Hydrometric network design in hyper-arid areas: example of Atacama Desert (North Chile)

Elisabeth Lictevout and Martin Gocht

ABSTRACT

Efficient water management needs hydrological information provided by hydrometric networks. In arid and mountainous regions, hydrologic models for water resources management and forecasting require a large amount of data due to the temporal and spatial heterogeneity of hydrometeorological variables. The interaction of complex oceanic and atmospheric circulations makes North Chile one of the world's most arid areas. Since the onset of large mining projects in the nineties, constant population and economic growth generates high pressure on water resources. The existing regional scale hydrometric network in Tarapacá allows for the description of general characteristics and trends at national, but not at water basin level and therefore does not meet actual demands. Methods for hydrometric network design were designed for temperate areas in general. Based on a review of existing methodologies, the paper identifies multi-criteria analysis (MCA) as best adaptable to the context. It develops a methodology for hyper-arid areas, complementing MCA with stakeholder and geographic information system (GIS) analysis, as well as optimization. The paper optimizes the existing hydrometric network in the Tarapacá region, characterized by strong constraints regarding access and topography. Three MCA techniques are compared. The result is an optimized network consisting of 36 rainfall and 21 streamflow stations.

Key words | arid, hydrometry, multi-criteria analysis, rain gauge, stakeholder, streamgauge

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INTRODUCTION

Efficient water resources management needs hydrological information collected through hydrometric networks. These are a group of data collection activities and devices, designed and operated to yield hydrological information for different purposes: spatial planning, design and management of water resources and related activities, which enable informed decision-making (WMO 2008). Increasing and conflicting water demands in a context of climatic and land use changes require the availability of appropriate and sufficient hydrologic data.

Mishra & Coulibaly (2009) reviewed several studies on the impact of hydrometric network density on estimation accuracy. They demonstrate that accuracy significantly deteriorates below a certain number of gauges and does not significantly improve above it. Furthermore, spatial location and distribution are at least as important as density and affect the accuracy of gauge-based areal estimates. Errors may be caused by inadequate temporal resolution, poor spatial coverage or location as well as instrument error (Mishra & Coulibaly 2009; Volkmann *et al.* 2010).

Topography and orography play a major role in rainfall distribution (Michaud *et al.* 1995). In arid and mountainous regions, a major characteristic of rainfall is the occurrence of intense convective storms that develop very rapidly over high terrain. Precipitation events are highly localized, heterogeneous in space and time and strongly influenced by topographic patterns. Therefore, the observation of temporal and spatial heterogeneity of hydrometeorological variables

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requires a larger amount of data than in lowlands or regions where frontal storm systems govern precipitation. Most existing observational networks in arid and mountainous regions do not adequately capture the variability of precipitation as they tend to be sparse and sample only locations that are relatively accessible and at low altitudes (Volkmann *et al.* 2010). Furthermore, streamflow monitoring is particularly challenging in arid areas; the hydrologic regime and stream morphology are characterized by low, ephemeral or intermittent flows with changing gullies in very wide cross sections shaped by flash floods. Inter-annual variability is extremely high.

Design of hydrometric networks has received considerable attention since the 1970s (Mishra & Coulibaly 2009). Numerous methodologies have been developed to respond to the diverse problems of network-design in different contexts, usually for temperate areas, characterized by availability of data-records from different sources, abundant resources, easy access and high security. Applicability of a certain method depends on numerous factors: data and budget availability, population density and economic potential of a region, objectives of the network, climatic and geographic characteristics, etc. WMO (2008) developed guidelines for optimal network design, which include recommendations for minimum densities of rain- and streamflow gauges for different climatic and geographic zones.

For many years, much effort has been put into the development of statistical methodologies (Nunes *et al.* 2004) that seek to minimize the overall uncertainty about rainfall or streamflow modelling error (Chacon-Hurtado *et al.* 2016). Among them, the most widely applied methods are the variance reduction approach and the dimension reduction methods. Odom (2003, 2005) used the principal component analysis (PCA) and clustering-based method which allow for the determination of the degree of data redundancy among sampling sites and assessment of the benefits of primary site data collection.

Other widely used methods are based on spatial interpolation techniques: Kriging allows estimation of the value at an unobserved location as a weighted average of observed values based on the key assumption of stationarity (Fisher 2013). Adhikary *et al.* (2015) used Kriging for the optimization of a rain-gauge network. They found the removal and relocation of redundant stations to improve network performance. Furthermore, external drift kriging (KED) allows for the use of spatially continuous secondary data to improve the interpolation of primary point-scale observations: Volkmann *et al.* (2010) improved rainfall interpolation by incorporating secondary stationary (elevation) and dynamic (radar) data. However, the assumptions of stationarity, spatial continuity and homogeneity limit the applicability of statistical and geostatistical approaches to homogenous hydrologic regions. These do not hold in arid and mountainous catchments where biases in the rainfall distribution on both short and long time scales occur (Michaud *et al.* 1995; Mishra & Coulibaly 2009; Volkmann *et al.* 2010).

Entropy-based methods seek to minimize transinformation between stations: observations should be independent from each other. Small transinformation values indicate the stations to share less common information and to be more independent, high values indicate a duplication of information (Mishra & Coulibaly 2009). The merit of entropy theory is its direct definition of information and quantification of uncertainty (Li *et al.* 2012), since the purpose of network design is to reduce the uncertainty associated with the estimation of variables at non-monitored locations (Alfonso *et al.* 2010).

Halverson & Fleming (2015) made one of the first attempts to apply network theory to the optimization of streamflow gauges based on small membership community (efficient measurements), high betweeness (capture of the hydrological processes heterogeneity at larger scale) and index stations with a large number of intracommunity-links (network with some degree of redundancy and therefore resilient to station failure) (Halverson & Fleming 2015; Chacon-Hurtado *et al.* 2016).

Methods using basin physiographic characteristics exploit the correlation between topography and spatial distribution of mean annual precipitation as well as the correlation between rainfall and runoff. The regression equations in many similar regions tend to have similar slope coefficients and similar intercept values, indicating that local climatic conditions govern the relationship between topography and the spatial distribution of precipitation. However, they differ for convective and advective environments (Mishra & Coulibaly 2009).

Optimization approaches are increasingly used in network design since optimally locating hydrometric stations can be seen as a multi-objective optimization problem where several criteria need to be satisfied simultaneously (Li *et al.* 2012). The advantage of multi-objective optimization and multi-criteria analysis (MCA) is their provision of different feasible solutions under different scenarios (Alfonso *et al.* 2010). A wide range of MCA techniques and optimization tools has been applied to hydrometric network design either for maximizing benefit from the network or minimizing its cost. Volkmann *et al.* (2010) postulate a need for optimization methods in regions where a priori guidelines cannot be applied with confidence.

MCA consists of a group of techniques for evaluating, through ranking or scoring, the overall performance of decision options against multiple criteria measured in different units. Weights can be assigned to criteria to differentiate relative importance. MCA techniques improve the transparency, auditability and analytic rigor of decisions (Hajkowicz & Higgins 2008). Hajkowicz & Collins (2007) described MCA process in eight steps: (1) selection of decision options; (2) selection of evaluation criteria; (3) generation of performance measures; (4) transformation of criteria into commensurate units; (5) criteria weighting; (6) ranking or scoring the options; (7) sensitivity analysis, and (8) decision based on MCA model results. Since the 1960s, many techniques have been developed to solve MCA problems. Recent review papers identify hundreds of them (Hajkowicz & Collins 2007, 2008; Huang *et al.* 2011). Comparative studies have shown that results from different MCA methods are in close agreement and that there is no clear methodological advantage of any single technique. The techniques most commonly used in the environmental field are multi-criteria value functions, outranking approaches, distance to ideal point methods, pairwise comparison, and fuzzy set analysis.

Other MCA techniques have been used for hydrometric network design, like questionnaire-based stakeholder surveys or sampling strategies. Surveys allow the assessment of the need to continue or abandon gauging stations depending upon the type of data requirements of the stakeholders in the basin. They highlight a set of parameters, e.g. record length, flood prediction accuracy, data usability for certain projects. The stations are assessed with regard to their contribution to the full set of priority parameters. The higher the total points of a particular station, the higher its relative value and benefit (Davis *et al.* 2010). Methods driven by sampling strategies investigate the number of gauges, rainfall sampling, and discharge measurement intervals to assess the effectiveness of different sampling options (Mishra & Coulibaly 2009). For example, for contexts with high space-time heterogeneity of precipitation, Volkmann *et al.* (2010) propose a high spatial resolution sampling campaign before the network design is accomplished.

In recent years, geographic information systems (GIS) have been increasingly used in network design, particularly as a complementary tool in MCA as reported by Huang *et al.* (2011). GIS analysis provides a complete set of feasible locations based on geographical criteria, e.g. users' needs, distances, land use, slope, elevation, etc. The capacity of GIS for integrating spatial information makes it well suited for decision-making procedures that have to account for multiple factors (Shepherd *et al.* 2004).

Mishra & Coulibaly (2009) detected a trend towards the combination of different methods, either using the output from one method as an input into another model or using the different methods in parallel in a MCA. Chacon-Hurtado *et al.* (2016) proposed a framework for classifying the different approaches. They suggested that the driving criteria should consider model performance in order to ensure that the model adequately represents the states and processes of the catchment, thus reducing model uncertainty. They considered different scenarios, namely station relocation, augmentation and reduction.

Each design-method introduced above privileges certain aspects of the set of features (constraints) that influence the variables to be measured and monitored, or privileges certain criteria that influence the performance of a hydrometric network: access and distance, security, operation and maintenance cost, value of information generated for users, high heterogeneity and variability of rainfall and other hydrometeorological variables, physiographic characteristics, redundancy, gradients, etc. The complete set or subsets of those, based on the context at hand and objectives of the network, may be considered advantageously as competing criteria. Therefore, the optimization of a hydrometric network in a multi-objective optimization framework appears the most promising approach in hyper-arid areas.

The overall objective of this paper is to contribute to the improvement of water resources knowledge and management in hyper-arid areas through the development of an MCA-based design methodology adapted to the context. Its aim is to propose a rain and streamflow gauges network for Tarapacá, providing representative, reliable and sufficient hydrometric data for management and planning. Building on an analysis of the existing regional hydrometric network that revealed its deficiencies and their causes, three approaches to MCA are applied and compared: weighted summation (WS), pairwise comparison and composite programming (CP). An optimized network for Tarapacá is developed. The results and the lessons learned during design lead to a discussion of possibilities and limitations.

THE STUDY AREA

Northern Chile's Atacama Desert is one of the most arid regions of the world due to the interaction of complex oceanic and atmospheric circulations (Weishet 1975). A part of it is the 42,223 km^2 Tarapacá region, located between 18°56′ and 21°36′ south and 68°24′ west of the Pacific Ocean (Figure 1(a)).

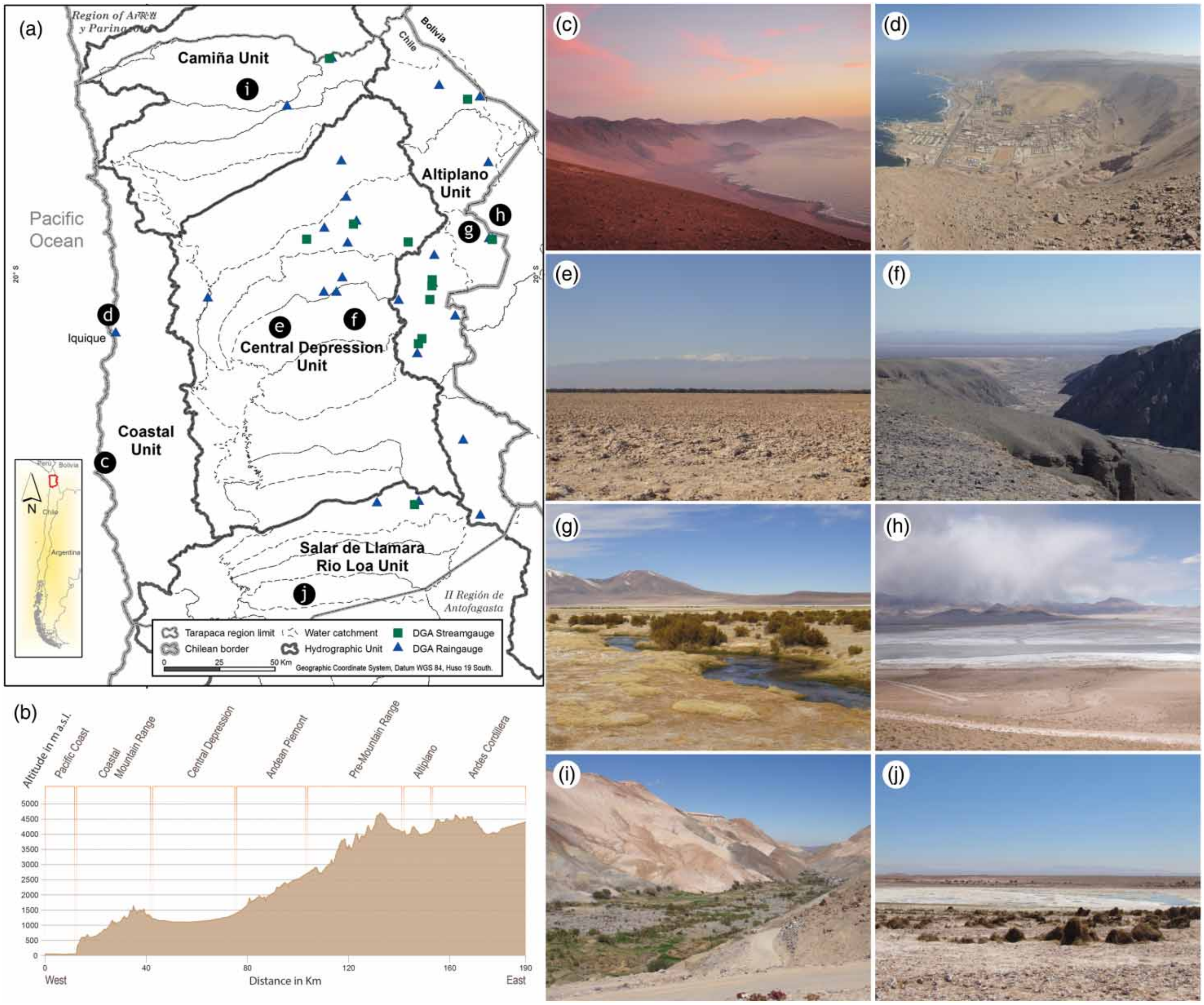

Figure 1 | (a) HU, catchments and existing official hydrometric network of Tarapacá. (b) Topographic profile. (c)–(j) Pictures of Tarapacá HU.

Figure 1(b) shows the region topographic profile to be shaped from west to east by the Coastal Cordillera (1,100 m a.s.l.), the Central Depression (1,000 m a.s.l.), the Pre-Cordillera (4,000–5,000 m a.s.l.), the Altiplano (3,700–4,500 m a.s.l.) and the Andes Cordillera (5,000–5,600 m a.s.l.). Average annual rainfall is almost nil on the Coast (0.45 mm), Coastal Mountain Chain (56 mm) and Central Depression (0.7 mm), leading to arid and hyper-arid climatic conditions. The lower limit of precipitation is between 2,000 and 2,500 m a.s.l. In the high parts of the pre-mountain range and the Altiplano, annual average precipitation is around 80 mm and increases to 150–180 mm above 4,130 m a.s.l. (Andes Cordillera; Lictevout *et al.* 2013). Rainfall events have an Atlantic Ocean and Amazonian basin origin (Chaffaut *et al.* 1998). During austral-summer (December–March), intense and sporadic rains generate flashfloods that spread downstream through the steep V-shaped valleys (*quebradas*) and alluvial fans into the Central Depression.

The *quebradas* incise the Pre-Cordillera from the eastern high reliefs downward to the Pampa del Tamarugal-lowlands. Thin soils and steep slopes promote rapid surface runoff and interflow of summer rains and flash floods with high sediment load. Tarapacá has 18 water catchments grouped in five hydrographic units (HU), based on hydrographic, physiographic and climatic characteristics (Figure 1(a)). Figure 1(c)–1(j) shows typical sights: The Coastal unit consists of arheic catchments (no runoff). The Central Depression Unit is an endorheic catchment where superficial runoff generated in the Pre-Cordillera evaporates or infiltrates before reaching the Central Depression except during extreme rainfall events. They naturally discharge into the *salars* (salt flats) located in the lowest point of the Central Depression. The Altiplano unit consists of six endorheic water catchments with a relative flat topography, where runoff discharges in the *salars*. The Camiña and Salar de Llamara – Rio Loa unit are exhoreic catchments with permanent flows, discharging in the Pacific Ocean.

With the onset of large mining projects in the nineties, constant population and economic growth generated strong pressure on water resources. In northern Chile, water demand exceeds supply today, boosting scenarios of competition and conflict over water uses (Lajaunie *et al.* 2011). The Chilean Water General Directorate (DGA), the state agency in charge of the management and administration of water resources, operates and disseminates the information generated by the official hydrometric network. It allows the identification of general characteristics and trends of water resources at national and regional, but not at water basin level. Recorded data exhibit deficiencies both in quantity and quality. To mitigate and remedy the hydrological data gap, some stakeholders have developed their own local networks.

METHODOLOGY

As a first step, a stakeholder analysis identified the relevant persons, groups and organizations with an interest in the data and information that is and will be provided by the network. Stakeholders were classified into three categories, according to their degree of involvement:

1. Co-operators are actively involved in the network design with direct participation in and contribution to the process.
2. Co-thinkers provide information and inputs to the monitoring network design process and are a source of knowledge.
3. Co-knowers do not play an active role in the process but should be informed about the process and results.

The second step was a critical assessment of the existing regional hydrometric network in order to evaluate the consistency, accuracy and representativeness of the data generated by the network. Besides the density, we investigated whether rain gauges are located in open and flat areas, in an accurately horizontal plane, away from obstructions, i.e. at a distance not less than twice (ideally four times) the height of objects that might disturb the airflow. According to Shepherd *et al.* (2004), the largest source of rain gauge error, after sampling error, is due to wind-induced precipitation loss. For streamflow stations, we monitored design and structure of the station, including technology and equipment, its hydraulic control and stability as well as sensitivity of the cross-section.

The third step consisted of identifying the hydrometric network objectives: The main objective is an increase of the hydrometric data utility for basin-wide water management at minimum cost (objective function). Specific objectives were defined in a participatory workshop with local decision-makers.

The fourth step was the selection of decision options (alternatives). Existing stations (operational or not) and all feasible locations allowing for installation of a monitoring station were considered as a decision alternative. In Tarapacá, the number of feasible locations is limited due to constrained access in general and to stream morphology in particular: frequently streams exhibit very wide cross-sections with low or intermittent changing gullies, hindering successful installation of streamflow gauges. All feasible locations were identified by GIS analysis and satellite images review first, and validated by field visits afterwards. Given those constraints, at least one feasible location per catchment was sought for (or one per sub-catchment for catchments exceeding 10,000 km^2). However, in some catchments, even this was not possible.

The fifth step comprised selection and comparison of three MCA-methods: WS, pairwise comparison (Analytic Hierarchy Process (AHP)) and CP.

The WS technique as the most simple and widely applied MCA technique (Hajkowicz & Higgins 2008) is part of the Multi-criteria value functions, often expressed as:

$$u_i = \sum_{j=1}^{m} v_{i,j} w_j \tag{1}$$

The weights (w_j) are non-negative and sum to 1, and $v_{i,j}$ are transformed performance scores on a scale of 0 to 1 where 1 represents best performance. The overall performance score is given by u_i.

The pairwise comparison techniques involve comparing criteria and alternatives in every unique pair giving $n(n–1)/2$ comparisons. The comparisons allow the estimation of criteria weights and decision option performance scores. Various scaling systems are applied. One of the most widely accepted is the AHP. Decision makers or experts are asked to express preferences for one criteria over another in each pair, e.g. on a nine point scale (Hajkowicz & Collins 2007).

The CP technique belongs to distance-to-ideal-point approaches that identify optimum and pessimum values for the criteria and then the decision options closest to the optimum and furthest from the pessimum. Among these techniques, compromise programming employs a hierarchical structure. Criteria that objectively belong together are organized in groups and arranged hierarchically. CP uses a double weighting scheme to consider the importance of the maximal deviation between indicators, p, specified by the decision maker (Gocht 2007). If p is high, only the worst objective value has an influence on the distance (Maniak 2011). With a smaller value of p, better compensation of the individual criteria is possible.

$$D(x) = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_{i\,max} - f_{i(x)}}{f_{i\,max} - f_{i\,min}} \right|^p \right]^{1/p} \tag{2}$$

where $D\ (x)$ = distance D of the alternative x from the ideal point I; f_{imax}, f_{imin} = best (or ideal) and worst (or anti-ideal) value for the target criterion; $f_{i(x)}$ = value of the target criterion; w_i = weight assigned by experts to the target criterion; p = compensation factor for each hierarchical group level.

Management options are evaluated by calculating the composite distance within each group of criteria. The preferred design option is that closest to the ideal point in terms of composite distance.

For the three MCA-methods, common evaluation criteria were defined. The criteria weights were estimated by three independent experts.

RESULTS

Stakeholder analysis

Figure 2(a) presents the results of the stakeholder analysis. Co-operators are generating water-related data in the region through monitoring stations. CIDERH, CEH and CDA are research centers focused on water resources, wetlands and fog water respectively. UNAP is the regional university. They are all connected to national and international academic networks, have good relations to local stakeholders and communities but little influence on decision-making. DGA, as per its mandate, manage the official existing hydrometric network. There is no collaboration between water-related state institutions; decision-making is centralized at national level and limited by available resources. The mining companies operate private

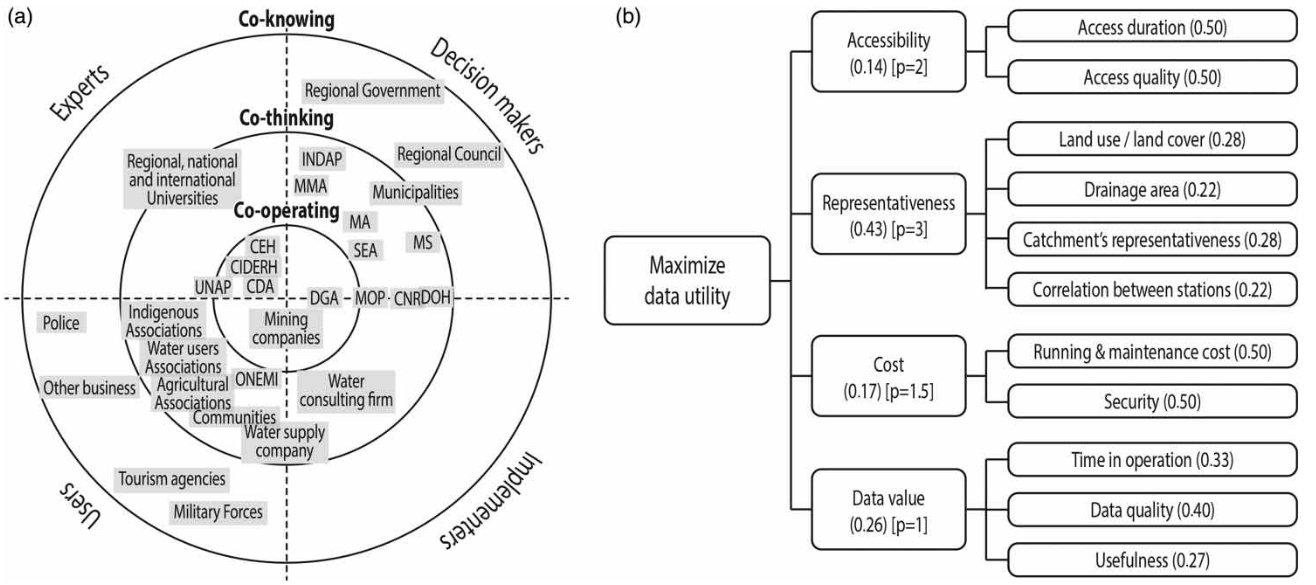

Figure 2 | (a) Target scheme of stakeholders involved in water resources monitoring in Tarapacá region. (b) Hierarchical structure, weights (figure in round brackets) and compensability (figure in square brackets) in CP.

monitoring stations for their own purposes. They are independent and have strong economic power. They, however, need official operation permits and rights of water use. This leads to a strong influence on institutional decision making and conflicts with communities.

Co-thinkers are all potential water-information users as well as the experts involved in criteria weighting. Co-knowers are regional and municipal authorities. The four quadrants – decision makers, implementers, users and experts – give information on the role of the stakeholders with regard to water resources.

Assessment of the existing hydrometric network

The official hydrometric monitoring network of Tarapacá comprises a total of 37 stations, 25 rainfall and 12 stream gauges. Twelve rain gauges are digitally equipped and provide hourly data, 13 are manually operated. Nine rain gauges with historical data series have been abandoned. Seven rain gauges are operated and maintained by other entities (mining companies, army), transferring data to the DGA. Twenty-eight per cent of rain gauges are not in a horizontal plane, 32% have obstacles nearby (cables and electric posts, trees and walls) and 28% of rain gauges are located in the bottom of the *quebradas* or on the hill slope (in the rain shadow), leading to the underestimation of rainfall quantity.

Twelve stream gauges are operated in the region, 13 with historical data record have been abandoned. Out of the 12 stream gauges, six are digital and five have a limnigraph. Streamflow stations show structural problems due to poor construction, flash flood events, or long term effects of water and environmental conditions: erosion of cross-section bottom affect 66%, 58% have a bad hydraulic control, or exhibit obstacles that do not allow proper flow into and out of the gauging section, 33% are not well located or not well designed according to their location.

A great variability in record length can be observed, ranging from one year up to 50 years: one third of the rain gauges have a record length of more than three decades and one third less than 10 years.

Rain gauges are neither evenly distributed within the Tarapacá nor within the HU. Of 27 catchments, 15 have no precipitation information at all and the rest lack precipitation registration in the catchment's head. Furthermore, 14 catchments do not have streamflow information at all. Some of the permanent streams are not monitored, records show poor data in either high or low flows. Whereas the density of stream gauges in the *Altiplano* HU is in agreement with the WMO (2008) recommendation of 967 km^2 per station, *Central Depression*, *Salar de Llamara-Rio Loa* and *Camiña* HU exhibit a density six times lower on average than recommended, negatively affecting station representativeness (Figure 1(a)).

The correlation between rain gauges in the region is weak except in the *Altiplano* (correlation coefficient R^2 between 0.8 and 0.95) where physiographic characteristics are more homogeneous. In the Pre-Cordillera (*quebradas*), correlation is weak, even between close stations ($R^2 < 0.6$). Rainfall-streamflow correlation and correlation between streamflow is even worse (respectively $R^2 < 0.2$ and $R^2 < 0.4$) meaning that the current streamflow gauges are not representative for runoff in the catchments.

MCA implementation and network design

Eighty-three decision alternatives were identified for the network, existing stations included (Figure 3(a)). Given the constraints described above and the comprehensive GIS analysis, we consider this the maximum possible number of decision alternatives in Tarapacá to be evaluated in the following.

Eleven criteria were selected for the evaluation of decision alternatives. Each criterion was evaluated quantitatively whenever possible, or qualitatively, according to its unit and evaluation scale (Tables 1 and 2). The selected criteria were common to the three MCA methods used in this work.

Based on the cross-correlation of paired stations (always lower than 0.95) and minimum station density at water catchment level, we concluded that there are no redundant stations in the network (Mishra & Coulibaly 2009; Vivekan & Jagtap 2012). Therefore, redundancy between gauges was not considered as criterion.

A questionnaire was designed for three water resources experts to assign weights to the criteria by scoring them from 1 (lowest) to 5 (highest value) (Table 3). Stakeholder preferences elaborated in the workshop were assessed by experts in this way. The final weight of each criterion is

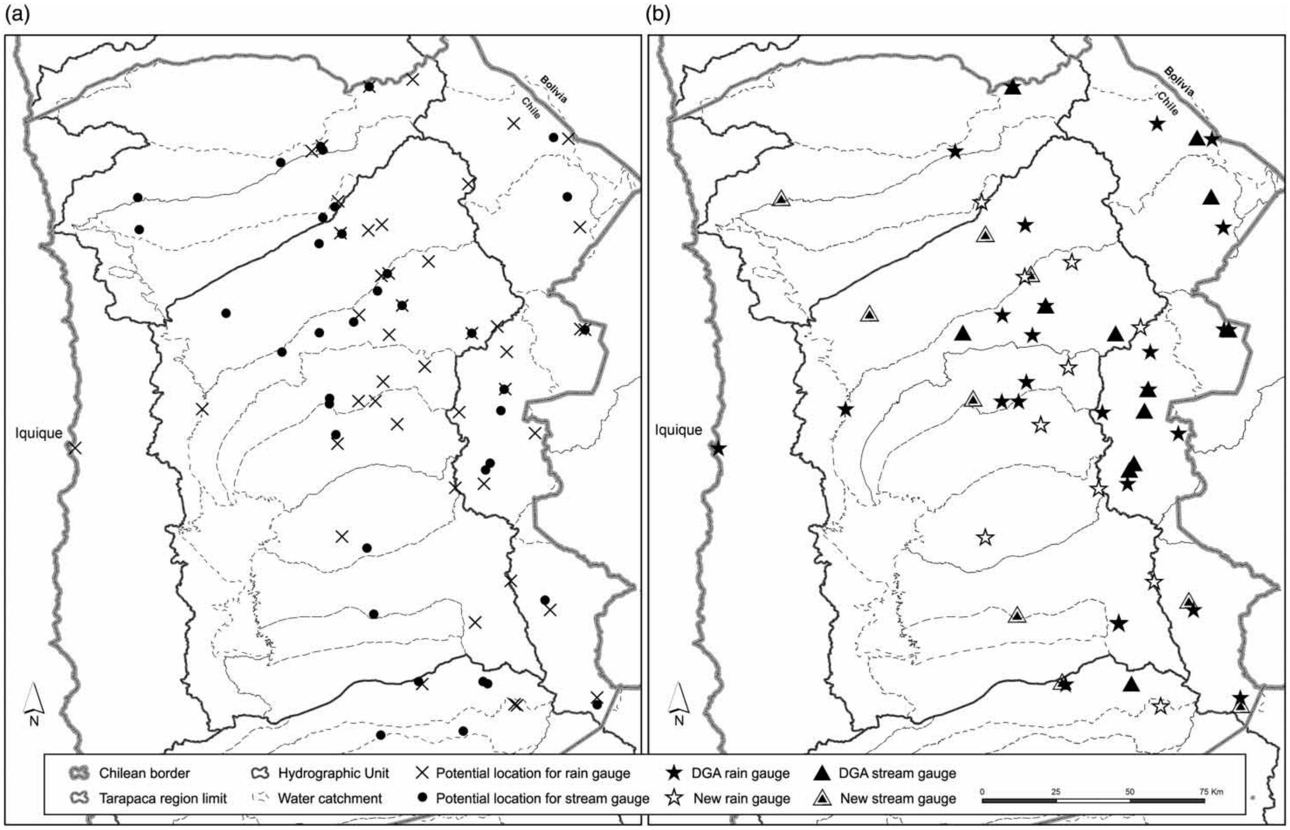

Figure 3 | (a) Decision alternatives identified for the network; (b) new optimized hydrometric network of Tarapaca.

Table 1 | List and definition of criteria selected

Criterion no.	Criterion name	Definition
C1	Access duration	Time necessary to access the station
C2	Access quality (easyness)	Asphalted roads provide easy and quick access to the locations. Most paths are unpaved tracks but accessible with 4 × 4 vehicles. Worse cases include unpaved track in bad state and access by foot
C3	Land use/land cover	Station's close environment: open space area or presence of obstacles like trees, building, walls, cables, etc. (for rain gauges)
C4	Drainage area at the station	Stream catchment, after an important stream's confluence or at the outlet of the catchment, based on Strahler's number (for streamflow stations)
C5	Catchment representativeness	Site physiography, i.e. high (over 3,000 m a.s.l.) open areas (for rain gauges). Type of stream at the site, i.e. major/permanent stream or small/temporary stream (for stream gauges)
C6	Level of correlation between stations	A low correlation (<0.5) means that the data recorded may not be representative of the area or that the distance between adjacent stations is too large for data prediction at ungauged locations. A high correlation between a station and the next closest station means data redundancy ($r > 0.99$)
C7	Running and maintenance cost	Additional cost of operating the station (depending on equipment, visit frequency, field mission organization, etc.) and maintenance (cleaning, spare parts, etc.)
C8	Security	Risk of vandalism and equipment theft
C9	Time in operation	Data record length
C10	Data quality	Data records continuity, quantity of data gaps (which hinder strongly its further use)
C11	Usefulness of the station	Value of data generated by the station for the users, on the basis of user surveys

the mean value of the weights assigned by each expert to this criterion. The process of weighting criteria differs slightly according to the MCA method: For WS and CP, the average of weights was normalized so that the sum of weights for each criterion is one. For the AHP, two criteria are evaluated at a time, in terms of their relative importance. Index values from 1 to 9 are used. A pairwise comparison matrix is elaborated and the weights of the individual criteria are calculated. The weights are already normalized.

For the compensation factor, we considered that the data value cannot be compensated and the cost can only be poorly compensated, whereas access and representativeness could be compensated by a better location of the gauge (Figure 2(b)).

Criteria weights differ according to expert and method (Table 3). For WS, the criteria with the lowest weights are access of the station and running/maintenance costs. The most important criterion is catchment representativeness.

For AHP, the criterion evaluated as least important is the usefulness of the station, followed by running/maintenance cost and security. The most important criterion is correlation, followed by representativeness.

For CP, we observed that access on one side, and running/maintenance costs and security on the other, have the same weights within their group (Figure 2(b) third level and Table 3). Usefulness again has the lowest weight within its group (below time in operation and data quality). Correlation and drainage area are less important than catchment representativeness and land use/land cover. On the second level of Figure 2(b), representativeness is the criterion with the highest weight (0.43) followed by data value and accessibility.

Decision alternatives were evaluated, according to each of the three methods, obtaining a final score for each location.

Sensitivity was analyzed by varying the compensation factors p. Two sets of p were applied: different compensation factors for each group and a low and identical compensation factor (1.5) for all the hierarchical groups. Only very slight changes were observed.

Finally, according to the scoring of decision alternatives and context knowledge, the optimal hydrometric network design was selected as presented in Figure 3(b).

Table 2 | Criteria scale and units

Criterion no.	Unit	Scale 1	2	3	4
C1	Hours	$C1 > 5$	$3 < C1 \leq 5$	$1.5 < C1 \leq 3$	$C1 \leq 1.5$
C2	Access	*Bad access* (only foot access. Station may not be accessible during part of the year)	*Regular access* (access by 4 × 4 vehicle but track in bad state. Station may not be accessible during part of the year)	*Good access* (unpaved track)	*Very good access* (major road or close to)
C3	Existence of obstacles	*Bad location* (presence of trees, building, cables)	–	–	*Very good location* (no obstacles)
C4	Strahler number	Station not located in strategic area (small affluent, before main confluence, etc.). Strahler number = 1	Station located upstream. Strahler number = 2	Station located after a major confluence. Strahler number = 3	Station located at the basin outlet. Strahler number >3
C5	Location	*Bad representativeness*: rain gauge in the valley bottom surrounded by hills. Stream gauge on a small and non-permanent tributary	*Regular representativeness*: rain gauge on the hill slope, surrounded by hills. Stream gauge on a small but permanent tributary	*Good representativeness*: rain gauge on the hill slope, with no hill shadow. Stream gauge on a main but non-permanent stream	*Very good representativeness*: rain gauge in high and open areas. Stream gauge on a main permanent stream
C6	r	$r < 0.5$	$0.5 \leq r < 0.65$	$0.65 \leq r < 0.8$	$r > 0.8$
C7	Currency	*High* (new station located in area of difficult access)	*Regular* (new station but in area of easy access)	*Low* (new station nearby existing stations)	*Very low* (existing stations)
C8	Risk degree	*High risk of vandalism/ equipment theft* (station out of inhabited area visible from road or major path)	*Medium risk* (station out of inhabited area but not visible from roads and major path)	*Low risk* (station located near inhabited areas)	*No risk* (station located inside a private area)
C9	Years	$C9 < 5$	$5 \leq C9 < 10$	$10 \leq C9 < 30$	$C9 \geq 30$ years
C10	Ratio full years data/total number of years	$C10 < 50\%$	$50 \leq C10 < 80\%$	$80\% \leq C10 < 100\%$	$C10 = 100\%$
C11	Percentage of users' approbation	*Low* ($C11 < 25\%$)	*Medium* ($25\% \leq C11 < 50\%$)	*Good* ($50\% \leq C11 < 75\%$)	*High* ($75\% \leq C11 < 100\%$)

Table 3 | Criteria weights obtained according to method used

		Weight		
Criteria		**WS**	**AHP**	**CP**
Access	01 Access duration	0.08	0.09	0.50
	02 Access quality			0.50
03 Land use/cover		0.11	0.1	0.28
04 Drainage area		0.12	0.11	0.22
05 HU representativeness		0.13	0.14	0.28
06 Level of correlation		0.1	0.16	0.22
07 R/M cost		0.08	0.06	0.5
08 Security		0.1	0.08	0.5
09 Time in operation		0.11	0.13	0.33
10 Data quality		0.1	0.12	0.4
11 Usefulness of the station		0.1	0.05	0.27

DISCUSSION

Our study supports the hypothesis that ranking differs only slightly according to the method applied. In general, the group of best scored alternatives is similar for the three methods, although the position within the group may differ. Actually, WS and AHP methods give more often similar results than CP.

AHP and WS emphasize the location of the station (representativeness) while CP prioritizes existing stations with data records over new stations with no or short data records. The sensitivity analysis showed that this difference is not due to the compensation factor.

The challenge of optimizing an existing hydrometric network lies in the trade-off between data value and station representativeness: should a station with long data record be relocated for better data accuracy, consequently losing the historical record? While station relocation is justified for redundant stations, the decision is less straightforward when the problem is a bad sampling site, affecting accuracy and representativeness of the data generated. This problem is more prominent in arid areas, where the high spatio-temporal heterogeneity of rainfall and streamflow entail long data series and a higher number of sampling sites for an appropriate characterization of processes. This dilemma is reflected in the results of the different MCA methods and could be solved by a consensus between experts and main decision makers on the criteria definition and weighting, i.e. stakeholder preferences.

The set of scored decision alternatives included all existing, as well as abandoned stations and feasible locations preselected through GIS analysis and field visits. The preselection in new sites is an important stage of the process with a strong impact on the final results. In our work, preselection resulted in a complete set of feasible locations in the region and a subset suitable for streamflow station installation.

It is the specific value added by GIS analysis that a set can be considered as complete given the geographical, geomorphological and climatic constraints. Therefore the optimum network is necessarily a subset of the decision alternatives. It might change only due to changing stakeholder preferences, but not due to additional feasible locations.

The optimized network consists of 36 rainfall stations, versus 25 currently and 21 streamflow stations, versus 12 currently. One rain gauge was abandoned, while seven of the 11 'new' rain gauges are existing rain gauges owned by research centres (four) and mining companies (three). Out of the nine new streamflow stations, three are existing stations owned by mining companies. Financial evaluation was carried out for repairing deficient structures and replacing manual equipment by digital recording devices with data transmission to reduce visit frequency. It was recommended to separate rain gauges from obstructing features where possible. In that way, the implementation of the optimized hydrometric network will add minimal additional burden to the operation and maintenance budget of DGA.

The work demonstrated key points to be taken into account when applying MCA in this domain:

- Different MCA methods tend to reach the same results (alternative scores), with slight differences. This is in line with the literature review.
- These differences seem to originate from the process of criteria definition and weighting, which appears to be a key stage of MCA, whatever technique used.

Each expert was asked to weight the defined criteria beforehand. This study corroborated that the process of weighting criteria is subjective and sensitive. Cetinkaya & Harmancioglu (2014) emphasize the subjectivity of the weighting process which is influenced by the 'weighters', therefore directly affecting the results.

Consequently, stakeholder preferences, subject to the context and the objectives of the hydrometric network, should be identified and agreed upon by group consensus between experts and key decision-makers. The stakeholder analysis, being a key success factor in this respect, should be carried out very carefully in order to identify all relevant stakeholders and their role in the process, especially the co-operating stakeholders who will have a preponderant role in the decision-making process. Thus, expert selection should take place during the stakeholder analysis and the experts should be involved from the beginning. Deliberately working out stakeholder preferences is much more important than the choice of the MCA technique. Concerning the techniques used, we note that the process of weighting criteria for the AHP differs to the simple assignation of weights to criteria for WS and CP. The comparison of criteria pairs obliges the expert to weight the criteria according to a reference and not individually. Therefore, the weighting will probably be more precise and accurate. On the other hand, the CP technique defines worst and best values for each criterion and groups the criteria by affinity. A better valuation of each criterion is carried out, as they are normalized within their group and groups are evaluated hierarchically. Either the compensation factor does not play a significant role, or the process of assigning a compensation factor is more complex than apprehended. Finally, WS will favor high valued criteria and the alternatives where these criteria have the best values, independent from other criteria by large differences.

With respect to criteria, it is suggested to use the access constraint as a proxy for cost as the operation and maintenance cost is quite difficult to estimate but is directly correlated to it.

CONCLUSIONS

Overall results show little differences between the three methods but identify key issues influencing MCA results, and confirm the appropriateness of GIS-supported MCA for optimizing a hydrometric network in an arid and mountainous context with high constraints and numerous criteria to be met:

- CP is probably the best method for integrating all criteria in the final results. However, the assignation of weights is subjective and AHP shows potential to improve precision and accuracy in the weighting process. Therefore, the best method for this study may be to weight the criteria with the AHP, and then calculate the alternative scores with the CP method.
- Criteria should be defined and weighted in a participative and consensual way by experts and a few key decision-makers in order to avoid bias in the individual weighting process. The key stages of the MCA receiving maximum attention are the stakeholder analysis and the determination of their preferences. Therefore, all MCA should start with a comprehensive stakeholder analysis.
- The use of GIS supported MCA for designing or optimizing a hydrometric network in an arid and mountainous area like northern Chile appears to be very appropriate given the constraints of the context and the different criteria that need to be met.

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