yanacocha* mine, *Cajamarca* city as well as several smaller agricultural areas have the highest water demand between 5,000 and 11,000 m^3ha^{-1}. The area from the South to the West is an area with a low water demand ranging prevailingly between 0 and 500 m^3ha^{-1}.

The annual water need for the *Mashcón* catchment for crop production, calculated with as water need 5,500 m^3ha^{-1} for an average crop type and without taking ryegrass into account, is evaluated at 17.06 Mm^3. The distribution of the demand of the ES 'water use' is heterogeneous and is displayed in Appendix 9A. Apart from two areas in the Southeast of the catchment and some spots in the Northwest with a water demand of more than 2,000 m^3ha^{-1} and apart from few areas with a water demand between 1,000 and 2,000 m^3ha^{-1}, the water demand is situated in the lower categories. The mean water demand of 338 m^3ha^{-1} indicates low average water consumption per hectare for the crop production.

The water demand for animal production including water for drinking, service and ryegrass production is estimated at 19.07 Mm^3 a year from which 18.56 Mm^3 is needed for ryegrass production. The annual water demand per hectare is presented in Appendix 9B. Two distinct areas, one in the Southeast and one in the Northwest, necessitate the highest water demand evaluated between the 2,000 and the 6,600 m^3ha^{-1}. The mean water demand amounts 613 m^3ha^{-1}.

The part of the *Yanacocha* mine situated in the *Mashcón* catchment and the inhabitants of *Cajamarca* consume an estimated 12.04 and 10.25 Mm^3 water a year respectively.

MYSRL is allowed to discharge 22.00 Mm^3 per year in the discharge points situated in the *Mashcón* catchment. This equals 25% of the allowed discharged water quantity. Assuming the water withdrawal in the catchment proportional to the water discharge, the water demand of the *Yanacocha* mine situated in the *Mashcón* catchment is of 1.04 Mm^3 surface water, 7.95 Mm^3 groundwater and 3.05 Mm^3 rain water. Knowing that the total discharged water quantity was 44.96 Mm^3 in 2012 and assuming 25% of this quantity is discharged in the *Mashcón* catchment via discharge points in the *Río Encajon* and *Río Callejon*, this represents 11.03 Mm^3 a year.

The yearly water demand for the 180,000 inhabitants of *Cajamarca*-city is 7.88 Mm^3. According to *Sedacaj*, the drinking water company of *Cajamarca*, there is 30% water loss between the water abstraction in the different rivers and the water offtake in the city. This increases the domestic water demand of *Cajamarca*-city to 10.25 Mm³ a year. The maximum total yearly water abstraction permission for *Sedacaj* amounts 9.24 Mm³.

4.3.2 ES cultivated crops

Supply

The supply of the ES ‘cultivated crops’ was measured with the productivity index (PI). The productivity index contains soil characteristics as well as the slope of the terrain. The PI is presented in Figure 4.3 (Left) and is distributed in a very heterogeneous way in the study area. This heterogeneity is induced by the slope component of the PI since on the map of the PI without the slope factor, different zones are clearly separated (see Appendix 9C). The mean PI of the study area corresponds to poor crop production conditions. Only few spots with a *good* PI and no spots with an *excellent* PI exist.

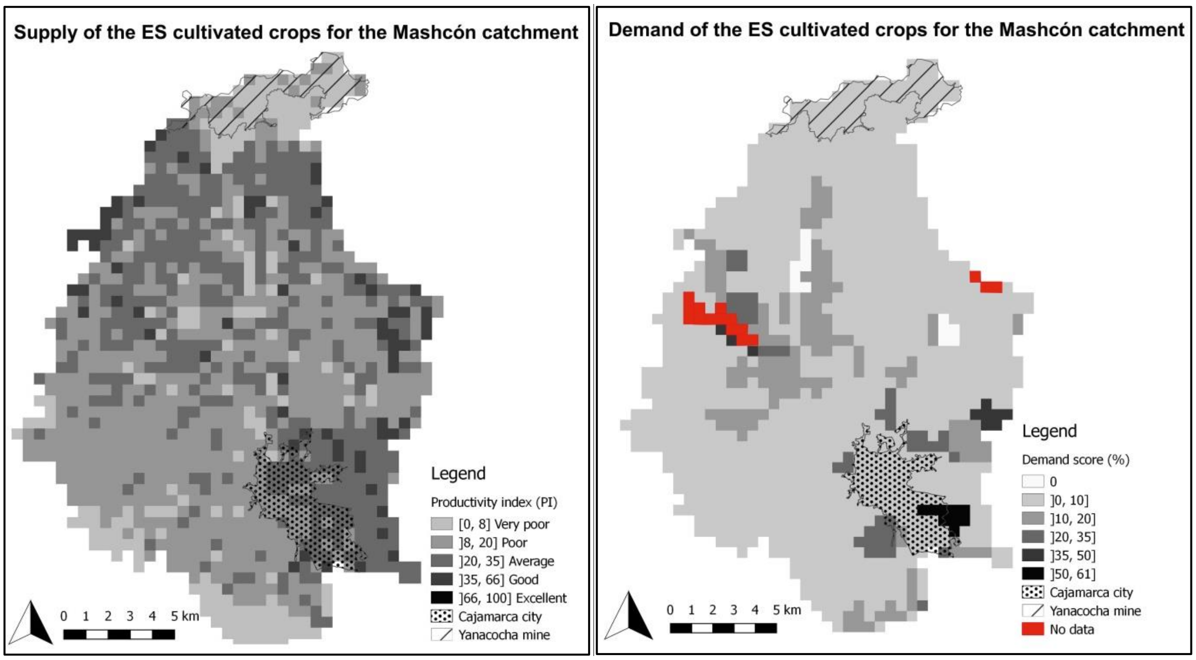

Figure 4.3. Left: Supply of the ES ‘crop production’ for the *Mashcón* catchment. Statistics: min=1, max=52, mean=17, SD=10. Right: Demand of the ES ‘crop production’ for the *Mashcón* catchment. Statistics [%]: min=0, max=60, mean=6, SD=8.

Demand

The demand of the ES ‘cultivated crops’, calculated based on the ratio of the cultivated area on the total area, is displayed in Figure 4.3 (Right). Except from the area in the Northwest of the catchment and from some clusters around *Cajamarca* city, the score of the demand for crop production lies between 0 and 10%. The only area with a score higher than 50% is situated between *Cajamarca* city and the *Río Mashcón*. No scores were calculated for the areas in red because they contained uncertain data.

4.3.3 ES reared animals

Supply

The supply of the ES ‘reared animals’, calculated based on the area of natural and cultivated pasture available for feeding the animals to the total area, is displayed in Figure 4.4 (Left). The scores range between 0 and 45% and have a mean of 5%. The highest scores are located in two areas: a Southeastern area situated in the *Cajamarca* valley, with a relatively flat terrain and surrounding the *Río Mashcón*, and a North - Northwestern area, located west of the *Río Grande*.

The mining area as well as *Cajamarca* city do not contain pastures and should have a zero value. These areas are, however, integrated into SEASs and the available data is averaged over these SEASs. It can be deduced that the scores next to the mining area and *Cajamarca* city should have a higher score. No data were calculated for the areas in red. Presumably, the scores would be highly uncertain since a mismatch between agricultural or pasture area and the area of the SEAs was found.

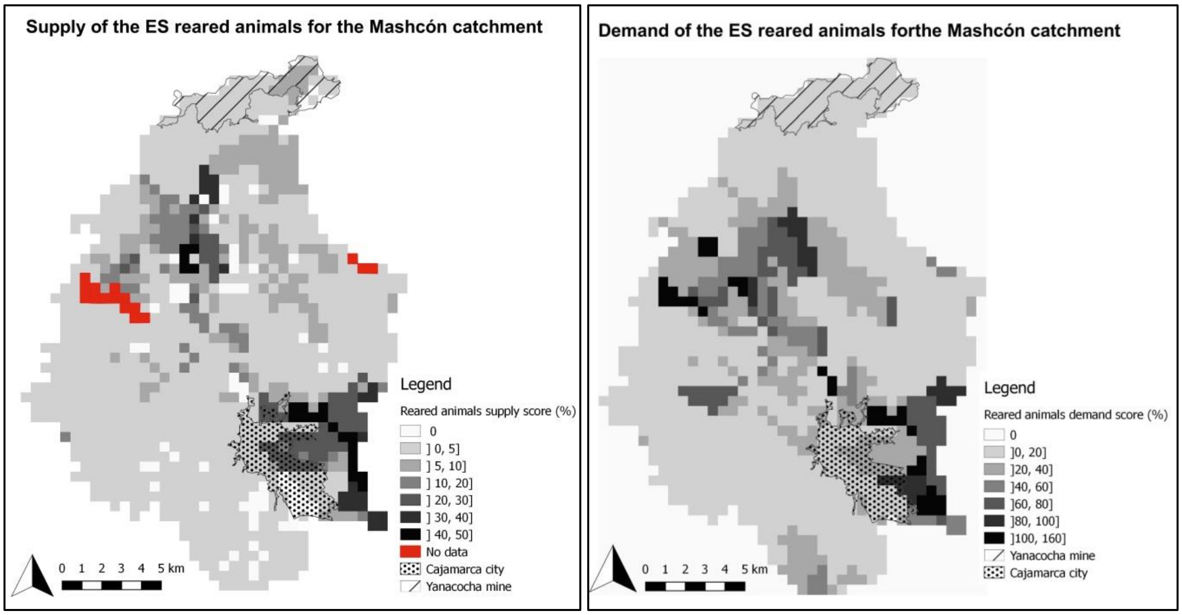

Figure 4.4. Left: Supply of the ES ‘reared animals’ for the *Mashcón* catchment. Statistics [%]: min=0, max= 45, mean=5, SD=9. Right: Demand of the ES ‘reared animals’ for the *Mashcón* catchment. Statistics [%]: min=0, max= 155, mean=23, SD=29.

Demand

The demand score of the ES ‘reared animals’ is shown in Figure 4.4 (Right). It is calculated based on the area of pasture necessary to feed the grazers to the total area.

The scores range from 0 to 155% and have a mean of 23%. Values higher than 100% indicate that the surface area of cultivated pasture necessary to feed the animals year round is higher than the actual surface available area. Two regions with high demand values can be seen in Figure 4.4 (Right). The first one, like for the supply of the same ES, is situated East of *Cajamarca* city and surrounding the *Río Mashcón*. The second one is located in the Northwest of the catchment. The other areas, except from few clusters, have demand scores between 0 and 20%.

4.3.4 Monetary valuation

The sales' value from the animal production in the *Mashcón* catchment is estimated at 15.9 million US$ per year, the one from the crop production at 4,707 US$. The revenues from sales of *Minera Yanacocha S.R.L.* for the year 2012 were 2241.1 million US$. From the 3,700.44 ha of the entire mining site, 1,235.31 ha are located in the *Mashcón* catchment. Taking this 34% into account, the revenues for the *Mashcón* catchment amount to 758.2 million US$. The revenues from the mine exploitation are almost 50 times higher than the ones from crop and animal production. The water used in the domestic context has a value of 7.3 million US$.

4.3.5 Overview

The ES 'water use' is better supplied in the high mountains than in the valley. In 2012, the demand of the ES 'water use' for animal and crop production required an estimated water quantity of 19.07 and 17.06 Mm^3 respectively. Two areas have a higher water demand than the rest of the *Mashcón* catchment namely the region in the East of *Cajamarca* city that surrounds the *Río Mashcón* and the region in the Northwest of the study area and in the West of the *Río Grande*. The mine displaced an estimated 11.03 Mm^3 of water from the high mountains in the North into the *Río Grande* that flows towards the city. *Cajamarca* city, which is situated in an area with a low water supply, consumed around 10.25 Mm^3 in 2012. The water use of the different sectors is shown in Figure 4.5.

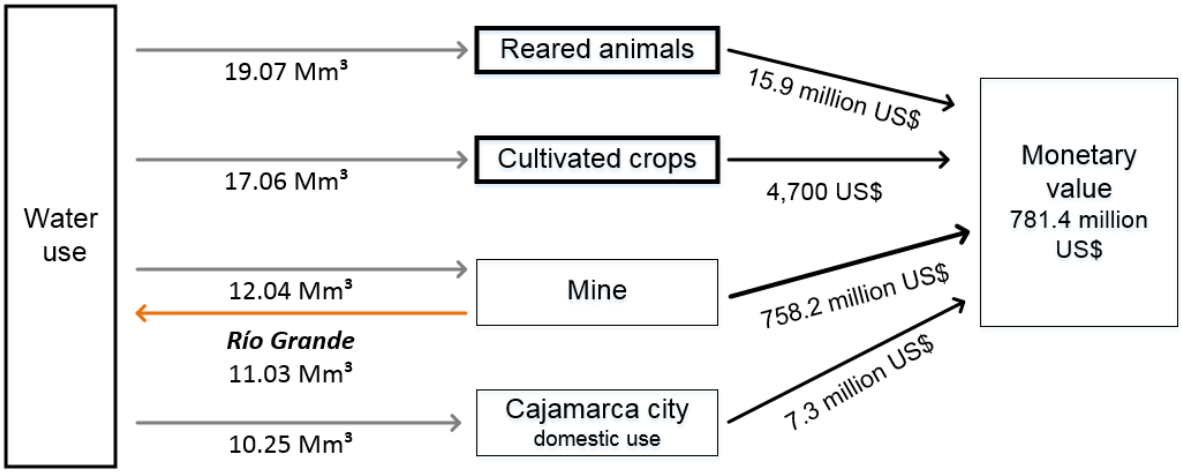

Figure 4.5. Ecosystem service assessment frame with obtained values.

The supply of the ES *crop production*, which is expressed as Productivity Index, is spread heterogeneously over the catchment and has a p*oor* mean value. The extreme North and South have a *very poor* PI, the area East of *Cajamarca* city has an *average* PI with some Good PI spots surrounding the *Río Mashcón.* Some *good* spots are located in the East and the Northwest. The demand of the ES *crop production* is rather low with an average of less than 10%. The highest demand is situated around the city and in the Northwest of the catchment and are principally situated on soils with an *average* or *poor* PI.

The supply of the ES 'reared animals' has an average score of 5% with scores between the 30 and 50% in the East of the city and the North (but not the extreme North). The demand is higher than the supply everywhere in the catchment but the deficit is the most pronounced in approximately the same areas as the ones with the highest supply. The average 'reared animals' demand score is almost five times the average supply score. Areas of high demand correspond predominantly with areas of high supply, but the upper boundary of the demand score of the ES is three times higher than the upper score of the supply score, which causes a deficit in the whole area.

The monetary value of the 'reared animals', the 'cultivated crops', the mine and the domestic water use are evaluated at 781.4 million US$. The monetary value created by the mine is 50 times higher than that of the 'reared animals' and the 'cultivated crops'.

An overview of the ES, their indicator and the results are summarized in Table 4.9.

Table 4.9. Overview of the assessed ES, their indictor and the assessment result.

Ecosystem service	**Indicator**	**Mean score or value**	**Standard deviation**	**Monetary value [USD for 2012]**
Water use				
Supply	Ability to supply water in function of precipitation and evapotranspiration [%]	41	30	7.3 million (domestic use)
Demand	Volume per hectare [m³ ha^{-1}]	1,643	2,672	
Cultivated crops				
Supply	Productivity Index [%]	17 (poor)	10	4,707
Demand	Surface crops over total surface [%]	6	8	
Reared animals				
Supply	Available pasture surface over total surface [%]	5	9	15.9 million
Demand	Required pasture surface over total surface [%]	23	29	

5 General discussion

5.1 System analysis

The settling of the *Yanacocha* mine has led to a set of direct and indirect pressures in the *Mashcón* catchment. A first direct pressure was land cover change on the mining site as well as in its surroundings due to the construction of access roads. The pumping of ground water and the building of the *Río Grande Dam* were two additional direct pressures. These pressures caused deterioration of environmental states: the removal of vegetation, drained brooks and springs, a decline in ground water table level of more than 100 m and the change in natural flow of the *Río Grande* due to its artificial source and its control via the dam (Cerdán, 2015; Vela-Almeida et al., 2016). As importantly, indirect pressures were induced by migration. The population of *Cajamarca* district has grown from 112,000 in 1990 to 247,000 in 2015 (INEI), probably contributing to changes in land cover. Presumably, the change of states in the ecosystem impacted the supply of ecosystem services, while population growth raised the demand.

In the *Mashcón* catchment, the ES ‘water use’ is of utmost importance for crop and animal production and for the *Yanacocha* mine operation, besides basic household needs. During mine exploitation, there have been issues between farmers and MYSRL about water rights and access to water resources (Cerdán, 2015; Sosa & Zwarteveen, 2012). The rural community depends on the ES ‘cultivated crops’ and ‘reared animals’ for own consumption and income generation (Garcia & Gomez, 2006). These are the three major provisioning ES in the study area.

Apart from the provisioning ES, several regulating ES are characteristic of the study area. The rugged landscape of the *Mashcón* catchment with its numerous steep slopes makes it prone to land slide and erosion. Therefore, the presence of natural vegetation is important to reduce soil erosion by wind or water and the root systems contribute to soil strength or cohesion (Stokes et al., 2009). Natural vegetation thus promotes the ES ‘mass stabilisation and control of erosion rates’ (Duarte, 2016). Furthermore, areas of natural vegetation are crucial for water recharge, influencing the ES ‘hydrological cycle and water flow maintenance’ (Gerten et al., 2004).

In 2007, 29% of the wastewater was treated in Peru against 69% in Belgium (Oblitas, 2010; Eurostat). This indicates the importance of the environment to purify water and the significance of the ES ‘maintenance of the chemical condition of freshwater’ and ‘waste mediation by biota and ecosystems’.

Even if the cultural ES of the *Mashcón* catchment are less addressed, there are some indications of it. For example, during the festival *Florecer en Cajamarca* the mystical meaning of man's relationship with nature is celebrated (Ponce et al., 2007). Also, the collection of medicinal herbs has a cultural significance. In general, the landscapes and nature offer opportunities for recreation, tourism, spiritual and religious contemplation (Alcántara, 2014).

In general, the dependency on provisioning ES is more tangible than the dependency on regulating or cultural ES since people rely directly on food and water (Layke et al., 2012; Martín-López et al., 2012). In addition to the advantage of being directly perceived by users, provisioning services are easier to quantify using readily available data from national statistics, compared to data for regulating and cultural ES (Layke et al., 2012).

Stakeholder consultation was not considered for this thesis, since the primary focus was on system understanding for developing site-specific biophysical models for ES. Thus, the scheme of ecosystem services in the *Mashcón* catchment (Figure 4.1) was made based on information collected from literature. This suggests that the covered topics and gathered information were tackled from a scientific and governmental perspective, and that the stakeholder's point of view was not necessarily taken into account.

The system analysis revealed that the ES 'water use', 'cultivated crops' and 'reared animals' are important in the *Mashcón* catchment. The choice to assess these more tangible ES was made because of two reasons. First, with the thought of communicating results of the ES assessment to the inhabitants and the government, it would be easier to convince them with tangible ES. The second reason was due to the better data availability for provisioning services. In contrast to the high quality and quantity of scientific data in European and North American countries, data availability in South American countries, and especially in remote mountain environments, is limited (Buytaert et al., 2014; Panagos et al., 2017).

5.2 Data availability

The collection and screening of data has been a significant time-consuming part of this research. Data had to be collected from multiple websites and governmental data, often available in Spanish only.

The available data for the assessment of the three selected ES could be categorised according to the source or the type of the data. All data, except part of the meteorological data and water use data of the *Yanacocha* mine, were obtained from public governmental sources. All data, other than data from meteorological stations and water flow measurements, were in GIS format.

The DEM, used for height determination and for slope calculation in this thesis, had a resolution of 12.5 x 12.5 m. The resolution of DEMs is getting finer with the years. Approximately ten years ago, a DEM with resolution of 10 to 20 m was called 'high resolution' while today 'high resolution' corresponds to 1 to 5 m (Hancock et al., 2006; Sangireddy et al., 2016). The highest resolution of Global open source DEM is of 30 m and available from the USGS EarthExplorer. The DEM used in this thesis has a high resolution compared to the one of global open source DEM, but low compared to highest resolution available. Studies on soil erosion, which are based on the terrain's slope, commonly use DEMs of 10 to 30 m, indicating that the resolution of the DEM used in this thesis was relatively high (Borrelli et al., 2015; Ochoa-Cueva et al., 2015).

Meteorological data were available from SENAMHI and from MYSRL. SENAMHI has several meteorological stations in the *Mashcón* catchment and the station 'Augusto Weberbauer' has the most complete data record in terms of time period and measured variables (see Appendix 4). Only this data of SENAMHI were trusted because other datasets showed inconsistencies for some parameters, like shorter measurements periods and many missing data. MYSRL has five meteorological stations, from which two are situated in the *Mashcón* catchment. The precipitations, temperature and wind speed data seemed consistent and presented an acceptable quantity of missing data, but they were collected for a shorter period compared to the data of 'Augusto Weberbauer'.

The WorldClim annual precipitation data, a raster with a resolution of approximately 1 km, matches well the annual precipitation GIS layer prepared by SENAMHI, which has a resolution of 30m (Cerdán, 2015). The precipitation values at higher elevations of the *Mashcón* catchment are, however, underestimated when comparing them to precipitation measurements of the MYSRL. From personal communication with the people in charge, it is known that the reason of this underestimation is that SENAMHI does not have meteorological stations at these high elevations. SENAMHI is, however, working on integrating the precipitation data of the MYSRL into their model.

Next to precipitation data, a limited amount of data on flow rates in rivers brooks and springs were available from INRENA (the national institute for natural resources) among others. Flow rates of irrigation channels were available from COMOCA (the monitoring commission of the irrigation channels in *Cajamarca*). The measurements of INRENA were only done once and spread over the months March until July 2007. The flows during the wet and the dry season are not comparable as such and the measurement was not repeated what made it difficult to use this data for the assessment. Data of irrigation channels was available for the years 2002-2014 but without detailed information on the regulation in the channels, these data could not be trusted to estimate water availability.

Soil characteristics were available from the ZEE project of the RGC in shapefiles of *Cajamarca* Region. The largest part of these soil characteristics were gathered via existing maps or collected in the field during the ZEE process in *Cajamarca*, which also applied public consultation to a certain level. For every soil type, qualitative classes of soil texture, pH, stoniness, organic matter, drainage and permeability were available. Quantitative classes would give more certainty about the soil characteristics than qualitative classes. Every coarse soil texture class contained two to four USDA texture classes. A detailed soil texture classification is useful as estimator for soil moisture data when the latter are lacking. Data on soil moisture, necessary for water infiltration and plant available water content (PAWC) calculations (Sharp et al., 2014), were not available.

The shapefiles containing agricultural surface areas and number of reared animals per SEA in the Region of *Cajamarca* were based on statistical data from INEI and transformed into shapefiles by RGC. The statistical data were collected via questionnaires and interviews of the producers of Peru (Cerdán & Quispe, 2016). The quality of the data thus depends on the accuracy of the reported values. A few research units contain higher agricultural or natural pasture surface areas than the total area of the research unit. This suggests that the sizes of certain agricultural units have been overestimated. Moreover, the uncertainty associated with the shapefiles was not communicated by the RGC.

It can be concluded that the availability of meteorological, hydrological and soil characteristic data was limited and too scarce for a precise assessment of the hydrology of the catchment. Data on animal and crop production were more abundant and detailed, but since they were collected via questionnaires, thus not measured on the spot, the accuracy could be questioned.

5.3 Methodology

The supply–demand assessment of ES is particularly useful for identifying areas where supply–demand pressures occur (van Jaarsveld et al., 2005). “However, the direct comparison of ecosystem service supply and demand in spatially explicit maps is not always applied in spite of the wide agreement about the importance of including the demand side into ecosystem service assessments” (Burkhard et al., 2012).

The rugged landscape with steep slopes and the milk production are local features of the *Mashcón* catchment that are important to include in the ES assessment. Existing ES models like InVEST do not include ‘animal rearing’ in their ES and are often developed in a context of sufficient data availability like in the U.S. The relative data scarcity in the *Mashcón* catchment and the importance of local features are reasons for developing simple and site specific methodologies. The elaborated methods for these ES were developed in a transparent way with respect to data usage, the choice of variables and parameters, and the limitations of using simple algorithms. This can presumably facilitate the understanding of the ES assessment and the outcome for stakeholders and authorities and thus persuade them of the usefulness of ES for future management purposes (Antle & Valdivia, 2006; Bagstad et al., 2013a). Hereafter a critical analysis is given for the ES assessment methods.

5.3.1 ES water use

The supply score was based on evapotranspiration variables (precipitation, temperature, wind speed and radiation) from the FAO Penman-Monteith method combined with water loss in function of land cover. The existing precipitation raster was used, even if the precipitation quantity at high elevations was probably underestimated in that raster. Although the latter could be corrected by interpolating precipitation data, a highly complex task for mountainous areas (Diodato & Ceccarelli, 2005), the goal of this thesis was to have an idea on the distribution of several ES rather than assess one ES with high precision.

Thus, precipitation data were not interpolated to a higher resolution. Conversely, temperature and wind speed where linearly interpolated with elevation based on data from three meteorological stations spread over the elevation range of the study area. The R^2 values were 0.9899 and 0.9993 respectively, which indicates that the linear interpolation with elevation is an acceptable interpolation method for scoring these variables. Since the above mentioned variables respond to changes in elevation, and the values obtained via interpolation were not verified, the choice of scoring the different variables based on elevation ranges seemed adequate.

Following the InVEST water yield model (Sharp et al., 2014), the evapotranspiration coefficient of the different land cover types was considered for the water supply calculation. It is necessary to mention that next to evapotranspiration, the capacity of different land cover and soil types to promote infiltration also influences the water supply of an area (Saxton & Rawls, 2006). The decision not to include this in the supply of the ES water use was made for sake of simplicity. ‘Plant available water content’ (PAWC) and ‘Root restricting layer depth’ are necessary for the InVEST water yield model, but these data were not available. They can be estimated using soil texture and soil depth respectively but since these data were available in coarse qualitative classes, estimations would presumably be inaccurate. Collection of these data was not convenient due to time, cost and technology limitations.

The demand side of the ES water supply was calculated based on estimations of the water use of *Yanacocha* mine, *Cajamarca*-city and the agricultural sector since data on actual water consumption were not accessible. Water demand was calculated based on water needs of the different sectors, without considering water spill and inefficient use. As can be seen in Figure 5.1, inefficient irrigation can increase the water demand (Howell, 2001), suggesting that the water demand in the *Mashcón* catchment can be underestimated.

5.3.2 ES cultivated crops

An adapted Productivity Index, which was calculated based on several soil characteristics and the slope, was used to determine the capacity of the *Mashcón* catchment to supply the ES ‘cultivated crops’. Compared to the original Productivity Index (Riquier et al., 1970) the adaptation made for this thesis omitted one variable, due to lack of available data, and added the slope variable. This omission leads to an overestimated PI, but the relative comparison between areas remains valid.

Figure 5.1. Inefficient irrigation water use in the *Mashcón* catchment (Picture taken by Eveline Beeckman in August 2017).

5.3.3 ES reared animals

The assessment was based on the capacity of pasture to provide food for grazers. Similar methods were used by Egoh (Egoh et al., 2010) and Reyers (Reyers et al., 2009) but only for the supply side.

Both the supply and the demand of the ES 'reared animals' was calculated taking into account grazers (cattle, sheep and alpacas). Pigs and poultry, that are also reared in the *Mashcón* catchment, were not considered because insufficient information about their feeding habits was available. Calculating supply and demand for these omnivores (Klasing, 2005; Nelson & Sanregret, 1997) is not straightforward in this context. If the pigs and poultry were raised on natural or cultivated pastures in the study area, the demand of the ES would be underestimated.

5.4 ES assessment map results

The supply and demand of the three assessed ES were represented via raster maps with a resolution of 500 x 500m. Maps as final result of ES assessment provide a good visualisation of the spatial distribution of the ES and have the potential to aggregate complex information (Burkhard et al., 2012). Different ES can easily be compared and supply-demand mismatches can be identified using maps. Also, stakeholders and decision makers can visualise the result without need of scientific background.

5.4.1 ES water use

The areas occurring at the highest elevations, including the *Yanacocha* mine, have the largest supply score while *Cajamarca* valley, containing *Cajamarca*-city, has the lowest score (Figure 4.2). The high supply score found for the *Yanacocha* mine area corresponds to a part of the hydrological center *Cajamarca-Hualgayoc*, the largest aquifer recharge center in *Cajamarca* region (Sánchez & Sánchez, 2012). Comparing the distribution of the demand and the supply, a mismatch can be observed in many areas. The most noticeable imbalance occurs in the area of *Cajamarca*-city and the area in the East of the city where the highest demand exists while the supply via precipitation is the lowest of the *Mashcón* catchment. The imbalance found in this study corroborates the fact that the city must depend on water from the *Río Grande, Porcón* and *Ronquillo* that bring water from areas at higher elevations (Atkins et al., 2005). The area from the South to the West border of the *Mashcón* catchment has a supply score between 60 and 80, while its demand is the lowest of the catchment. The *Yanacocha* mine is situated in a high supply and demand zone but since the supply is a score and the demand a water quantity, a quantitative contrast cannot be derived from this comparison. In general, the resulting maps provide knowledge of areas of potential deficit, revealing locations that are recommended to be studied more in detail.

When comparing the areas of water demand with the distribution of the irrigation channels (Figure 3.1), it is noticeable that areas with a high water demand correspond to areas with an extensive irrigation channel network next to the river network as is the case in the Northeast of the catchment. The Southwest is devoid of irrigation channels, has a less dense river network and a lower water demand than the rest of the catchment.

The results suggest a mismatch between areas of high water supply and demand and thus an important flow of this ES. The water for the high demand areas is taken from rivers or from irrigation channels that originate mainly in high supply areas and especially in the region of the *Yanacocha* mine.

5.4.2 ES cultivated crops

Based on soil characteristics and on the slope, the average PI of the study area is poor. The two areas with the highest but still average PI scores of the catchment are located in the East of *Cajamarca*-city and between the Río *Porcón* and *Río Grande* in the North. The former has an imperfect drainage, a finer texture but more acceptable slope values with a maximum of 10° compared to the latter, which has a slightly excessive drainage, a medium texture and slopes reaching 60°. Dryland crop cultivation is rated as non-suitable for slopes above the 17° and irrigated crop cultivation above the 3° (Van Wambeke & Radcliffe, 1996). With an average slope of 14.0° (±9.2°), the *Mashcón* catchment is not very convenient for crop cultivation.

The demand of the ES has a mean of 6% (±8) what indicates that a relatively small part of the catchment is used for agriculture. This confirms the research of (Garcia & Gomez, 2006) that indicated crop production as second income and for own consumption. This also matches with the presence of steep slopes and the lack of sufficient water availability or irrigation possibilities. The areas of higher demand are rather situated in areas of average to good PI even if the latter are scarce. It can thus be concluded that the demand, which is restraint to crops for own consumption, is quite well adapted to the supply of the ES 'cultivated crops'.

5.4.3 Reared animals

Even if the areas of high and low demand largely correspond to those of high and low supply respectively, the average demand of 23% (±29) is almost five times higher than the average supply of 5% (±9). This indicates that the available pastures, natural and artificial, do not provide enough food for year round grazing taking into account the need regarding the number of reared animals. This matches the findings of Garcia (2006) where farmers use concentrates or crops like alfalfa and oats as supplement for their milk cows. Crops are mainly grown locally but concentrates are imported. The potential increment in reared cattle numbers, following the increase of approximately 75% from 2001 to 2012 (Regional Office for Agriculture statistics), could lead to overgrazing in the future, degrading the 'reared animals' ES supply as well as the supply of other ES like 'control of erosion rates' (Reyers, 2009; Swinton, 2007).

5.5 Impact of *Yanacocha* mine in present and future situation

Considering the lowering of the ground water table, the desiccation of brooks and springs outside the mining area (Cerdán, 2015) and the displacement of 11.03 Mm³ of water in 2012 (Figure 4.5), the most considerable environmental impact of the *Yanacocha* mine exploitation is presumably the one on water resources.

The results on the water use for the *Mashcón* catchment suggest that water is an indispensable resource for livelihood maintenance and economy (Figure 4.5). Water is at the base of the ES 'reared animals' and 'cultivated crops' as well as of the exploitation of the mine and of the domestic life of the Cajamarquinos. Apart from the importance of water for these anthropocentric uses, water is crucial to sustain a functioning ecosystem that is the base of all ecosystem services (Haines-Young & Potschin, 2009).

When looking at absolute values (Figure 4.5), both crop and animal production require more water than the mine exploitation or *Cajamarca*-city. The spatial distribution is, however, totally different. As can be seen in Figure 4.2 (right) the highest water demand per hectare is concentrated at the mining site and *Cajamarca*-city with approximately 10,000 and 7,000 m³/ha respectively. On the contrary, the water demand for animal and crop production is spread over the entire catchment and has an average of 951 m^3ha^{-1}.

Cajamarca-city is dependent on water from the *Río Grande* for 70% and 57% during dry and wet season respectively. As mentioned earlier (Section 3.1.4), the *Río Grande* is artificially formed by water discharges of MYSRL where an estimated 11.03 Mm³ of water is discharged annually. The San José reservoir, constructed by MYSRL in 2007 after complaints of flow reduction in several brooks, supplies water to five irrigation channels. Also, several other channels originate in the mining area (Figure 3.1).

The inhabitants of the *Mashcón* catchment are thus quite dependent on MYSRL for the discharged water as well as for several important ES that result from this water. The development of the catchment has been influenced since the settling of the mine and currently the MYSRL has a dominant position in the distribution and the availability of water in the *Mashcón* catchment.

Next to impact on water quality, the mine exploitation caused water and soil quality deterioration. Between 2010 and 2014 MYSRL committed 12 environmental infractions and had to pay more than 500.000 $. These infractions concerned the failure to comply with environmental protection standards and with Maximum Permissible Effluent Limits. In March 2014 acid drainage was detected by inhabitants of the *Mashcón* catchment and in December 2014 the Environmental Assessment and Inspection Agency (OEFA) affirmed that there was acid mine drainage from the *Yanacocha* mine. In the meantime farmers reported approximately twenty dead cows (Chicana, 2015). These type of events are very likely impacting ES services that require water or soil.

In April 2016, the CEO (chief executive officer) of Newmont mining company, one of *Yanacocha*'s owners, announced the probable closure of the mine in 2020 (El Comercio, 2016). The *Yanacocha* mine closure would mean the end of the necessary pumping of groundwater and the collection of surface and rain water for operations and thus the potential end of the discharge in the *Río Grande*. *Cajamarca*-city as well as many farmers would experience severe water shortage, impacting the delivery of ES and the local economy.

In 2012, the monetary value of the catchment based on the revenues of the mining and agricultural sector, was estimated at approximately 774 million US$ (Figure 4.5). However, the revenues from the mine only were 50 times higher than the ones from the agricultural sector. After the mine closure, MYSRL will be left with long term costs for the reclamation, lowering the net economic value of the catchment. According to Sergio Sánchez Ibáñez from the Regional Government of *Cajamarca*, the mine reclamation will last for 20 years (La Republica, 2017). Following the hypothesis of reduced water availability, the revenues from agriculture would also decrease due to loss of ES services.

Based on the evolution of the *Yanacocha* revenues and the economic development of the *Mashcón* catchment, the created monetary value in the study area is likely to follow a trend like the curves in Figure 5.2. First, the development of the mine combined with the increase of the gold price induced an increase in value creation of the mine. This induced the economic development of the catchment and led to an increased value creation for the inhabitants. The actual trend towards the depletion of ores combined with the start of the mine closure causes a decline of value creation. The closure and reclamation phase are associated with high costs spread over a long period. Due to the damaged ES and the partial dependence of the local economy on the mining activities, the value creation for the inhabitants is likely to decrease too.

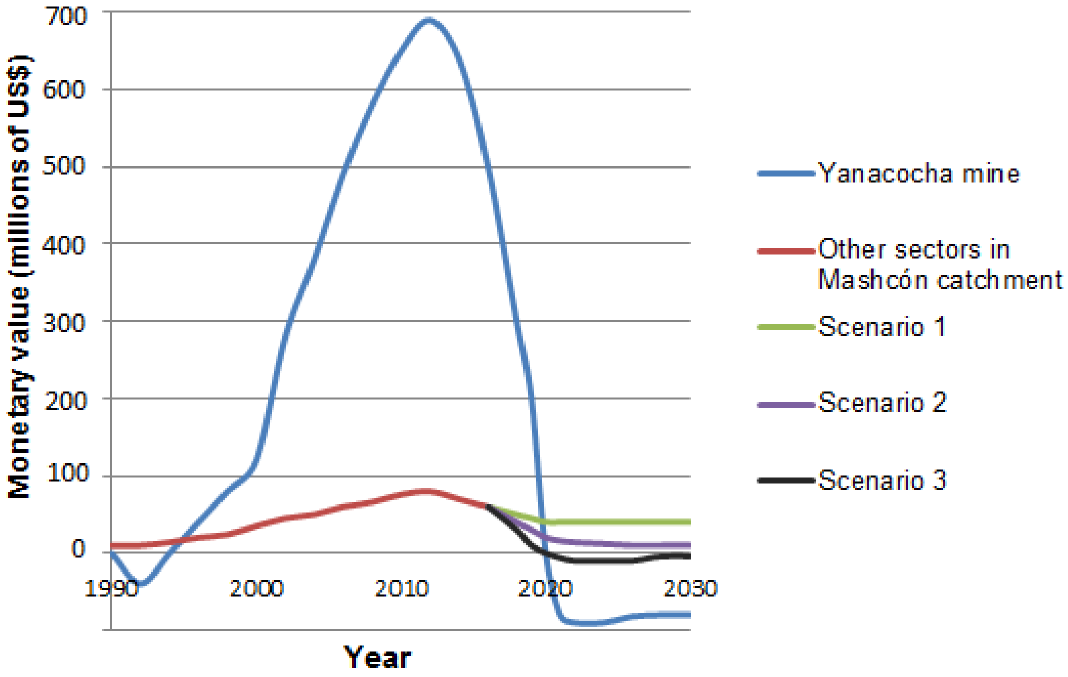

Figure 5.2. Evolution of the monetary value of the *Yanacocha* mine and the *Mashcón* catchment during the mine life cycle. Scenario 1: Monetary value from other sectors than mining decreases but stays higher than the value before the mine settling Scenario 2: Monetary value from other sectors than mining decreases to approximately the value before the mine settling Scenario 3: Monetary value from other sectors than mining becomes negative due to damaged ES and loss of employment due to mine closure.

Before the settling of the mine, the supply of the ES ‘water use’ was natural. The only artificial constructions were the irrigation channels built by farmers to conduct water to the valley (Sosa & Zwarteveen, 2012). Since the settling of *Yanacocha*, the supply of the ES ‘water use’ has evolved towards an artificial supply in some parts of the *Mashcón* catchment. Following complaints on water quality and water shortage, MYSRL had to pay for the construction of reservoirs, the treatment and the displacement of water etc. (Sosa & Zwarteveen, 2012) to account for the destruction of the supply of the ES ‘water use’. After the mine closure, MYSRL will probably need to continue this payment to a certain extent for the maintenance of this ES.

It can be concluded that the *Yanacocha* mine exploitation has an impact on the ES ‘water use’ and thus indirectly on the ES ‘reared animals’ and ‘cultivated crops’. The damage to the ecosystem service ‘water use’ is associated with costs to artificially deliver this ES. Also after the mine closure, there will very probably be costs to maintain this artificial delivery and to restore damaged ecosystem services.

6 Conclusion

The objective of the identification of the most representative ecosystem services in the *Mashcón* catchment in Peru via literature has been reached. Multiple provisioning as well as regulating and cultural ecosystem services have been identified. The representation via pressure-state-impact offered a systemic view of the environmental problems. However, stakeholder consultation to identify ecosystem services in the *Mashcón* catchment would provide a high added value since local people have a good insight in their dependence on natural resources.

Based on the system analysis and the better data availability for provisioning services compared to the two other categories, the ES ‘water use’, ‘cultivated crops’ and ‘reared animals’ were selected for the assessment. Meteorological, hydrological and soil characteristic data were limited and too scarce for a precise assessment of the hydrology of the catchment. Data on animal and crop production were more abundant. Next to data on soil moisture, additional and regular surface and groundwater data collection would be needed to be able to perform a more precise assessment of water supply in the *Mashcón* catchment.

After the elaboration of simple, site-specific and transparent methods, the spatial distribution of the demand and the supply of these ES was mapped, reaching the second objective. It was found that the mining site and *Cajamarca*-city have the highest water demand per hectare. The results also suggest a mismatch between areas of high water supply and demand. The assessment of the ES flow could identify areas of deficit clarifying the unsustainable nature of mining operations. The water for the high demand areas, except for the *Yanacocha* mine, is taken from rivers or from irrigation channels that originate mainly in high supply areas and especially in the region of the *Yanacocha* mine. Regarding the ES ‘cultivated crops’, it can be concluded that the demand, which is restraint to crops for own consumption, is adapted to the low supply of this ES. The demand for the ES ‘reared animals’ is approximately five times higher than the supply of this ES what could lead to overgrazing in the future and to the degradation of this ES supply as well as of the supply of other ES like ‘control of erosion rates’.

Due to data scarcity, the assessment methods were simple and some data had to be approximated. Therefore, generating scores as assessment output, instead of more precise values, is useful to give relative indication of the state of ES. Using maps as final ES assessment output is also convenient because complex results can be represented in a simple manner and spatial variation visualised at a glance. Therefore, such maps are practical for communicating with stakeholders and decision-makers.

The most representative environmental impact of the *Yanacocha* mine exploitation is likely the one on water resources. *Cajamarca*-city and rural livelihoods in the *Mashcón* catchment are dependent on the groundwater discharges from Minera *Yanacocha* SRL in the *Río*

Grande and in irrigation channels. At present, there is already a shortage in water supply for *Cajamarca*-city and several springs have dried up in the higher rural parts of the *Mashcón* catchment, probably due to excessive groundwater withdrawal by Minera *Yanacocha* S.R.L. The closure of the mine, scheduled for 2020, could strongly impact the supply of the ES 'water use' due to presumed decreasing water discharges by Minera *Yanacocha* S.R.L. Since water is indispensable for the ES 'cultivated crops' and 'reared animals', the supply of these ES would decrease too. The actual value creation of the catchment, which is dependent on the ES assessed in this thesis, is thus likely to decline in the future. In addition, the costs to maintain the artificial delivery of the ES 'water use' and to restore damaged ES will make the monetary value of the *Mashcón* catchment even lower.

The conclusion of this thesis is that ecosystem services are useful to analyse potential impacts of mining on livelihood, as is shown for the case-study of the *Yanacocha* mine. To be more effective, ecosystem service assessment should be mandatory in EIAs and more precise guidelines should be available to support this practice.

7 Recommendations for further research

It was found that water is an essential resource for the *Mashcón* catchment. Water shortage in *Cajamarca*-city, complaints about desiccation of springs and brooks as well as the uncertainty about water availability after the mine closure indicate that a good understanding of the hydrological cycle of the watershed would be very valuable to understand the water supply in the catchment. Data availability on water resources is, however, scarce. It is recommended to start a monitoring program with regular water flow measurements in rivers and channels to gain understanding in the fluctuation of the water flow during the year and between different areas of the *Mashcón* catchment. To determine the water supply by precipitation, evapotranspiration needs to be known. To run the InVEST water yield model that is based on evapotranspiration, data on soil moisture or more detailed soil texture data are still required as well as hours of sunshine. According to the developers, the output of this model can be used with confidence on subwatershed scale but not on pixel scale (Sharp et al., 2014). Next to that, the InVEST water yield model is very simplified. To have a more correct and detailed idea on the water yield, evapotranspiration and water flow, the SWAT model is indicated (Arnold, 1998). The data requirement is much higher though (see Table 2.1). Next to surface water and evapotranspiration, measurements of the evolution of the groundwater level would be valuable to identify a potential change in groundwater reserves.

The monitoring of the actual water use in the rural areas of the catchment would provide a better insight of the demand of the ES ‘water use’ than the demand based on consumption estimates. The more accurate supply and demand of this ES could then be used to assess the flow of this ES through the catchment. This could clarify the unsustainable nature of the *Yanacocha* mining operations regarding water use.

Another important part of an ES assessment is stakeholder participation. The early engagement of stakeholders and decision-makers can provide a more correct and precise insight of the economic, ecological, social and cultural importance of the site (Peh et al., 2013). It is suggested to organise workshops to gather information to supplement or adapt the insight in ES use gained via scientific articles and governmental reports. Next, questionnaires could be used to collect detailed information on ES demand. An ES assessment is only successful if scientists work on a constant basis with decision-makers and stakeholders to make sure goals are well defined, results well understood and translated in policy decisions (Voinov et al., 2014).

A last recommendation, once data availability would be improved, would be to assess the impact of future scenarios of the mine closure and reclamation on ES delivery to find the reclamation plan with the less negative impacts and the most value creation for the *Mashcón* catchment. Questions that could be answered are ‘which ES can the rehabilitated areas offer to stakeholders’, ‘what are the associated costs and benefits to the mining company and its stakeholders', 'is there a net loss of ES after mine closure and what is the impact on inhabitants of the *Mashcón* catchment' (Houdet & Chikozho, 2015).

Of course it is advised to value the ES during the whole mining life-cycle and within the scope of the EIA (Houdet & Chikozho, 2015) to add the impact of the mine exploitation on human livelihood in addition of the impact on air, water, soil etc. Some examples of an ES assessment integrated in an EIA exist such as for the *Dundee Precious Metals Ada Tepe Deposit Krumovgrad Project* in Bulgaria and the *Zonnebloem Coal Mine* in Mpumalanga, South Africa (Rogers, 2014; Houdet & Chikozho, 2015). The assessment of ES in EIA is mentioned in the EIA guideline of Peru, USA, New Zealand, The European Union among others but detailed guidelines are lacking (CAFTA DR, 2011; McGuinn & Hernandez, 2013; MINAM, 2011; Womersley & Boothroyd, 2015). The elaboration of more precise guidelines on ES assessment and the explicit obligation of its integration in EIA would be a step forward in ES conservation.

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