Monitoring to Support Water Quality Management in North-Central Chile

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Abstract

After describing the general relevance of water quality monitoring for sustainable water resources management this paper presents the current water quality issues and monitoring practice in Chile and approaches to optimize it, focussing on the semi-arid region of North-Central Chile.

Water quality management requires scientifically sound data as a base for the decision making process. This data should be provided by suitable monitoring systems. In Chile, like in other countries, information requirements with regard to water quality are determined by the national water policy and legislation.

In addition, monitoring system design needs to take into consideration the variability of the natural processes as well as pressures exerted to the systems by human activities, including pollution, water abstractions and climate change. At the end, social and political aspects determine how important water quality monitoring is for the country or region and economic aspects determine which monitoring intensity is feasible. However, a sound scientific knowledge can help to allocate resources for monitoring in the most efficient way.

The objectives of the presented contribution are to scrutinize recent water quality legislation in Chile regarding information demands and to analyse spatial and temporal variability of key water quality constituents in four river basins in North-Central Chile along the 26-33 ºS realm (Huasco, Limari, Choapa, Aconcagua) based on existing water quality related data through GIS and statistical analysis. This analysis lays down the basis for suggestions on an improved monitoring system in these watersheds.

The water quality legislation is analysed according to the stipulated quantitative information requirements regarding water quality constituents. These requirements belong to the fields of impact, compliance, and trend monitoring, each type having different demands according to the statistical design. The four watersheds, which differ in size, climate, land use, and development status, are analysed according to their topography, surface water networks, water flows, point and diffuse sources of pollution, and land use.

The spatio-temporal analysis on a watershed basis illustrates that in some cases spatial correlation allows the exclusion of several existing monitoring sites, whereas in other cases the high temporal variability of parameters asks for higher measuring frequency than the actual (four times a year) in order to satisfy statistical needs and to support an effective decision-making process. To provide an example the case of nitrate in the Aconcagua watershed is elaborated in more detail. Modelling results show that spatio-temporal variability asks for a redesign in terms of monitoring site location and frequency, supporting an optimized allocation of financial means to satisfy the requirements of the secondary water quality norm. At the same time the study reveals the existing knowledge gaps regarding the behaviour of constituents within the watershed systems, which inhibits an improved monitoring design.

Subsequently, concrete suggestions for a future research programme are elaborated in order to fill the data gaps. In particular it seems necessary to study the behaviour of pollutants like heavy metals and nutrients at a sub-watershed level.

Finally, some qualitative statements are presented regarding a possible impact of climate change on water quality issues. Here, special reference is made to the design of trend monitoring networks in the watersheds under scrutiny.

Keywords:

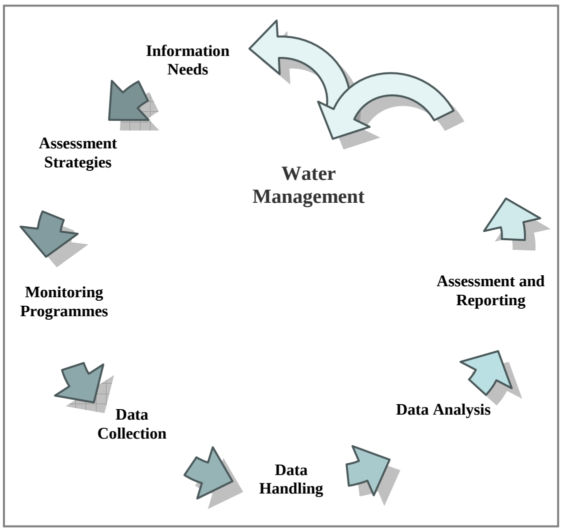
Water quality monitoring, decision making process, Chile, semi-arid environment, Norma Secundaria, watershed management

1. Water Quality Monitoring and its Relation to Water Management

Any decision making process in the water sector demands sound knowledge on the state and the processes of the system which needs to be managed. Adequate information is typically provided through surveys or monitoring programs, the latter being long term measurements of variables of the natural or human environment. However, many water quality monitoring programs do not provide the necessary information as they measure the wrong variables at inadequate locations with an insufficient frequency.

WARD et al. (1986) stated that many water quality monitoring programs can be classified as *data rich but information poor*, referring to the fact that often large data sets of water quality monitoring are available but they were gathered without clearly defined objectives derived from actual water management issues. This leads to a large amount of "useless" data and most countries are still at the beginning of the process to harmonize data collection strategies with real information requirements. In many less developed countries, due to budget constraints and other capacity bottlenecks, one could even state that they are actually not only information but also *data poor*. Especially in lower income countries the problem of insufficient data availability is common while the need to economize is even more prevalent. In addition, many governments pay little attention to data gathering activities as they are costly while the benefit is less visible. Benefits indeed show up only after many years and decades when the improved decision making based on sound information leads to positive effects in the overall political economy. In any case, monitoring programmes need to be designed under budget constraints. The availability of financial resources for operating the monitoring networks which require extensive laboratory and human resources is limited. Thus, a restriction to most relevant monitoring sites, variables and frequencies is important to generate required information at reasonable costs.

Today, there are many approaches available to streamline monitoring design in order to measure only data which actually provide the relevant information for decision making. The general role of monitoring within water management can be expressed in a monitoring cycle (Fig. 1).



Source: modified based on UN/ECE 2000

Fig. 1 Monitoring cycle

Often it can be observed that general information needs are formulated but that transpositions to quantifiable operational objectives which permit to determine exact monitoring frequencies or spatial coverage of monitoring are missing. Another problem is that in many countries so far limited use is being made of quality assurance and quality control (QA/QC) mechanisms in the whole chain of data collection, analysis and reporting. Thus, outliers or other shortcomings are frequently being introduced to data sets putting their usefulness, reliability and credibility under question.

Typical shortcomings of monitoring networks as operated today are:

- Frequencies do not reflect parameter's variability in the environment,
- locations are not set where the generated information is at optimum,
- variables are not selected according to site specific major issues of water quality, but rather according to general recommendations, one-fits-all standards.

These shortcomings and the discrepancies between monitoring objectives and actual monitoring practice lead to redundant data on one hand and significant data gaps on the other. This means a double waste of resources due to badly designed monitoring networks and due to the wrong decisions taken on the basis of unsuitable data!

Information needs in water quality monitoring are usually defined by two major sources. On one hand water policy and legislation defines the needs to report in certain formats, to abide with certain laws, and to check for compliance with regulations. On the other hand the characteristics of the systems which are monitored determine which type of data needs to be monitored and how. It does not make sense to apply the same monitoring system to all watersheds in a nation if they are diverse in the sense of natural conditions and anthropogenic impacts.

The next two chapters analyse the information requirements as they emerge from water policy/legislation and from the analysis of water quality issues in individual watersheds in Chile.

2. Objectives of Water Quality Monitoring derived from Water Policy and Legislation

Nowadays, it is generally accepted that any approach to water management should be based on the hydrological unit "watershed". Therefore, monitoring concepts have to be reconsidered in order to correspond to this new paradigm. In the **European Union**, for example, the Water Framework Directive (WFD) (EU 2000) clearly demands all water management activities to be based on the watershed approach. Regarding monitoring it is required that all river basin institutions define a monitoring plan in order to support river basin characterization. This allows identifying the impacts of measures which will be established in accordance with the main objective of the Directive to achieve good status of all water by 2015. In particular, monitoring under the WFD should be designed to support the classification of status and causes of pollution, detect system changes and trends, and provide a basis for load estimates (EU 2003). Here, the multiple objectives of monitoring become obvious.

In the **USA**, the *Clean Water Act* determines the current water quality regulations. Here, the watershed approach is implemented to a large extend (FORAN et al. 2000). The GOVERNMENT ACCOUNTABILITY OFFICE (2002) documented the inadequacy of current environmental monitoring practices. The subsequent process of redesign of the monitoring efforts led to a new strategy. In 2006, the National Water Quality Assessment Program (NAWQUA) started with a revised status and trends network with the ultimate aims to determine reference values, support the TMDL (Total Maximum Daily Loads) approach, evaluate the effectiveness of environmental protection measures, and to support future optimization of monitoring programs (USGS 2006).

In **Chile**, the broad objectives for monitoring are set by the National Water Policy (DGA 1999a) and are specified by the DGA (Chilean Water Authority). According to the DGA's Department for Water Resources Conservation and Protection, monitoring activities should be designed to (DGA 1999b):

- Characterize water quality at national, regional and watershed level and determine spatial and temporal trends;
- Determine reference (natural) water quality;
- Identify point and non-point pollution process;
- Verify compliance of water quality standards regarding public health (“Normas Primarias”) and the environment (“Norma Secundaria”); identify zones of non compliance (“Zona Saturada”) and zones in danger of not meeting compliance (“Zona de Latencia”);
- Follow/track the plan for decontamination and prevention;
- Determine the impact of specific projects and the efficiency of means of mitigation, contingency, restoration and prevention;
- Detect and control environmental emergencies, provide necessary data for management of emergencies;
- Provide data for reports on the compliance of international agreements;
- Effectively control compliance
- Provide data for environmental education and information of the public.

These are the qualitative objectives of the monitoring program. In many cases it is extremely difficult to base the design of a monitoring network on general statements like these and they should be transformed to quantitative statements of information demand. Generally, the above mentioned objectives can be translated to information on the "state" (e.g. mean) or "trend" of one or more water quality variables in a given system.

In Chile the Secondary Environmental Quality Regulation (Norma Secundaria) is the newest relevant legislation regarding water quality standards and thus relevant for monitoring design. The following paragraphs elaborate this legislation to some more extend and reflect on the implications for monitoring water quality.

Environmental regulation and environmental institutions in Chile are rather new. The mainframe law for the environment, the law 19.300, was enacted in 1995. This *Law of General Environmental Regulation* defines three kinds of regulations: Primary Norms, Secondary Norms, and Emission Norms. *Primary Environmental Quality Norms* are those intended to protect the life and health of the population. They are common for the whole country and they must be fulfilled where human populations are present. The *Secondary Environmental Quality Regulations* are intended to protect the environment and natural life. They are not common for the whole country but may vary from watershed to watershed according to natural conditions and water quality issues of concern. Finally, the *Emission Regulation* refers to the maximum allowable quantity of a given pollutant in an effluent (contamination source) which is emitted to the environment.

The coordination and surveillance of the process oriented towards the formulation and reviewing of the environmental quality regulations, as well as the emission regulations, are a responsibility of CONAMA, the Chilean Commission for the Environment.

The process of formulation of the secondary norm for a watershed follows three stages: (a) Formulation of a preliminary (draft) norm, which takes 150 days and includes the conformation of a responsible committee, as well as the gathering of scientific and technical information; (b) The consultation phase of the draft norm, which takes at least 60 days and consists of a public consultation process, as well the consultation to specific committees; (c) The process of elaboration of the final norm, which considers the observations received in the previous stage.

For the Aconcagua River watershed, the preliminary regulation was formulated and went to the stage of public review on January 10th, 2006. However, at the time of preparation of this contribution, it has not been enacted as a definitive regulation. In particular, its main objective is to "protect, keep, and recover the inland, surface water quality of the Aconcagua River watershed, in order to secure the use and availability of the water resource, the protection and conservation of the aquatic communities and the ecosystem, maximizing environmental, social and economic benefits". Also, it is stated that "this regulation will allow the protection and conservation of the current water quality avoiding the future impairment of the resource, ensuring an acceptable level in accordance with the available and scientific criteria". In the Huasco and Limari the preparation of the secondary regulation has recently started while in the Choapa it is expected to start within the next years. (Zepeda 2008).

The implementation of the secondary water quality regulations is coincident and concordant with the sustainable development model carried out by Chile in the last decades, highly based on exports and international trades of prime materials and natural commodities. Also, the Chilean Government has undertaken the endeavour to transform Chile into a leading world-wide food country by 2010 (Ministerio de Agricultura 2006.). This will mean that international environmental regulations, as well as the use and conservation of clean waters will be a basic premise for Chile in order to trade the agricultural-related products. However, the attempts to develop and implement these water quality secondary regulations are yet not free of problems.

A regularly criticized aspect of the current process of the elaboration of secondary regulations is related to the definition and establishment of the "current and natural water quality" to be preserved. This is due to the fact that the corresponding threshold for a given parameter (e.g. Cu) has been determined based on available historical yet normally incomplete data considering normally the 66 percentile value of the available time series, chosen as representative of the "natural" condition for each stream reach. However, no further analysis and evaluation is normally carried out, and these thresholds still lack of a sound scientific basis and an in-depth analysis in order to better define the background situation.

Also, up to now only surface waters are included in the proposed regulation, whereas groundwater, estuaries and lakes are ignored yet. It is widely recognised as a good practice to study and consider all surface and ground waters together in a more comprehensive approach, in order to be more effective in the protection of the environment and the management of natural resources.

Finally, another aspect that remains unclear yet relates to the monitoring and control process that must be undertaken by governmental institutions. The secondary regulations establish that the DGA, as well as the *Servicio Agrícola y Ganadero* (Agriculture and Lifestock Service, SAG), are going to be responsible for the periodic monitoring of the waters and to implement required measures as consequence of the monitoring results. DGA currently has an active monitoring network, and SAG tends to perform water sampling and analysis based on private complains (e.g. a farmer that is worried by the potential contamination of a nearby mining activity). However, the application and enforcements of the secondary regulations will require improving current levels of monitoring in terms of a more systematic and comprehensive approach regarding site selection, measurement frequency and needs to include parameters that are not currently measured. This will require an important amount of financial resources and personnel which should go hand in hand with an institutional strengthening and coordination of the responsible institutions at a regional level, especially DGA, CONAMA and SAG. In addition scientifically sound procedures of monitoring network design need to be developed and followed in order to generate the necessary information, omit redundancies and allocate resources wisely.

Regarding the water quality monitoring of the DGA current practice is to sample and analyse surface water three to four times a year for a wide range of parameters (typically around 30). In order to determine the compliance with the secondary norm, the 66th percentile of all samples taken in the preceding three years will be taken as a basis for decision making. This means that one third of the highest values are excluded from analysis. In other words, of the twelve samples taken in three years, the four highest values will not be considered. If a clear seasonality of data exists, these four measurements could represent the prevailing concentration of one particular season, which would be systematically neglected for the decision making process.

The Chilean water quality legislation provides clear guidance on the analytical methods to be used for water quality monitoring but it leaves open how to determine adequate monitoring sites or frequencies. It is furthermore questionable if any reliable information is acquired with the sparse current measurements and to which extent conclusions can be drawn regarding an optimized water quality program i.e. an improved selection of monitoring points and sampling frequencies of the variables in any given watershed.

These important aspects should be considered while adapting the monitoring to comply with the secondary water quality norms in each watershed. Here, prevailing natural conditions and human alterations of each watershed under consideration need to be taken into account in order to determine an adequate monitoring network, both in terms of sampling frequency and the spatial pattern of sampling stations.

3. Sample Watersheds in Chile

In the following section four major river basins in the North-Central part of Chile are analysed and compared regarding their water quality issues and concerns with the objective to draw conclusions on a responsive water quality monitoring strategy. These case studies are the Aconcagua, Choapa, Limari and Huasco River Basins located in the Valparaiso, Coquimbo and Atacama Regions between 28 and 33°S (Fig. 2). These regions correspond to the transitional area from the Arid North Chile to the more humid south central part of the country. Also it is a common trait of this realm the relative importance of fruit tree species such as table grape that is cultivated and exported to foreign markets such as Europe and USA.

The three catchments north of Aconcagua (Choapa, Limari, and Huasco), are being studied within a project which has goal to broaden the existing data base with information necessary as background information for the secondary water norm. It also gives a first approximation about optimizing the present water quality monitoring system. All these factors influenced the watershed selection in this work.

In the whole region under study, a Mediterranean type climate is prevailing with warm, dry summers and wet, cool winters. Precipitation varies widely with a general tendency to decrease from South to North. In the Andes mountains precipitation is higher than in the lower areas reaching values of up to 1500 mm a^{-1} in the Southern part of the Aconcagua basin. In the middle part of the basins between the Andes mountains and the Pacific coast precipitation is significantly lower, ranging from 300 mm a^{-1} in the Aconcagua around Los Andes to around 35 mm a^{-1} in the middle part of the Huasco basin near Vallenar (CADE-IDEPE. 2004c). All basins face high intra-annual as well inter-annual variations in water availability. Also, precipitation amounts increases in two folds on El Niño (ENSO) years, whereas the opposite situation occurs on La Niña years. Precipitations concentrate from May to August. The flow regime is nivo-pluvial with usually a peak of natural discharges occurring during snow melt in the summer months (November – January). Agriculture is by far the biggest water user with a peak demand during December-February. Vegetation is getting sparser from south to north due to prevailing climatic conditions. While in the Aconcagua some forests are observed, in the more northern basins matorral with sparse bush vegetation is the most common natural vegetative cover. The higher mountainous regions are void of vegetation and often covered by permanent snow or glaciers.

The **Aconcagua Basin** is located entirely in the Valparaiso Region. It provides the drinking water for around one million inhabitants inside the basin and in the Valparaiso/Vina del Mar metropolitan region. Irrigated agriculture extends over 60 000 ha producing above of all avocado and table grapes for export, making it a significant economic factor. Many small mines and the "CODELCO – Division Andina" mine –one of the largest in the country- is another important economic activity.

The **Choapa** river basin is located in the southern part of Coquimbo Region of North Central Chile. The minimum average temperature is 7.0 ºC, and maximum average temperature is 21.9 ºC (CADE-IDEPE, 2004c). The Choapa is the main river of the basin, flowing from the Andean mountains towards the ocean in a SE to NW direction. Most headwaters in the Andean range could reach 4,000 masl. Since this part of the Chilean territory is one of the narrowest, reaching ca. 90 km, rivers show important gradients and turbulent flows. The agricultural activity in the basin has been traditionally related with extensive crops (pastures, cereals); the recent construction of the Corrales reservoir (50 MCM) and the ongoing construction of the El Bato dam (25 MCM) will improve the inter- and intra-annual water availability. It is expected, as it has occurred in the other basins of the Region, that these hydraulic works will foster the agriculture of the Choapa Province favoring the development of high valued crops such as fruit trees. Also, this will be likely supported by the Chilean government program oriented to transform Chile into a world wide food producer power by 2010. The catchment development is one of the least in the region of Coquimbo.

In 2000 the Copper mine Los Pelambres located in the Choapa basin started to excavate the Los Pelambres deposit, placed in the basin headwaters (above station 1), being one of the country largest copper porphyry deposit, with reserves of thousands of millions of copper (molibdenum)-sulfide mineralized rocks. Also, the Choapa basin concentrates more than half of abandoned tailing deposits of the Coquimbo Region, which are perceived as important sources of heavy metal pollution for surface waters.

In the **Limari** basin agriculture plays an important role regarding water consumption and potential pollution. The main economic activities in the Limari province are agriculture (31.8 %) and commerce (38.5 %), the latter concentrated in the main city of the province: Ovalle (PTI, 2005). The mining activities are summing up to 2.86%. Other than in the Aconcagua the water discharge is highly regulated. The area is characterized for the presence of three water reservoirs: the Recoleta, the La Paloma, and the Cogotí dams, which in total have a storage capacity of 1,000 Mm^3, becoming the largest irrigation oriented infrastructure in Chile. The system secures water for three consecutive years of droughts. The area holds only a few mining activities (copper and gold).

The **Huasco** river basin is located in the Atacama Region, where a frost-free period of 11 months is observed; the land use is less developed in this catchment. The Santa Juana reservoir (160 MCM) is been in operation some kilometers downstream of the confluence of the upper catchments and leads to a higher irrigation security. Therefore also in the more industrial zone of Vallenar some major plantation of olives can be found. A big food (meat) processing plant has been started recently its operation in the same downstream area. The southern part of the upper sub-catchment is been influenced by the mining project Pascua Lama, where as the other part of the upper catchments are used for less intensive agriculture, mainly potatoes and alcachofa (PTI, 2006). The perennial cultivars are mainly grapes and avocado.

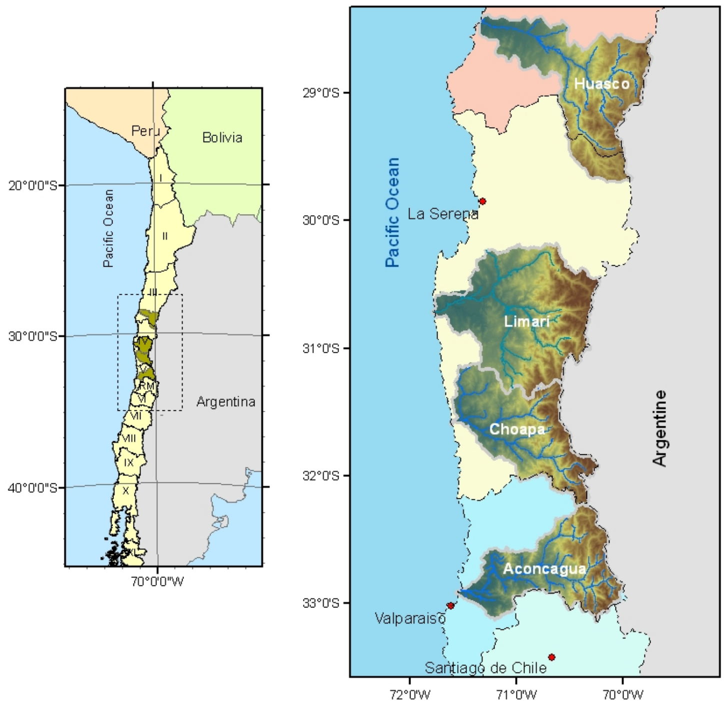
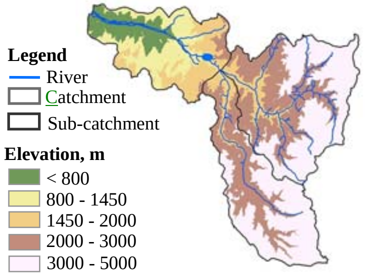
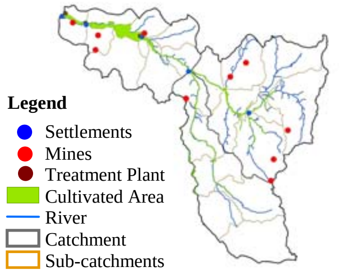
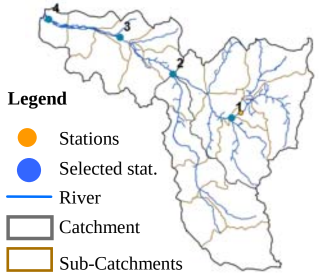
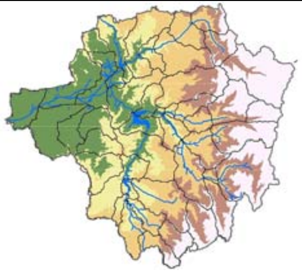
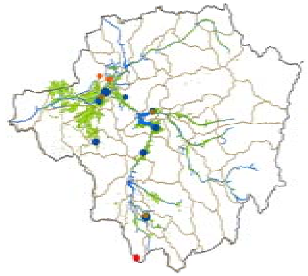
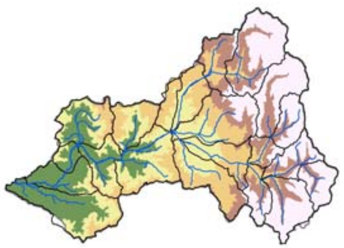
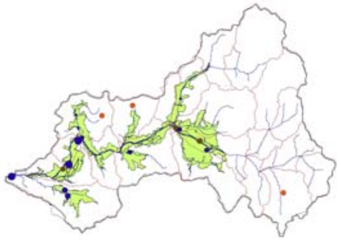


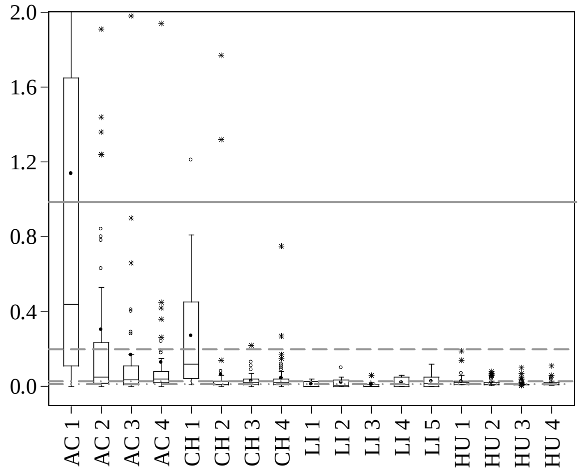
Fig. 2 Location of the four river basin case studies

A closer look on the main characteristics of the case study basins is given in the following table (Tab.1). In this table, each watershed is described within GIS framework and characterized according to their physical settings, anthropogenic impacts, and existing monitoring stations.

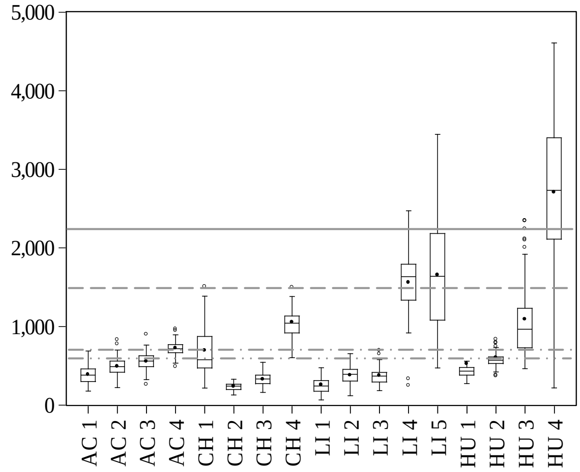
As mentioned earlier in this paper, monitoring system design needs to take into consideration the variability of the natural processes as well as pressures exerted to the systems by human activities. Similarly, data collected from monitoring activities can be interpreted and utilized to analyse the effectivity of the monitoring practice. Fig. 3 presents information related to the status of surface water quality which is monitored in the case study areas. The water quality status is represented by some selected physico-chemical parameters which correspond to the impact of main activities of the watershed (mining and agriculture), i.e. *Cu*, *Conductivity*, $N(NO_3^-)$, SO_4^{2-}, and Chemical Oxygen Demand (*COD)*. The data is presented as boxplots and is obtained from the Chilean Water Authority (DGA) from its monitoring activities in various stations in the watersheds during various monitoring periods, with maximum monitoring period of 1980-2006. It is expected that the information gathered from the monitoring such as given in Fig. 3 can help a better understanding the spatial behaviour of the variable determine the watershed characteristics as displayed in Tab. 1, and vice versa.

Tab. 1 Main characteristics of case study basins

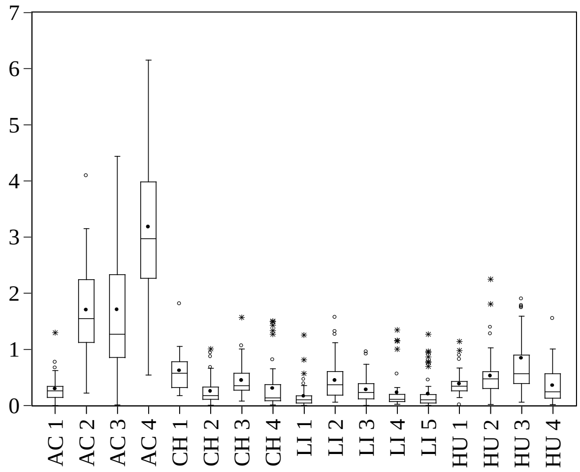
	Physical settings	*Anthropogenic impacts*	*Selected Quality Monitoring Stations*
Huasco (HU)	 **Area:** 9,814 km² **Average annual precipitation:** 50 mm (in lower part of the catchment) **Average discharge:** 3.73 m³/s (Algodones)	 **Irrigated area:** 8,087 ha **Industrial Activities:** *Mining*: mining and processing to iron blocks; harbour to ship the mining products *Industry*: food, vine and pisco. **Population:** *Total*: 66,491 *Major cities*: Huasco, Freirina, Vallenar, and Alto del Carmen.	 **1: HU 1**, Rio Chollay antes Rio Conay **2: HU 2**, Rio Transito antes Rio Carmen **3: HU 3**, Huasco en puente Panamericana **4: HU 4**, Huasco en Huasco Bajo
Limari (LI)	 **Area:** 11,696 km² **Average annual precipitation**: 130 mm **Average discharge,** 7.5 m³/s (mouth of Limari), 50 m³/s (wet year)	 **Irrigated area:** 65,000 ha (below the canels?) [CNR, 2005] **Industrial Activities:** *Mining:* few active, mainly copper and gold. **Population:** *Total:* 156,141 *Major cities:* Ovalle (53,395) and Combarbala (4,866)	 **1: LI 1,** Cogotí entrada embalse Cogotí **2: LI 2,** Huatulame en el Tome **3: LI 3,** Grande en Puntilla San Juan **4: LI 4,** Estero Punitaqui antes Limarí **5: LI 5,** Limarí en Panamericana
Choapa (CH)	 **Area:** 7,631 km² **Average annual precipitation:** 210 mm **Average discharge:** 9.8 m³/s (Puente Negro Station)	 **Irrigated area:** 31,150 ha **Industrial Activities:** *Mining:* mainly copper, with main mine (Los Pelambres) next to the Cuncumen river, and smaller ones at the Aucó confluence *Industry: pisco* **Population:** *Total:* 64,230 *Major cities:* Illapel (21,830) and Salamanca (12,690)	 **1: CH 1,** Choapa en Cuncumén **2: CH 2,** Cuncumén antes Río Choapa **3: CH 3,** Choapa en Salamanca **4: CH 4,** Estero Aucó antes Río Illpel
Aconcagua (AC)	 **Area:** 7,530 km² **Average annual precipitation:** 450 mm **Average discharge** (Chacabuquito): 13 m³ (May); 80 m³ (Dec); 57 m³ (1987) 11 m³ (1996);	 **Irrigated area:** 60,000 ha **Industrial Activities:** *Mining (and refining)*: copper *Industries:* food processing, oil refinery, and chemical **Population:** *Total:* 460,000 *Major cities:* Quillota (69,000), San Felipe (54,000), and Los Andes (49,000)	 **1: AC 1,** Aconcagua in Chacabuquito **2: AC 2,** Aconcagua en Romeral **3: AC 3,** Aconcagua en Puente Colmo **4: AC 4,** Las Vegas Stream



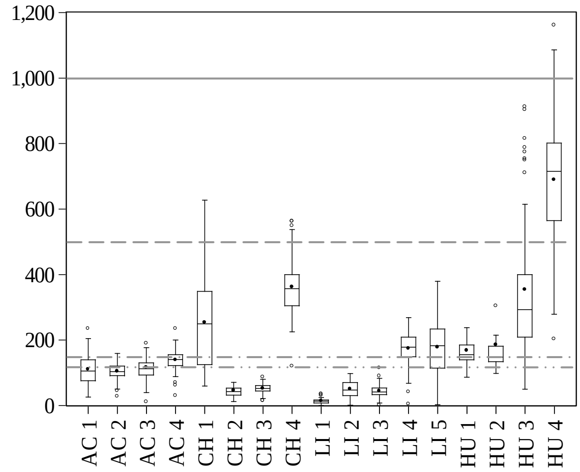
(a) Cu, mg/l



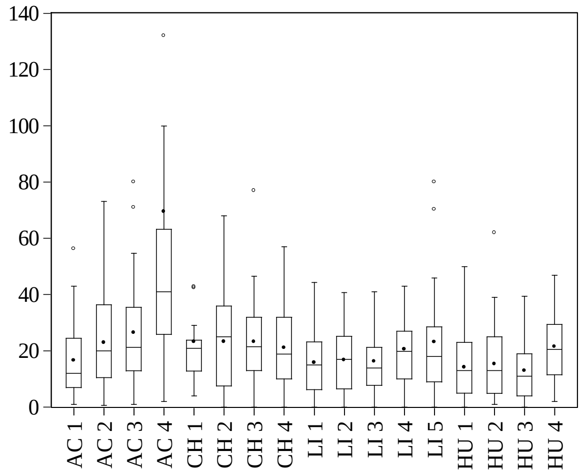
(b) Conductivity, µS/cm



(c) $N(NO_3^-)$, mg/l



(d) SO_4^{2-}, mg/l



(e) COD, mg/l

Legend:

AC = Aconcagua; CH = Choapa; LI = Limari; HU = Huasco

		Cu, mg/l	Conductivity, µS/cm	SO_4^{2-}, mg/l
——— (solid)	Class 3*)	1	2250	1000
— — — (dashed)	Class 2*)	0.2	1500	500
—·—· (dash-dot)	Class 1*)	0.009	750	150
—··— (dash-dot-dot)	Exceptional class*)	<0.0072	<600	<120

*) *Upper limit according to the norma secundaria*

Remarks:

- The limit standard for $N(NO_3^-)$ and *COD* are not available in the *norma secundaria*. However, the limit standard for $N(NO_3^-)$ is available in NCh 1333 (for potable water): 10 mg/l.
- Due to display issues, almost all far outliers are not shown (except for *Cu* in Choapa, Limari, and Huasco).

Fig. 3 Comparative boxplots of 5 selected water quality parameters in some stations in the case study basins

In reviewing the *copper* boxplots (Fig. 3a), it can be observed that the surface water quality of the Aconcagua valley shows much higher values than the other basins, even though mining activities are also very intense in the Chaopa. the highest contamination can be observed in the upper watershed which is directly relted to the the location of the larger mines. It has to be considered also that the sample size regarding *Cu* from the Aconcagua valley is around 20% higher than in the other catchments (statistics are not shown); station CH1 in Choapa, for example, was established more recently, i.e. in 2000 when the mine of Pelambres started to go in operation. The median values of *Cu* in Choapa are generally in class 2 (according to the guidelines for the secondary regulation), except for CH1 which is in class 3. It is obvious that the decision which was taken by DGA to establish a new station downstream the mine (CH1) has been adequate and should be remained. The mean values of the other catchments are all within the limits of class 2. The maximum values of Cu in Aconcagua and in the two upper stations of Choapa can be found in class 3 and above.

Nitrogen-nitrate $(N(NO_3^-))$ is much higher in the Aconcagua valley than in the other basins. Nevertheless, downstream of agricultural areas**,** for all the four basins, the values are in general getting higher (see *AC2*, *AC3*, *AC4*; *LI2*, *LI3*; *HU2*, *HU3*; and *CH3* in Fig. 3c). Looking at the northern watersheds (*LI* and *HU*), it is interesting to see that the more developed and more intense agriculture of the watershed *(e.g. LI),* the less problems with *nitrogen–nitrate*. Looking at their agricultural yield and production, the most developed watershed is probably Aconcagua, with the highest *N*-problems due to the excess of fertilization.

The *COD* values show a similar pattern as N(NO3-), in the sense that values in the Aconcagua are all higher than in the other basins; the only one which is in the same range is the upper station in Choapa basin.

The values for *conductivity* show similar pattern with *sulphate*. The mean values of the *AC* data are all in the exceptional class or in class 1. *CH1* (located downstream of extensive agriculture) and especially *CH4* (located downstream of old mine deposits), make some exceptions. *LI4* and *LI5* are at the downstream part of an intensive agricultural area in the valley. The values of *HU* stations are higher compared to stations in other watersheds at similar locations. This may be explained with higher evapotranspiration and lower rainfall in the Huasco watershed. The conductivity of *HU4,* however, is clearly influenced by the intrusion of sea water at the mouth of the river.

From the above analysis, it can be concluded that the major characteristics and water quality issues in the four river basins are relatively similar. Major water quality impairments can be expected from intensive irrigated agriculture (fertilizers, pesticides), mining (heavy metals) and municipal wastewater (microbial and organic pollution). Salinization of surface water seems to be no relevant issue so far, while sulphate concentrations are often quite elevated due to a combination of high background levels and additional anthropogenic impacts especially from domestic wastewater.

Differences exist regarding the extent of impairments. Agriculture is more intensive and more significant in the Aconcagua and Limari watershed. Domestic pressures exist in the Aconcagua watershed, while in the other watersheds the populations are quite low, and impairments due to domestic wastewater are less pronounced except under very low flow conditions. Here the general trend of lower discharges in the more northern river basins is important with the Huasco having a discharge of a mere 4 $m^3 s^{-1}$ at average and much lower during dry periods due to a pronounced seasonality [CADE-IDEPE. 2004a].

The identified water quality issues can be grouped into three main areas: impacts resulting from agriculture, settlements, and mining. Some general conclusions can be drawn from this analysis regarding the location of monitoring sites as response to the spatial occurrence of pollution sources, and regarding the indicators which should be measured at the various locations as response to the type of expected pollution. However, regarding adequate monitoring frequencies little can be said since the variability and seasonality of data is yet unknown. In order to derive recommendations for improved monitoring the application of watershed modelling to determine spatio-temporal variability of parameters is an option, which is presented in the following section.

4. Redesign of the Water Quality Monitoring Network in the Aconcagua Watershed

As described in section 1, monitoring programmes need to be (re)designed in order to be responsive to the information demands set out by the water quality management system and to the type and nature of the water body under scrutiny. Suggestions for an adequate and science-based approach to the design of water quality monitoring systems can be found in many standard texts and specialized articles (compare SANDERS et al. (1983), WARD et al (1990), HARMANCIOGLU et al (1999), STROBL and ROBBILARD (2007)).The three major questions which need to be answered for monitoring design are: *where to sample?, what to measure?, how often to sample and analyse?.*

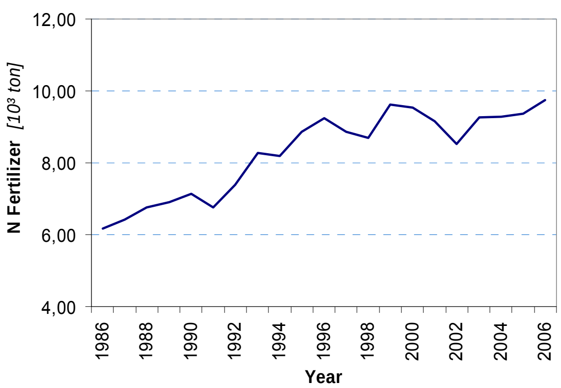
Virtually all methods described in literature for water quality monitoring design demand a profound understanding of the temporal and spatial dynamics of the various constituents within the system under observation – in our case the watershed. For most watersheds worldwide -especially in developing and emerging economies as in the four case studies presented above- neither a high spatial nor temporal coverage of observations of water quality and other elements is available. Hence, other ways must be found in order to create a more complete system understanding. Recent developments in GIS and modelling capacities allow even for larger watershed to estimate the variability of parameters over long time periods at high spatial and temporal resolutions.

The following section describes an approach to optimise the water quality monitoring network in the Aconcagua watershed based on a comprehensive modelling and GIS analysis. It takes the constituent nitrate as an example. However, a similar approach may be applied for other parameters.

A watershed water quality model was set up for the period 1986-2006 in order to produce a relevant data base for a scientifically sound monitoring design. In order to describe the spatio-temporal behaviour of nitrate in the Aconcagua watershed, several data sets were elaborated and analysed within a GIS framework. They encompass digital elevation data, network model describing the hydrological system by nodes and reaches, run off and water use time series, land use dynamics, as well as point and diffuse sources of nitrogen covering the period of 1986 to 2006. (Fig. 4 and Fig. 5 show examples of driving forces nitrogen fertilizer inputs and location of wastewater emissions)

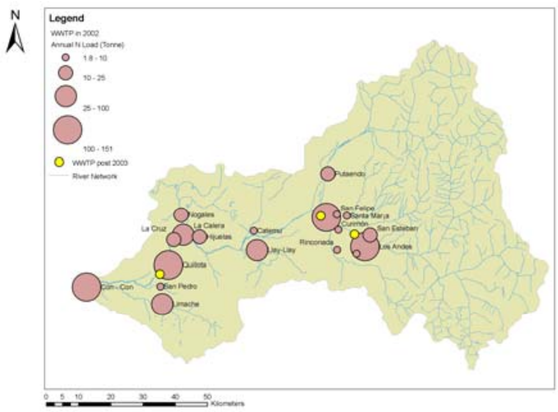
The nitrogen sources entering the river were quantified for agriculture, industry and municipalities. Using population data and historical data on land and fertilizer use time series were produced. Later these time series for nitrogen inputs were superimposed with time series of river discharges partially based on measured discharges and partially on modelled runoff and on the water balances at each node of the system according to water inflows and abstractions. As a modelling framework Mike Basin (DHI 2005) was used.

The resultant time series of nitrate concentrations for several points in the hydrological network was used to determine the nitrate variability in space and time within the river network and based on that to derive conclusions for monitoring design, especially regarding the selection of monitoring locations and frequencies.



Data based on long term changes on cropping pattern and overall change of fertilizer applications

Fig. 4 Temporal dynamics of fertilizer use (1986-2006)



note: since 2003 new treatment plants were constructed, outlets marked in yellow

Fig. 5 Spatial distribution of nitrogen inputs and amounts through municipalities

Site selection

The modelling results could be used to determine spatial correlation of time series of neighbouring stations. The stations Romeral and San Felipe, for example, showed a significant correlation (correlation coefficient = 0.76, compare Fig. 6). In such a case it can be recommended to exclude one of these stations from the system. Furthermore the results of the nitrate modelling could be used to determine the likelihood to surpass certain limit values. This way priorities of stations can be determined with respect to the likelihood that critical values may be reached. Modelling showed, for example, that in those watersheds heavily impacted by agriculture, the likelihood of nitrate contamination is higher, providing higher priorities to these stations.

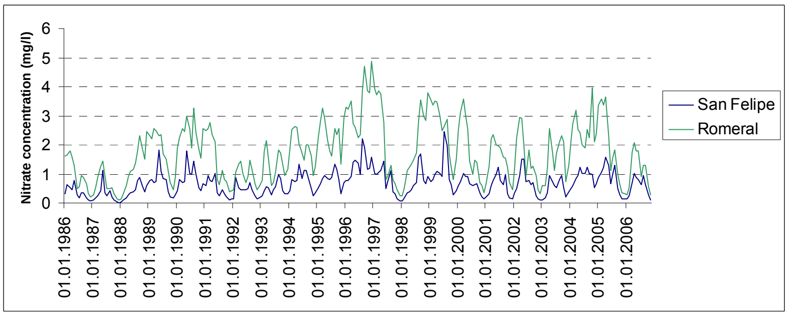


Fig. 6 Graphs of simulated nitrate concentrations at two stations in the Aconcagua

Modelling of nitrate 1986-2006, variance and measuring frequencies

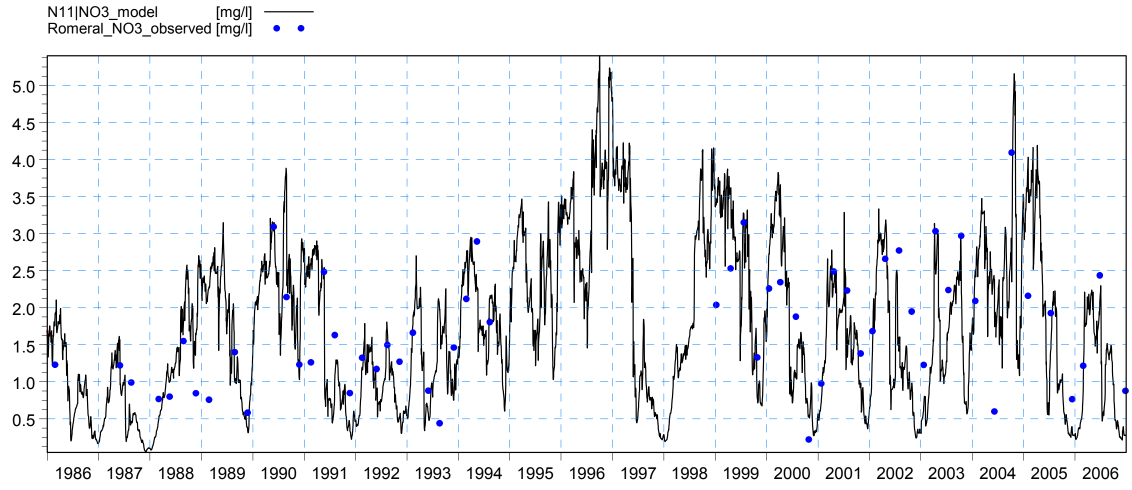
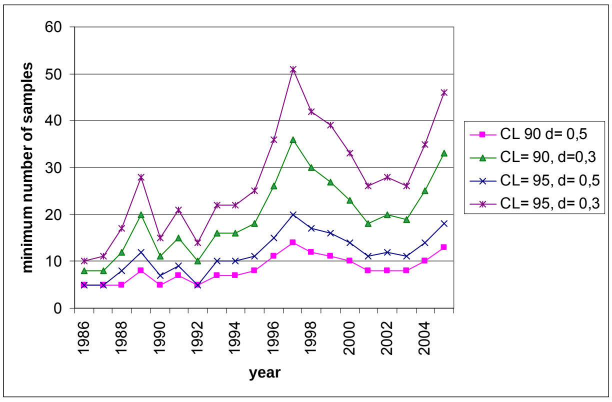


Fig. 7 Results of the modelling of nitrate concentrations 1986 - 2006

The modelled time series for nitrate (Fig. 7) was used to derive the variance of nitrate concentrations for each hydrological year. Sub-sequently the variance served as a basis to calculate the minimum number of samples which needed to be taken in order to provide reliable estimates of a mean. Years with higher variability of modelled nitrate concentration require higher number of samples in order to reach the same statistical level of confidence (Fig. 8).



CL= confidence level, d= permissible error,

Fig. 8 Required number of samples in hydrological years 1986-2006 according to different statistical criteria for Romeral station

Formula applied to calculate minimum number of samples: $n = s^2 \frac{t^2_{(\frac{\alpha}{2})}}{d^2}$

Where:
n = minimum number of measurements
d = maximum permitted error ($\bar{x}$ - μ)
t = value t-Student for the selected significance level (α)
s^2 = variance

The above approach shows that watershed system analysis and modelling can be useful instruments in order to support monitoring design. In this particular case study it reveals that monitoring frequencies –at least for the parameter nitrate- should be much higher than the current four times a year in order to provide a statistical confidence of the measured data. Depending on the statistical criteria at least biweekly sampling is suggested. On the other hand in a river like the Aconcagua at some upstream and downstream stations nitrate concentrations are spatially correlated which would allow to exclude a monitoring station from the network or at least to monitor it rather sporadically.

5. Conclusions and Outlook

This paper lays down an overview of the water quality issues in the major river basins of North-Central Chile. Main impacts are agriculture, mining and municipal water uses, each leading to different water quality related problems and consequences for monitoring design. A case study on the Aconcagua showed how a science based approach can be employed in order to support the design of water quality monitoring systems.

The legal framework in Chile provides guidance on how to manage water quality of natural waters in order to protect human and ecosystem health. The "secondary regulations" which are the central instrument for the protection of natural waters adequately provides the opportunity to control water quality and in the case of deterioration to take measures to improve it. However, the adequate forms of water quality monitoring still need to be found.

For the watersheds under study some general conclusions can be drawn: monitoring site selection should reflect the spatial distribution of potential hazards, frequencies should be increased since the temporal variability of the constituents is generally high, some sites need to be analysed for spatial correlation to verify if in some cases stations may be omitted. These issues were underpinned by a case study on improving the site and frequency selection for monitoring nitrate based on a GIS and watershed modelling approach in the Aconcagua watershed.

General monitoring guidelines should be developed for the whole nation including: methods for site, frequency and variable selection, QA/QC of labs, sampling and preservation techniques.

Important to note is that water quality monitoring should not be considered as an isolated activity but as part of the wider information management in a region or nation, where diverse data types at different scales need to be managed and interpreted in a systematic and holistic manner. Here, water quantity data as well as other environmental and socio-economic information need to be managed and assessed comprehensively. FLÜGEL (2007) elaborates the requirements for an adaptive integrated data information system (AIDIS) as a basis to implement IWRM at the river basin scale. Monitoring results need to be integrated in such kind of information system in order to serve for comprehensive modelling and decision making processes.

Climate change is likely to increase overall temporal variability of water discharges and consequently of water quality constituents (Souvignet et al 2008). These changes will call for an adaptive strategy of monitoring design.

Regarding future research and towards an improved monitoring design, it is important to perform in depth analysis regarding spatial and temporal correlations between sampling stations within each watershed as well as between them. Methodologies such as multivariate analysis (cluster, principal component), self organizing maps and others are intended to be used by this contribution's research group. This, it is expected that a more comprehensive understanding of the processes controlling water quality will be attained including anthropogenic impacts (soil use, mining) and natural factors. In particular, factors such as climate and geology that act on a regional and not only watershed scale.

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