Mining and River Ecosystem Services

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Research aims:
This project aimed to identify the opportunities and challenges for effective use of freshwater ecosystem service concepts in the context of assessing and managing sustainable development of mining in the tropical Andean nations via:

- A desk-top study
- A field visit to La Oroya mining region, Peru
- A workshop
- Preparation of research and training proposals

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Powerpoint Presentation:
"Mining and River Ecosystem Services"

IM4DC
Action Research Report

International Mining for Development Centre

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Summary of Action Research Activity

Mining and river ecosystem services

The problem of developing common understanding and agreement about the risks and benefits of mining has been especially notable in Peru, with serious conflicts about equitable use of land and water. The concept of freshwater ecosystem services is now commonly used to identify the broad value of rivers, aquifers and lakes in terms of the services they provide to society. The concept requires us to look further than the easily quantifiable values of freshwater resources, such as providing water supply for households, agriculture and industry, to less easily quantifiable 'regulating' and 'cultural' services.

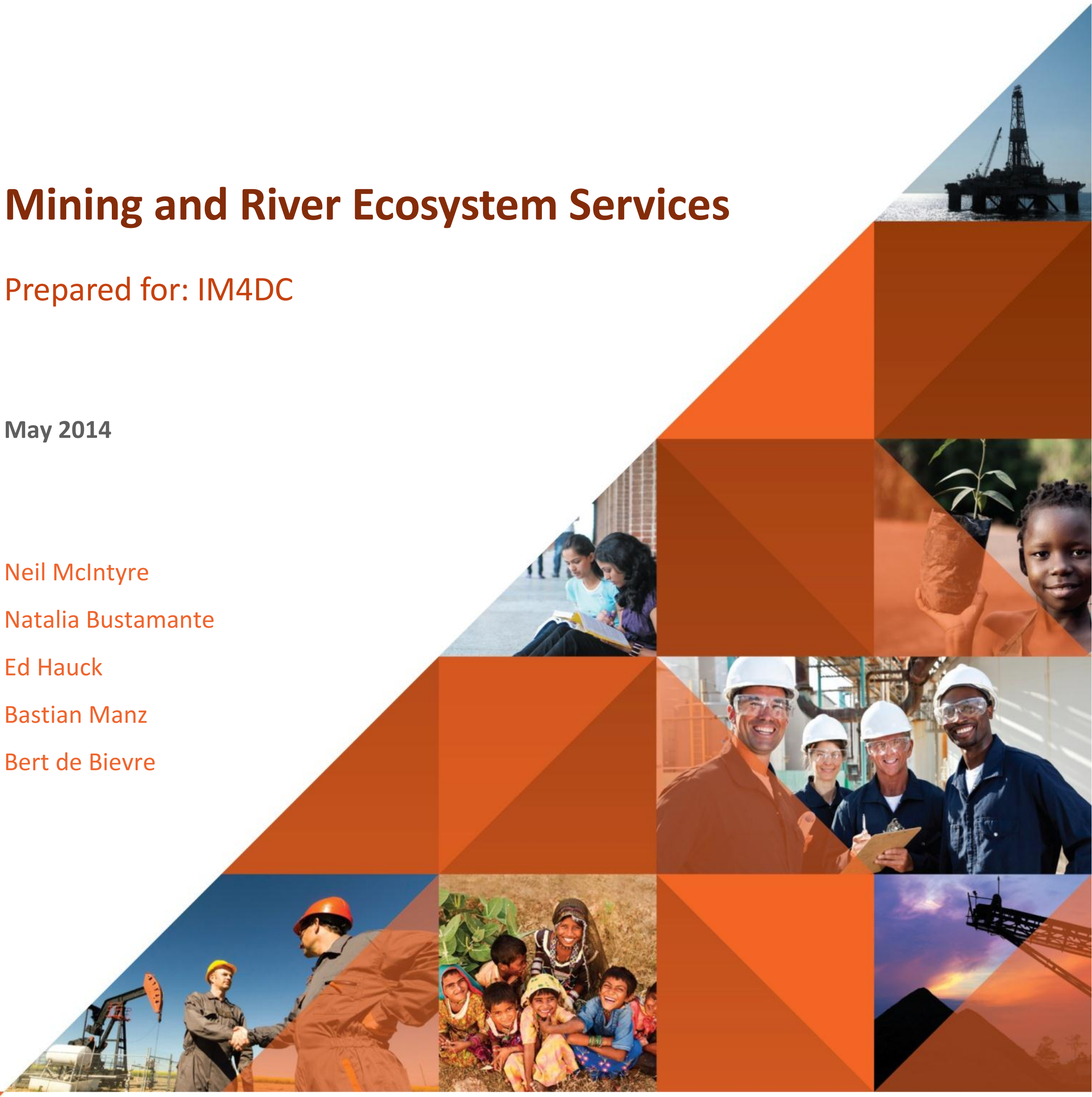
This project aimed to identify the opportunities and challenges for effective use of freshwater ecosystem service concepts in the context of assessing and managing sustainable development of mining in the tropical Andean nations. The focus was on overcoming the technical challenges associated with monitoring, modelling, evaluation of service, communication and training, rather than the institutional and regulatory challenges.

The project aims were therefore to:

- Identify the potential and challenges for more effective use of freshwater ecosystem service concepts in the context of assessing and managing sustainable development of mining, including perspectives from university, government research institutions, an NGO and industry
- Develop outlines of at least two research proposals involving collaboration between the project partners
- Draft a paper that sets a research agenda for improved application of freshwater ecosystem service concepts to mining in the tropical Andes
- Develop existing and establish new collaborations between international research institutions, NGOs, industry and government agencies
- Gather local knowledge of capacity building priorities, and outline a training proposal

The main findings are presented in the Executive Summary.

Action Research Final Report



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The **International Mining for Development Centre** was established to promote the more sustainable use of minerals and energy resources in developing nations by assisting governments and civil society organisations though education and training, fellowships, research and advice. Our focus is three core themes—governance and regulation, community and environmental sustainability, and operational effectiveness.

This report prepared by:

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Executive Summary

This project aimed to identify the opportunities and challenges for effective use of freshwater ecosystem service concepts in the context of assessing and managing sustainable development of mining in the tropical Andean nations. The focus was on overcoming the technical challenges associated with monitoring, modelling, evaluation of service, communication and training, rather than the institutional and regulatory challenges.

The project included four types of activity:

1. Desk-top study on: a) the application and applicability of the ecosystem service concept; b) the strengths and limitations of models for evaluating risks to freshwater ecosystem services from mining; c) the applicability of visualisation tools and on-line media for communicating risks; d) research, training and education needs
2. A field visit to La Oroya mining region of Peru, including a tour of the Yauli metal mine hosted by mining company, Volcan
3. A three-day workshop consisting of representatives of NGOs, universities, government research agencies and industry, which focused on discussing the commentary topics in context of the mining industry in the tropical Andes
4. Preparation of outline proposals for research and training proposals, and outline journal publications, and plans for taking these forward

The main findings were:

1. Further development of the concept of freshwater ecosystem services is a potentially valuable avenue to understanding the value of water to multiple stakeholders and solutions for equitable and sustainable management of land and water resources
2. In many cases, the implicit consideration of ecosystem services in mining impacts assessment has been over-simplistic, especially with regard to focusing on the value attached to water volumes rather than hydrological regimes and associated ecosystems. Better knowledge about which indices of hydrological and hydrochemical regimes are most relevant to stakeholders would help guide investment in baseline data
3. Literature review shows that explicit consideration of the broad range of freshwater ecosystem services in mining impacts assessments is rare. Where peer-reviewed papers have been published, they indicate that the large economic benefits from mining do not offset the long-term loss of ecosystem service, and illustrate the shortfalls in data and understanding needed to conduct such evaluations. Inter-disciplinary research is needed to understand how to approach ecosystem service evaluation and reduce gaps and uncertainties involved
4. Payment for ecosystem services is currently being used in Peru. Water supply companies are paying for catchment headwaters to be protected by landowners

While mining requires different management solutions, the development of understanding of ecosystem services and their value to different stakeholders made under that programme is relevant

5. Mining presents some special challenges for evaluating ecosystem service impacts: the importance of underground impacts; the importance of rehabilitation and post-closure as parts of the mine life cycle; the uncertainties associated with informal mining; and the manifest changes that most mines cause to the landscape

6. Current research covering the tropical Andes is establishing a database of land use change effects on hydrological regimes for small catchments, although this does not extend to mining. Development to include mining regions and larger catchments is considered a next step

7. Perceptions and understanding by communities of the water impacts of mining, including all stages of the mining life cycle, is key to responsible mining development. For example, there are current efforts to develop more effective translation of technical information to empower communities in Colombia

8. Virtual observatories, where data and predictions can be viewed interactively online at a level of complexity and context suitable for the particular user, are viewed as helpful in developing understanding in general; further research is needed on how to best implement such methods

9. There is lack of basic climate data, especially to represent high climate gradients and inaccessible regions in the tropical Andes. The shortage of rainfall data is being addressed by integration of remote sensed products with ground gauging. Relatively rapid useful results can be achieved for annual average rainfall; research is underway towards mapping extremes. Within this, it would be useful to show areas with lower quality, so decision makers could see where there is a lack of data

10. Other immediate challenges facing mining companies in Peru include: Transitioning to meeting stronger regulatory requirements; duplication of effort in compliance monitoring; unreliability of energy sources (companies investing in private sources); and lack of capacity to implement good practice

11. Capacity issues include: lack of high level capacity in universities (e.g. few staff have PhDs); lack of incentive for doing research; funding controlled regionally; and lack of central research and development strategy. There is a particular shortage of hydrogeological capacity in universities and government

12. Knowledge, ability and commitment of postgraduate students and young professionals is clearly high, and there are many candidates who are well suited for postgraduate study at international universities

The main outputs of the project are:

- Outline research and training proposals, including new collaborations between international universities, CONDESAN and government research agencies

- A draft paper on the applicability of river ecosystem service concepts to mining in the tropical Andes
- A library of PowerPoint presentations delivered at the workshop
- This final report including edited versions of the four commentaries

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1 Introduction

Perceptions about how mining activity may impact on traditional uses of land and water are obstacles to economic development through mining (Hodges 1995). The perceptions and counter-perceptions are often not underpinned by science or its effective communication. The problem of developing common understanding and agreement about the risks and benefits of mining has been especially notable in Peru, with serious conflicts about equitable use of land and water (Bebbington et al. 2008).

The concept of freshwater ecosystem services is now commonly used to identify the broad value of rivers, aquifers and lakes in terms of the services they provide to society. The concept requires us to look further than the easily quantifiable values of freshwater resources, such as providing water supply for households, agriculture and industry, to less easily quantifiable 'regulating' and 'cultural' services. This breadth and depth of scientific understanding, and its effective communication between groups, is needed to assist a common view of sustainable development of mining regions.

The impact of formal mining is, in general, managed by well-defined environmental regulations and guidelines. For example, regulations covering the operation of the mine usually include specific limits on quality, quantity and locations of water discharges, and quantity and location of water abstractions. In principle, these limit-based regulations are designed to protect freshwater ecosystem services. However, the uniform application of limits over large regions with variable hydrological and social contexts, and limitations in knowledge about mining impacts on freshwater ecosystem services and in how this knowledge is applied, mean that there is a large arbitrary component in specified limits. Improved understanding of mining impacts on freshwater ecosystem services will support a less prescriptive and more outcomes-driven approach to regulation, which should have benefits for water users and for governments who are committed to sustainable development through mining.

The concept of freshwater ecosystem services also requires dialogue and developing understanding of the value of water across different stakeholder groups, as opposed to applying generalised limits on water use. The ecosystem services approach to planning therefore can deliver benefits through its process as well as through the evidence generated.

However, there are many challenges associated with developing understanding of mining impacts on freshwater ecosystem services. These include technical, social and institutional challenges. Recognised challenges include improving (relevance, quality and quantity of) observations of freshwater ecosystems before and after the influence of mining, improving accuracy and precisions of predictive models, effective communication of data and its significance to different stakeholders, and defining useful indicators of freshwater ecosystem services.

The tropical Andes region presents particular technical challenges of diverse and complex hydrology and hydrogeology, with limited monitoring and knowledge of the hydrogeochemical processes that influence water-related risks. Along with the demands of rapid mining development, there is reliance on freshwater to support strongly traditional livelihoods, and in many mining areas there is a legacy of poor environmental assessment and management especially with regard to post-mining management.

The general need for monitoring, research, tools and capacity building, towards better and more common understanding of risks to (and opportunities for) freshwater ecosystem services associated with mining, is well known. The priorities, the transferability of progress being made in other contexts, and the specific pathways to relevant research and training initiatives, are not well known; and the inter-disciplinary and international collaborations are not yet well enough developed. This Action Research Project aims to address some of these knowledge gaps.

2 Objectives and scope of project

The project aimed to:

- Identify the potential and challenges for more effective use of freshwater ecosystem service concepts in the context of assessing and managing sustainable development of mining, including perspectives from university, government research institutions, an NGO and industry
- Develop outlines of at least two research proposals involving collaboration between the project partners
- Draft a paper that sets a research agenda for improved application of freshwater ecosystem service concepts to mining in the tropical Andes
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The project focused on directions for overcoming the technical challenges associated with monitoring, modelling, evaluation of ecosystem services and communication, rather than the institutional and regulatory challenges. The project could not significantly address any specific science questions behind ecosystem functions, how ecosystems services interact or procedures for ecosystem service optimisation.

The project focused on particular challenges of the tropical Andean nations. The project scope does not cover in detail the literature and current activity on assessing the broad range of freshwater ecosystem services, rather it focuses on the underlying problems of data, models, communication and capacity that act as obstacles to these assessment methods being applicable.

3 Methods

The project included four stages of activity.

The first stage of the project was a desktop review, leading to four written commentaries and PowerPoint presentations on:

1. The reasons for the current lack of clarity in the links between river and lake ecosystem service functioning and mining projects, and the application and applicability of the river ecosystem service concept
2. The strengths and limitations of models and risk assessment tools for evaluating risks to ecosystem services from mining
3. The applicability of visualisation tools including on-line media, for communicating risks
4. The associated research, training and education needs

The second stage of the project was a field visit to La Oroya mining region of Peru, including a one-day tour of Volcan's Yauli multi-metal mine and development of a presentation about this trip and its contribution to the project.

The third stage of the project was a three-day workshop in Lima with the 16 participants listed at the start of this document.

During the workshop, the participants developed the commentaries through: presentation of the commentaries, presentation of additional case studies related to the commentary topics, follow-up discussion of these presentations and associated prioritisation of research needs and outlining follow-up activities.

The final stage of the project was the integration of project stages 1-3 into outline research and training proposals, the draft of a journal paper and a library of project presentations.

4 Post-workshop commentaries

The first four commentaries included here, are based on those written prior to the workshop and edited to consider the discussions that took place in the workshop. The fifth commentary reports on the field trip and discusses its significance. The associated PowerPoint presentations are available on request.

4.1 Links between river ecosystem services and mining: overview of reasons for poor understanding

4.1.1 Introduction

This commentary aims to provide a basis for discussing the barriers to understanding, predicting and communicating risks to fresh water ecosystem services in the mining context. This is approached by literature review and review of selected case study projects.

First, some general definitions are made to clarify what is meant by ecosystem services:

- *Ecosystem*: An ecosystem is represented by the links among organisms and their physical and biological environment (Millennium Ecosystem Assessment 2005). According to the United Nations (1992) an ecosystem is a dynamic complex system of plant, animal and microorganism communities and the non-living environment, interacting as a functional unit
- *Ecosystem functions*: This term describes the processes (biological, geochemical and physical) that take within an ecosystem. Ecosystem functions purify water and air, generate oxygen and stabilize or climate, and creation and regulation of soils (Sodhi and Ehrlich 2010)
- *Ecosystem services*: These are the aspects of ecosystems and ecosystem functions that are useful to or enjoyed by humans (Millennium Ecosystem Assessment 2005)
- *Ecological service (eco-service)*: refers to mutual interaction between people and nature to provide each other with promoting or restricting conditions and processes through which sustainable relationships can be maintained (Bai et al. 2011)

The Millennium Ecosystem Assessment (2002) has classified ecosystem services according to functional lines using categories of provisioning, regulating, cultural and supporting services (also see Coles 2014):

- *Provisioning services* are those from which products are obtained, for example river flow produces water supply
- *Regulating services* are services obtained from the regulation of ecosystem processes, for example the river flow regime regulates nutrient supply to flood plains

- *Cultural services* are related with non-material benefits obtained from ecosystems, for example pleasure might be obtained from la healthy river
- *Supporting services* are habitats that support the production of all other services, for example a native forest may be important in supporting a good freshwater supply

4.1.2 Freshwater ecosystem services

Freshwater ecosystem services are related with all the benefits that people take from fresh water directly or indirectly. Common human uses of water are domestic, irrigation, power generation and transportation. In addition, the hydrological cycle provides regulating, cultural and supporting services through conserving rivers, forest, lakes and wetlands (Sodhi and Ehrlich 2010). The Millennium Ecosystem Assessment provides examples of freshwater ecosystem services under their four categories (Table 1).

Table 1 Ecosystem services provided by freshwater and the hydrologic cycle

Provisioning Services	Regulatory Services	Cultural Services
• Water (quantity and quality) for consumptive use (for drinking, domestic use, and agriculture and industrial use) • Water for nonconsumptive use (for generating power and transport/ navigation) • Aquatic organisms for food and medicines	• Maintenance of water quality (natural filtration and water treatment) • Buffering of flood flows, erosion control through water/ land interactions and flood control infrastructure	• Recreation (river rafting, kayaking, hiking, and fishing as a sport) • Tourism (river viewing) • Existence values (personal satisfaction from free-flowing rivers)
Supporting Services		
• Role in nutrient cycling (role in maintenance of floodplain fertility), primary production • Predator/prey relationships and ecosystem resilience		

(Adapted from Millennium Ecosystem Assessment 2005)

The quantity, quality, location and timing of water are crucial factors to determine the risks and benefits associated with water (Sodhi and Ehrlich 2010). The impact of human activity on freshwater must include analysis of changes in the spatial and temporal distribution of freshwater on relevant scales. When water is distributed through the hydrological cycle, it interacts with other ecosystem services. For instance, forest and aquatic services influence the hydrological cycle, moderating climate change and reducing flooding risk (Sodhi and Ehrlich 2010). Moreover, fresh water is a source of numerous species that support other ecosystem functions. Table 2 shows the effects that some ecological functions have on hydrologic services.

Growth of population and changes in lifestyles have also increased demand for fresh water ecosystem services that has led to natural ecosystem functions being replaced by engineered systems. Water resources developments have in general decreased flows in rivers and have changed the natural distribution of water and its biochemical conditions. It has been estimated that inland water abstraction has increased at least 15 times over the past two centuries (Millennium Ecosystem Assessment 2005); and according to the World Water Commission, more than half major rivers of the world are polluted (World Water Commission 1999).

Table 2 The effects of hydrological ecosystem process on hydrological services

Ecohydrologic process (what the ecosystem does)	Hydrologic attribute (direct effect of the ecosystem)	Hydrologic service (what the beneficiary receives)
Local climate interactions Water use by plants	→ Quantity (surface and ground water storage and flow)	**Diverted water supply:** water for municipal, agricultural, commercial, industrial, thermoelectric power generation uses **In situ water supply:** water for hydropower, recreation, transportation, supply of fish and other freshwater products **Water damage mitigation:** flood and landslide risk reduction, water quality and sediment regulation **Spiritual and aesthetic:** provision of religious, educational, tourism values **Supporting:** Water and nutrients to support vital estuaries and other habitats, preservation of options
Environmental filtration Soil stabilization Chemical and biological additions/subtractions	→ Quality (pathogens, nutrients, salinity, sediment)	
Soil development Ground surface modification Surface flow path alteration River bank development	→ Location (ground/surface, up/downstream, in/out of channel)	
Control of flow speed Short-and long-term water storage Seasonality of water use	→ Timing (peak flows, base flows, velocity)	

(Adapted from Sodhi and Ehrlich 2010)

4.1.3 Mining projects and freshwater ecosystem services

Economic growth has improved the demand for and consumption of fresh water ecosystem services in industry and communities; and mining is one of the powerful industrial activities linked to economic growth. Mining operations have strong relations with water, which is needed throughout the mine life cycle: exploration, resource development and design; mining, minerals processing and refining; shipping of products; rehabilitation, and post-mining and closure, and monitoring before and after operation (Australian Government 2008). In this vein, demand for provisioning fresh water ecosystem services has increased due to mining operations, while the supply of regulatory, cultural and supporting services have often decreased downstream of the mine (Carpenter et al. 2009).

Mining is one example of human engineering that has impacts on freshwater ecosystem services. In many respects, its potential impacts are similar to those of other human activities such as agriculture, urban development and other industries. However, there are some aspects of mining that make impacts difficult to evaluate and manage:

- Mining can cause major changes to the surface landscape and the sub-surface. Changes to the sub-surface can cause wide water footprints, which are difficult to evaluate due to hydrogeological and geochemical uncertainty and other influences; and are expensive to monitor due to the potentially widespread impacts and expense of drilling and monitoring observation wells
- Mine projects are also dynamic so that water use and impacts on hydrology may change considerably over the mine life cycle. Although a mine's working life may be relatively short, changes in geochemistry caused by the mining activity mean that impacts are long-term, well beyond the active mine life. Understanding these long-term impacts is a critical part of ecosystem service impact analysis
- Small-scale and informal mining often leads to particular problems of quantifying sources of risk, with little or no data available on water and chemical use and releases, and an uncertain number and location of sites
- Evaluating cumulative effects in mining regions requires understanding of regional hydrology, hydrogeology and geomorphology, and how these interact with the physical, chemical and biological environment. Understanding from localised studies is difficult to apply at regional scales due to heterogeneity and dynamics of the environment
- As well as the direct changes to the landscape, water use and releases caused by mining, there can be considerable indirect effects. For example, urban development, afforestation as part of offsetting and rehabilitation schemes, plantations as energy sources and transport infrastructure are all associated with mining projects and may impact upon fresh water ecosystems. Thus the complete impacts of a mine project cannot be understood until these indirect effects on land and water use are understood
- Mining has a bad reputation in general because of several high profile disasters due to poor mine design and project management, and due to many legacy problems from old mines. This means that mining must not only overcome the engineering challenges of sustainability, but overcome prior perceptions through effective community relations and science communication

All these challenges mean than evaluating and communicating the impacts of mining on freshwater ecosystem services can be more difficult than for other water users.

In contrast to potential negative impact on water, mining can bring economic benefits by stimulating the local economy, increasing local revenues and bringing social benefits such as more employment opportunities and corresponding infrastructure (Bai et al. 2011). These contrasting views emphasise the importance of offsetting these streams in order to find a more acceptable balance point that allows sustainable development in the mining industry. Seeing that, software and visualization tools like maps and interactive simulations can benefit communication and management risks of freshwater ecosystem services associated with mining projects (see sections 4.2 and 4.3).

4.1.4 Case studies

Three case studies from the literature are used here to illustrate some of the challenges of, and opportunities for, understanding and communicating risks to fresh water ecosystem services from mining.

Conga Mine Project Environmental Impact Assessment-Peru

The Conga mining project is located in the region of Cajamarca in northern Peru. The project is controlled by the company Mineria Yanacocha S.R.L (Yanacocha), which is one of the world's largest gold mining operations. However, the existing mines are running out of mineable reserves, and the company has invested resources in developing the Conga project as a way of continuing operations (Swedish Geological AB 2012).

The Conga project identified in its environmental impact assessment (EIA) the main impacts on environment and societies. Nevertheless, the EIA was argued to be unclear and relatively inaccessible, which limited the effectiveness of the consultative process. Furthermore, it was argued to over-rely on modelling approaches for predicting impacts, when it could have support these predictions with data and experiences from the existing Yanacocha operations (Swedish Geological AB 2012). Finally in November 2011, the Ministry of Environment submitted a report to the Peru Cabinet Chief, which stated that the EIA needed to be redone (Robert 2012).

Among other problems related with the EIA, there were deficiencies in communication within stakeholders. The complexity of graphs, indicators, etc, prevented effective interaction between consultants and end-users. It may be concluded that the lack of clarity of the EIA should have been supported by models and visualization tools that engaged stakeholders with the project, for example tools presented in Buytaert et al. (2012), Burkhard et al. (2013), and Nelson and Daily (2010).

Evaluating and modelling ecosystem service loss due to coal mining: A case study of Mentougou district of Beijing, China (Li et al. 2011 and Bai et al. 2011).

Mentougou district is located in the west of Beijing region. This region has more than 100 years of coal mining history. The research of Li et al. (2011) evaluated the ecological and environmental loss resulting from coal operations in the region. This study applied the theory of ecosystem service, ecological economics, social investigation and analysis, and other research methods. The Bai et al. (2011) research presented a model designed to evaluate cost and benefits of coal mine process, which analyses the economic and social benefits of coal mining, as well as the cost of local water eco-services by estimating the water eco-service damage caused by mining.

The Mentougou studies revealed that surface and underground water have been affected by coal operations in this region. Groundwater levels and flows have decreased, and there are serious water pollution issues caused by acid mine drainage. It was concluded that coal mining in Mentougou has a negative effect on local water eco-services. In economic terms, it was estimated that the value of the coal resource was $870 million, while the corresponding loss of ecosystem services caused by coal mining was approximately $2000 million in the past 50 years. Additionally, some ecosystem service losses cannot be evaluated economically.

For services rendered? Modelling hydrology and livelihoods in the Andes: payments for environmental services schemes (Quintero et al. 2009)

The study focused on two Andean watersheds: Moyobamba (Peru) and Pimampiro (Ecuador). In the first case, a municipal water company was preparing a payment for environmental services (PES) scheme to reduce upstream sediment loads. In the second, a similar conservation-oriented municipal PES scheme had operated since 2000, but the hydrological linkages had never been tested. Applying the Soil & Water Assessment Tool (SWAT), in both watersheds helped to identify biophysically critical areas for service delivery. Services for current land uses were compared using change scenarios: deforestation, reforestation, live barriers, and Agroforestry were compared. Then, the ECOSAUT optimization model was used to predict net economic benefits for service providers.

The study concluded that the combination of a distributed hydrological model, SWAT and a socioeconomic optimization model, ECOSAUT, effectively assessed the income effects of land-use scenarios, enabled the discrimination in space of watershed services and the livelihood consequences for land users from changed land uses. It also permitted screening projected impacts from PES Schemes. However, the lack of vital input data and model uncertainty will inevitably trigger uncertainties in predictions. Moreover, services come from heterogeneous landscapes such as the Andes where rainfall, soils, land uses and slopes have high variations showing dramatic differences in the provisioning services that are problematic to capture in modelling exercises (Buytaert et al. 2012, Burkhard et al. 2013, Nelson and Daily, 2010).

4.1.5 Key points on understanding links between mining and ecosystem services

It can be concluded that the reasons for the lack of clarity in how mining affects ecosystem services include:

- The potential importance of complex interactions between hydrological and ecosystem functions
- The need to understand how the space-time distribution of water affects ecosystem functions and services
- The rapidity of changes to the freshwater environment and lack of data to characterise this, and to distinguish between causative factors

- The need to define indicators of ecosystem services that are easily measurable, and hence the need to define the locally important freshwater ecosystem services
- The particular difficulty of quantifying impacts of mining: the lack of information about informal mining; the importance of hydrogeochemistry; the foresight needed to assess the mine life cycle; the indirect land use changes associated with mining; and overcoming prior perceptions attached to mining impacts
- Environmental models are typically developed by complex scientific codes, hypothesis, and analytical interpretations that are difficult to translate effectively to communities and other stakeholders
- Lack of incorporation of new data, process knowledge and models, and general failure to take up the opportunity to incorporate 'citizen science'

4.2 Models for evaluating risks to freshwater ecosystem services from mining

4.2.1 Introduction

This commentary is a discussion of what research is needed to make better use of computer models in evaluating risks to ecosystem services from mining. For easy discrimination between the different types of models involved, the discussion is structured into a *Source-Pathway-Receptor* risk framework. In the project context:

- Sources = Mine projects
- Pathways = Freshwater ecosystem functions
- Receptors = Ecosystem services

This is a broad topic and so this discussion is necessarily brief, aiming to identify the key obstacles to effectively modelling the source-pathway-receptor risks in the project context.

4.2.2 Sources

The quantification of source is in many cases straightforward, primarily being the estimation of how much water is used by a mine, how much it discharges, and its quality. Many large-scale operational mine sites publish records of these, derived from direct measurements or mine site systems models (Cote et al. 2009). The Mineral Council of Australia's Water Accounting Framework aims to provide clarity in the meaning of reported inputs and outputs.

However even accurate and well-defined records are often averaged over long periods (e.g. monthly or annual), whereas much of the risk may come from how the project affects the variability of hydrology and water quality. An example is increased discharges during and after flood events, which requires dynamic data; and to attribute changes to hydrological regimes, dynamic data on mine site outputs would be required. Accidental spills and catastrophic events such as tailings dam failures are un-controlled cases that require alternative approaches to estimating sources.

Furthermore, sub-surface water balances to/from mines sites are uncertain and challenging to measure or model. Sophisticated groundwater models or simple water balances are often used to do this (Younger et al. 2002; Kunz and Woodley 2013); but complex geology and local fault and fracture properties often make it difficult to locate and quantify sub-surface leakage or inflows to mine pits. In cases, detailed geological, hydrogeological and geochemical studies are needed to determine multiple different sources of groundwater entering a mine site, for example to isolate good quality groundwater inputs from poor quality groundwater inputs.

In more small scale and unregulated mining, inputs to and outputs from mines are relatively diffuse and unquantifiable despite their potentially high significance (Cordy and Veiga 2011). Generalisations about water use and sediment and pollution generation would usually have to be used in place of formal modelling or monitoring.

A mine project is never the sole source of risk to freshwater ecosystem services in a catchment. Mines are often co-located with other mine projects, agriculture, urban areas and other industry that affect water balances and water quality; as well as naturally occurring influences on water volumes, distribution and quality. Isolating the effect of a mine project requires good models of these other sources. Identifying and quantifying these sources is a major challenge in general for integrated catchment modelling (Candela et al. 2009).

4.2.3 Pathways

River, lakes and groundwater systems, including their physical, chemical and biological processes, are the primary links between mining and freshwater ecosystem services. Changes to water balances, hydrological responses, sediment disturbance, chemical pollution and ecology will be transmitted through these systems.

Freshwater systems models can be classified in many ways. A classification of relevant models is given below according to the modelled variables (Table 3). Integrated systems models may include a few of these types linked together (e.g. commonly a hydrogeological, transport and biogeochemical model work as one system of models). Any of these model types may be integrated into a decision support system, which takes relevant performance indicators from model outputs and compares with targets, and may also include optimisation of decision variables.

Table 3 Classification of freshwater systems models according to modelled variables

Type of model	Examples of applications/variables		
Hydrological	Water balances	River flow responses	Glacier melt
Hydrogeological	Groundwater levels	Underground inflows/outflows	Well yields
Hydrodynamic	River depths	Flood extents	Lake stratification
Solute transport	Advection	Dispersion	Transient storage
Geochemical	Saline water production from mine sites	River water quality	Acid mine drainage production
Geomorphologic/sediment transport	River erosion	Sediment accumulation	Sediment loss
Hydro-ecological	Hydrodynamical quality of fish habitat	Water-nutrient-vegetation interactions	Physical behaviour of invertebrates in rivers
Water infrastructure	Water supply distribution	Wastewater transfer	Flood water storage

While sediments, biology and ecology are important components in understanding links between mining and ecosystem services, this discussion touches upon them relatively briefly and focuses more on hydrology, hydrogeology and water quality.

Changes in hydrological, hydrogeological and water quality responses can be measured using a variety of methods (indeed measurements are critical, as discussed below); however modelling is also usually essential because:

- The incompleteness of measurements in time and space (including absence of baseline data)
- The need to isolate the effects of mine projects in observed aggregated effects
- The need to predict effects as part of social and environmental impact assessment (including cumulative effects)

There are many published reviews of the challenges and uncertainties in using models in general (Reckhow 1994; Beck, 1997, 1999; Chapra, 1997, van Straten 1998). Here, the focus is on the modelling challenges most relevant in tropical Andean nations:

- Climate gradients (variable hydrological response within one catchment; and difficulty of estimating rainfall and evaporation at useful scales) (Bookhagen and Strecker, 2008; Espinoza-Villar et al. 2009) and uncertainty about effects of climate change in the Andean region

- Complex geology and geochemistry (highly faulted and fissured geology; much uncertainty about connectivity between aquifers and between surface water systems)
- Very large basins and flood plains (challenge of modelling and gauging very large catchments with non-linear flow responses and variable biogeochemical influences)
- Data availability (sparse gauging networks; difficult environments for gauging; limited on-line databases) (Paiva et al. 2011, Zulkafli et al. 2012)
- Multiple influences and non-stationarity (multiple perturbations to flow regime makes it difficult to establish baseline), and limited applicability of environmental models for predicting effects of change (Bormann and Diekkruger 2004)

The modelling challenges associated particularly with mining are:

- Mine regions and mixed land use (the number of influences can pose a complex picture, and requires models that are precise in order to understand that picture) (Ferrari et al. 2009)
- Importance of groundwater (with the complexity of regional hydrogeology, modelling the groundwater system over regions to understand cumulative effects is the greatest challenge)
- Changes to flows, geochemistry and sediments are all potentially important and interacting, and have combined and individual effects
- The dynamics of the mine life cycle and the indirect land use effects of mining (plantations, urban areas, roads, etc) require (often highly uncertain) land use change models (Diaz et al. 2011)
- Potential sensitivity of mining to climate change and its effects on floods and water scarcity (Sharma 2013)

The importance of environmental assessments to large-scale mining companies also provides opportunity for progress in environmental measurement and modelling.

4.2.4 Receptors

The receptor in this context is an ecosystem service. A model of an ecosystem service is defined here as one that quantifies (or qualitatively expresses) the value of the service and the change of service associated with mining.

The value of water as an ecosystem service is widely recognised as complex, involving multiple water stakeholders, and impossible to treat objectively with generalised metrics of value (Batten 2007, Savenije 2002, Whittington et al.1990).

The different values attached to freshwater may be summarised as:

- The value of a kilolitre of water to support commercial activity (direct economic value of abstractions and also less direct provisioning services)

- The value attached to a kilolitre of water to safeguard human health, for example meeting minimum per person water supply guidelines (provisioning service)
- The value attached to a kilolitre of water to support non-commercial activity, and cultural and spiritual values, for example the quality of life value attached to living nearby a healthy river (cultural service)
- All the above, but the dependence of that value not just on the amount of water present but on the hydrological regime (e.g. seasonality, flood inundation extents, baseflow, etc) (provisioning or cultural service)
- All the above, but the dependence of that value not just on the amount of water present but also on the physical, chemical and biological water quality (provisioning or cultural service)
- The value of freshwater as a regulating and supporting ecosystem service, covering all freshwater's roles in the broader physical, chemical, biological, social, cultural and economic systems that contribute to quality of life (regulating and supporting services)

This classification, while not intended to be comprehensive, is enough to highlight four sets of challenges in the mining context:

- Objective valuation of human health, cultural and spiritual attributes of freshwater. Although attaching a monetary value to these services is not considered a sufficient valuation (although it is necessary for a mine project to calculate a monetary value needed to preserve these services through investment in efficient measures or new sources of water), it is considered useful to have some objective approach to valuation; for example, a rating or score, to act as a basis for clear communication, negotiation and review
- Identifying metrics of value that capture the importance of the hydrological regime and water quality, as well as averaged volumes of water. Some impacts assessments have failed because there was too much emphasis on overall water volumes and efficiency, and not enough understanding of how mine projects can change the hydrological regime and water quality. A simple example would be the value attached to reliability of baseflows, rather than the annual average flows; but more difficult examples exist. This recalls the challenge associated with lack of baseline data and perceptions about changes that may not always be consistent with facts
- Identifying the full range of water stakeholders and assets potentially perceived to be affected by a mine project, and effective engagement and communication with stakeholders to reach agreed ecosystem service metrics and shared views on how mining can, and should, manage its effects
- Identifying how values are defined in regulatory frameworks and how compliance reporting and modelling will support the achievement of the desired outcomes

While the value of water has received considerable attention in the mining context (Evans et al. 2006; Damigos 2006), this has been done in general terms, and evaluation of the broad range of effects on ecosystem services is rare. A few attempts have been made to understand and represent ecosystem functioning and services more comprehensively in mining impacts assessments, and to develop evidence of how mining presents risks and opportunities (Rosa and Sánchez 2013; Bai et al. 2011; Li et al. 2011; Nyoka and Brent 2007). However, in this project context, there are numerous data, research and capacity building challenges prior to meaningful application of such methods in the tropical Andean nations.

4.2.5 Key points on modelling technology

Models can be split into those used to quantify sources, pathways and impacts. Each area has been subject to much research and advanced tools are available, and are already much used in the context of mining. However, key challenges are:

- Monitoring, modelling and reporting mine water inputs and output according to well-defined standards
- Development of monitoring programmes and databases designed to support modelling of risks, and detection and attribution of change
- Capacity building to effectively apply mine site, hydrological, hydrogeological and geochemical modelling tools
- Research to understand appropriate metrics of ecosystem services

4.3 Web-based services for communicating environmental systems, model simulations and risk

4.3.1 Introduction

This commentary is an introduction on the use of web-based services for facilitating the communication and understanding of environmental and ecosystem services. Firstly, the case is made for the need of a closer inclusion of all stakeholders in the process of analysing and communicating environmental risks. Drawing on experience from a number of recent projects in the UK and in South America (Vitolo et al. 2012), the role of web technologies as a central pivot between data-leveraging, environmental modelling and public decision-making is illustrated. The workshop presentation in Lima further illustrated these aspects by directly exploring some of the web-based interfaces of recent projects.

However, the concepts and experiences presented in this project do not directly pertain to mining impacts on water resources, but instead to lessons-learnt in other hydrological applications (i.e. flooding, diffuse pollution, climate change impacts and adaptation measures, catastrophe risk modelling, etc.). It is designed to inform discussion about what aspects are relevant to mining impacts on and risks to water resources in Peru and, by corollary, what the specific challenges are to the application of web-based services in this context.

Traditional communication between environmental sciences and public decision-making follows a one-way, “top-down” flow of information whereby collection of data is carried out by designated public authorities, researchers and industry who use these to perform model simulations, the results of which are then reported to support impact assessment, compliance reporting and potentially public benefits. For scientists the challenges are, on one hand, having to deal with limited data availability in relation to the complexity and variability of the environmental phenomenon being assessed; while, on the other hand, effectively communicating the resulting uncertainties in model simulations in an informative way that is beneficial to decision-making processes.

For decision-makers (both in policy and other public stakeholders) the issue is a general lack of understanding of how simulations were performed, what information was used, which assumptions were made and what the implications at their relevant scale of interest are. Failure to be able to reproduce results or at least associate them with personal knowledge or past experience of the phenomenon further adds to a lack of confidence and trust in the modelling process itself. The challenge lies in turning this disengagement into a cycle of active participation, interaction and dialogue between scientists and stakeholders.

4.3.2 **Environmental Virtual Observatories (EVOs)**

What is therefore required is a central access point that enables presentation and scrutiny of the entire knowledge generation process, i.e. from data collection through the design and parameterisation of models to simulation results, and ultimately the risks and implications for decision-making. Utilising advances in information technology, there have been several research projects attempting to combine environmental data, models and decision-support systems into a common web-based platform, also termed an environmental virtual observatory (EVO) (El-Khatib et al. 2014).

The central concept of EVOs is to move environmental modelling from academic computing clusters to the *cloud* (Vitolo et al. 2012). Here processes such as data analysis and storage as well as environmental modelling are hosted by large computing networks (e.g. Amazon web-services). Data, models and simulation results can then be accessed through an online user interface by both scientists and stakeholders. From a scientific perspective this has the advantage that software no longer needs to be installed on a particular machine. Instead, a virtual machine in the cloud, accessible to all, allows accelerating simulation processes through the increased memory availability or caching of previously performed simulations, such that these are available to the user within a significantly reduced time period. This makes the entire service more flexible and robust. The ability to use computing resources much more flexibly and ad-hoc (e.g., allocating more computing nodes only when needed) makes the entire service far more demand-orientated and efficient. Furthermore, users can engage more with the model simulations themselves through visualisation tools such as interactive maps (e.g. Google Map Maker), graphs and user-tuneable scenario analysis. Examples of this include the UK Government’s *my2050* simulator, which provides an engaging user experience through interactive scenario definition for mitigation of carbon emissions.

Even more stakeholder empowerment can be achieved by yet further integration of end-users into the actual data assimilation process, which is becoming increasingly more realistic through the advance of *citizen science*. Here data in the form of observations and information can be provided directly to the end-user by (automatically) up-loading measurements from low-cost sensing equipment or even photographs or videos. Making use of this increased availability of such data sources together with global observation technologies, such as high-resolution satellite images, results in two challenges from a scientific perspective. Firstly, the development of a common vocabulary (ontologies) is essential to integrate these data sources into a modelling framework. This necessitates web standards, e.g. the Open Geospatial Consortium's Web Processing Service that define how inputs and outputs for geospatial processing need to be formulated, but also data standards such as waterML for processing of hydrological time-series. Secondly, further exploration of scientific methods is required to effectively integrate these innovative data sources into the familiar model calibration and validation frameworks. For example, automatic tagging of geographic location and timestamp via GPS-enabled smartphones can facilitate comparison of citizen science data with other data sources, providing a first level of quality analysis.

The key to maximizing the potential of these new technologies for stakeholder engagement and empowerment is to involve users in the design and development of web-based platforms. For instance, the UK's *EVOp* (Environmental Virtual Observatory pilot) project has achieved this through workshops between scientists and local stakeholders (farmers), whereby it was identified that the use of a simple graphic interface to define model parameter values conveyed a much better understanding of the model sensitivity to the end-user than defining numeric values, which requires scientific understanding of the system and familiarity with the models. Equally, event-based simulation rather than modelling of long historic time-series allowed stakeholders to better link the model results with their personal, local knowledge of noteworthy events.

Hence, while the provision of innovative data via stakeholders contributes to hydrological understanding and model development, it is imperative that web-based platforms are also effective at reporting back feedback to the users. Interactive scenario definition and analysis can facilitate communicating uncertainties and sensitivities of model simulations. In the *my2050* simulator this happens mostly on the national scale. However, the *water2invest* project, which allows for user-defined calculations of water availability under climate change and technological development scenarios, shows how this can be scaled from local "water provinces" to continental or even global comparative analysis. Furthermore, tools from social-media such as: hashtag (twitter) or "thumbs-up/ like" (facebook) can be used to gauge understanding, responses and opinions of public stakeholders. As a result, web-services that utilise these approaches can also progress to become a vehicle for innovation, allowing businesses to develop, test and promote technological solutions to environmental risks. In remote regions such as the Andean highlands or African tropical rainforests pilot studies have shown that the use of smartphones and other comparatively low-cost communication technology enables local communities to engage both in reporting and receiving information about their environment and its management, respectively.

4.3.3 Key points on using web-based services for more effective communication

Recent and current research projects internationally are encouraging more direct engagement of stakeholders, from problem definition, data collection and analysis/ modelling to, ultimately, decision-making. This type of engagement benefits from a common platform, where data can be collected, assessed and presented to all users in an informative way. In all examples considered, the design of the applications and therefore the technological aspects are specific to the environmental phenomenon and the stakeholder context. Therefore, it is important to define these aspects for the context of mining impacts on water resources in the tropical Andes to optimise the usefulness of technological tools and web-based services. Further research on this is called for.

4.4 Research, training and education needs, and the roles of international and local universities in meeting these needs

4.4.1 Introduction

This commentary aims to provide a basis for discussion about what research, training and education is needed towards better water management in mining regions of the tropical Andes. The commentary first reviews two previous studies conducted at the University of Queensland and then adds the findings from the workshop held as part of the current project.

The University of Queensland produced a report for IM4DC in 2012 called 'Water issues associated with mining in developing countries' (Danoucaras et al. 2012), which aimed to identify the water issues that are currently being experienced in developing countries due to mining, with the aim of creating water management teaching and workshop materials. Sections 4.4.2 and 4.4.3 present edited versions of that report.

4.4.2 ICMM review

Danoucaras et al. (2012) reviewed an International Council of Mining and Metals (ICMM) report (Moran et al. 2009) on challenges affecting training needs globally, which was based on information collected in Chile, Peru, Argentina, Australia, South Africa, Guinea, USA and China. The ICMM report highlighted the following challenges and recommendations:

- Challenges of changes in water uses, regulations and community expectations
- Technical aspects of water management: two priority areas are water treatment technology and groundwater yields
- A general concern is water-related risk arising from climate variability
- Data and information management: research needed to improve the Global Reporting Initiative's metrics related to water use

- Policy and regulations: water access policy and regulations need to be investigated on a global scale
- Cumulative impacts: a framework to address cumulative impacts on regional water systems is called for
- Mine closure: there is a lack of investment in research and knowledge transfer

4.4.3 Literature review

Danoucaras et al. (2012) also reviewed the scientific literature to discover priority areas of research and training. The review focused on the following countries: Mozambique, Zambia, Ghana, Peru, Mongolia, Philippines, Papua New Guinea and Indonesia. Priority issues affecting research and training needs were found to be:

- Community relations, the protection of the environment and enforcement of regulations
- Although there is unbiased information available in the scientific literature, it is not in a format that is accessible to communities. There is scope for government and academia to communicate results in a way that can be better understood by communities
- There is a need for companies to go beyond providing infrastructure and capacity building to the community, and involve them in the monitoring of water quality
- Artisanal scale mining was identified as having severe impacts, but the capacity to solve the problems exists. The government must enforce regulations and close down illegal mines. Companies can provide training to miners to ensure that the mining is done safely
- Companies are concerned about water access in light of increasing scarcity. Governments will have to adopt integrated water resource management principles to ensure that water is sufficient for all users

4.4.4 Recent interviews

The University of Queensland also surveyed delegates at a Water in Mining knowledge exchange event held in 2013 to identify training needs, with interviewees from Peru, Mongolia, Philippines, Indonesia, Ghana and Zambia (Woodley et al. 2014). Priority training needs were related to:

- Impacts of artisanal mining for example: safety training to prevent cave-ins or dangerous use of chemicals, deeper understanding of best practice for small-scale minerals separation and rehabilitation strategies to minimise negative environmental legacies
- Strategies to develop better mine and community relations
- Training in leading practice technical capabilities within mining operations and improved strategies for handling climate variability/climate change

4.4.5 Outcomes from the workshop

Table 4 summarises the training and education needs analysis covering six discipline areas (across columns) and eight types of audience (down rows).

Table 4 Matrix of training and education needs for different audiences

	Hydrology	*Geo-sciences/ hydrogeology*	*Environ-mental pollution/ remediation*	*Models & visualisation*	*Regulation/ governance/ consultation*	*Mine water management*
Under graduate	Already compulsory in civil engineering courses. Quality variable across universities, especially Andean hydrology	High priority: Monitoring and investigations, modelling, hydrogeologic processes, impact assessment. Especially non-mining stakeholders	Specific mining issues (e.g. mercury, arsenic , AMD). UTEC are focussing on this. Mine pollution remediation; closure, rehabilitation.	Principles needed. Model use too advanced/specialist for undergraduate.	Sustainability and adaptation	Yes, in mine engineering courses; there is a severe lack of water related modules in mining courses
Post graduate	There are water resources, and hydraulic engineering. There is a need for PhD level training	As above Geochemistry (including isotope studies)	As above	Higher priority for post-graduate. Modelling procedure including uncertainty analysis.	As above	Mine water systems, planning, optimisation
Mine site staff	Understanding of local hydrology in support of corporate strategies and commitments	Understanding of local hydrology in support of corporate strategies and commitments	Operations applications		Data analysis and compliance reporting	Water balance Mine water systems and optimisation (operational). Treatment technologies.
Mine corporate level staff	May have good foreign advisors but need for better knowledge of Andean hydrology	May have good foreign advisors but need for better knowledge of Andean geosciences	EIA	Investment in and use of communication tools. Systems analysis methods. Risk analysis methods.	Understanding of regulations; conflict management. Understanding of water values	Mine water management methods
Research institute staff	SENAMHI (Peru); Universities	INGEMMET (Peru); IGP (Peru); Universities	IGP (Peru); Universities	Universities	Universities	Universities

Regulators	EIA, compliance auditing, cumulative impacts	EIA, compliance auditing, cumulative impacts	EIA, compliance auditing, cumulative impacts	Use of communication tools. Systems analysis methods. Risk analysis methods.	Community consultation process. Developing clear and understandable regulations. Conflict management. Compliance and understanding of regulations in order to enforce. Understanding of water values	Compliance and enforcement
Local authorities	Catchment water management	Translation of scientific language; understanding local hydrology. Understanding drivers of changes.	Health risks from mines. Ability to participate in EIA process.	Understanding outputs of models; and options/scenario analysis	Consultation methodology. Conflict management. Understanding of water values; and water rights.	Understanding of mine water management problems
Communities	Translation of scientific language; understanding local hydrology; understanding drivers of changes. Key hydrological indicators (e.g. chemical signals)	Translation of scientific language; understanding local hydrology. Understanding drivers of changes.	Health risks from mines. Ability to participate in EIA process.	Understanding outputs of models; and options/scenario analysis	Consultation methodology. Conflict management/ negotiation. Understanding of water values; and water rights.	Water use in a mine.
General	Need for technical skills training (gauging etc) across different groups	Broader understanding the basics of groundwater and management of groundwater systems	Sampling and reporting methods	Understanding links between data, information, modelling and decision making	Sampling for citizen science. Understanding evidentiary based frameworks, and applications in EES assessment and regulation.	Sampling and reporting methods

4.4.6 Key points on training and education needs

Previous surveys of training and education needs in countries with rapidly developing mining economies have made variable conclusions and highlighted a wide range of potential priorities. The workshop focused on the tropical Andean nations. Results showed a wide range of needs; however, disaggregating this by type of trainee/student and drawing on perspectives of national and international universities, government agencies, NGOs and industry, helped to constrain priorities for particular groups, as reported in Table 4. Further workshops focusing specifically on developing the matrix above would be valuable. The project activities also highlighted the excellent quality of young students and professionals in the Andean nations and their suitability for challenging training and education programmes.

4.5 Visit to Volcan's Yauli mine site

Volcan's Yauli mine site is around 100 km east of Lima at an altitude of 4300 m ASL, in the Atlantic watershed. The area receives 300 mm/year precipitation per year. The Yauli underground mine is part of a complex of Volcan mines in this area, mainly open pit. The complex was owned by state up to 1997 then mainly owned by Volcan (government sold last off interest in the company two years ago), which is Peru's largest mining company.

Figure 1 Location of the Yauli mine site

The Yauli mine produces Lead, Zinc, Copper, using traditional methods of grinding, flotation and separation and dewatering. The ore is transported by truck or train to port at Lima. Power is obtained from the national grid.

Figure 2 Grinding and dewatering plant

The mine is dewatering at a rate of 400-800 L/s depending on rainfall. The water can exceed allowed sulphate concentrations (300 mg/L) and treatment solutions are being considered. pH ranges from 4-7, and adaptive lime dosing and two-stage clarification is used before discharge to a stream.

Processing by-products are separated into fines and coarse material, with coarse material going to landfill and fines to the tailings dam. Water decanted from tailings dam is recycled to the processing plant. Twenty per cent of the operations water use is recycled and 80 per cent is abstracted from the river.

Figure 3 Tailings facility and clarification tank following lime dosing

The mine water managers aim in future to separate mine drainage into good and poor quality water, which will reduce treatment costs. Hydrogeological studies are underway to understand how to achieve this.

The site’s power supply comes from the national grid, although within the next few years Volcan intend to produce 90 per cent of power on site to improve reliability.

The key points arising from the mine site visit were:

- Ambitious sulphate targets are a major challenge due to the expense of reverse osmosis treatment. The site is located in the headwaters of a large (Amazonas) catchment and some cumulative impacts assessment and risk-based assessment of sulphate targets may be useful

- Recycling of water is limited and there is no use of pit water. Although the climate is semi-arid (300 mm of rainfall per year), competition for water in this area is low due to low population and almost zero agricultural activity. However, planned expansion, possible climate change impacts, new demands from planned on-site energy generation, and expected catchment-based regulations, there is an interest in water efficiency
- The Rimac valley (which we drove up to reach Yauli) is arid, with severe stresses on water resources, including from mines. As rainfall in Lima is only around 20mm per year, the water yield relies on the headwaters which are dominated by operational mines and mining leases

5 Research, training and publication proposals

Nineteen collaborative research and training proposal ideas were generated at the workshop, based on the findings presented above. The authors may be contacted for more information about the content and status of these proposal ideas. Brief information for the four priority proposal ideas is reported here:

1. The workshop participants agreed that a 'Masterclass' training programme, aimed at high-achieving students and early-career professionals in Australia and the tropical Andean countries, would be a timely and effective way to accelerate capacity building in water management in developing mining economies. Champions: Ed Hauck and Neil McIntyre

2. The workshop participants agreed that the progress already made in Peru in applying freshwater ecosystem service concepts to land and water stewardship should be built upon in the mining region context. Champion: Bert de Bievre

3. The workshop participants agreed that the data gaps and uncertainties are a key obstacle to effective ecosystem service impacts assessment, for example the lack of climate data to support hydrological analysis. Imperial College are currently working on new ways to map precipitation extremes in the tropical Andes, and will take forward the idea of combining these improved maps with other water scarcity risk indicators. Champion: Bastian Manz

4. The workshop participants agreed that improved understanding of hydrogeochemistry was critical for impacts risks assessment for operational and closed and abandoned mine sites. Although INGEMET is making substantial progress in this area, this is limited by lack of hydrogeochemical modelling capacity. Champion: Sheyla Palomino

Two scientific publications have also been outlined:

- A position paper on the application and applicability of freshwater ecosystem service concepts to mining regions in the tropical Andes\
- Dvelopment of large-scale impact risk maps based on new national scale data sets.

It is envisaged that these will in draft form by August 2014.

6 Concluding remarks

The potential benefits of applying freshwater ecosystem concepts to mine water management are widely recognised, especially in regions such as the tropical Andes where these services are central to sustainable communities and local economies. While impact assessments and mine water management plans already consider freshwater ecosystem services (at least implicitly), this IM4DC Action Research project has focused on contributing to overcoming key technical barriers to more comprehensive, more evidence-based and more successful applications.

To conclude the report, it is worth highlighting some of the key questions that have been identified but not substantially addressed in the project:

- How can science best support regulation and outcomes defined in strategies and planning processes?
- How best to contextualise ecosystem services, for example what protocols are needed for contextualization?
- How can knowledge about ecosystem services be used to inform practical regulation of mine water abstractions and discharges?
- How can mine water regulations and mine water management plans recognise dynamics and changes associated with ecosystem values and functions?
- How best to consider water environment baselines in complex systems with substantial anthropogenic footprints?
- What are the core principles for managing ecosystem service tradeoffs and how are they best developed with stakeholders?
- How to deal with the scale issue: local, regional, global – what is the appropriate scale and context, and how should trade-offs between scales be managed?
- Resilience of systems: Timeframe of recovery versus timeframe of operational life, and exploitability relative to recovery (or loss) of ecosystem service

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