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Introduction

1 Despite being an arid region with from 150 to 300 mm of annual precipitation (Capitanelli, 1967; Viale and Nuñez, 2011), the Argentinian Province of Mendoza in the Andean piedmont is populated by 1.7 million inhabitants (INDEC Census, 2010), essentially located in the Metropolitan Area of Mendoza (1.5 million inhabitants) or in other cities such as Tunuyán, San Martín or San Rafaël. 97% of the provincial population live in oases. In fact, in this Province, four rivers (from the north: Mendoza, Tunuyán, Diamante and Atuel) (Fig. 1) irrigate three oases[1] (Northern, 2,500 km²; Central, also called Valle de Uco, 800 km²; and Southern, 1600 km²) and supply the cities. The Northern and Southern oases are located downstream of large dams and superficial run-offs are artificially regulated. The Central oasis does not benefit from human regulation and farmers mainly use groundwater, but a new dam is planned by the local managers in the Upper Tunuyán river catchment to regulate the water discharge upstream of the oasis of Valle de Uco. The Province of Mendoza and the organisation responsible for managing water, the General Department of Irrigation (DGI for *Departamento General de Irrigación*), have adopted an on-demand management (Lavie *et al.*, 2015): until recently, they have sought to increase supply to fulfil needs rather than trying to moderate the demand to match the available resource[2]. For example, low winter flows (snow jams) are stored in big dam reservoirs, and thus there are no instream flows to feed wetlands in the plain downstream of the oases. Yet, from 2008, winters with little snow in the Andes and very hot summers have obliged the managers to modify their policy, by trying to stabilise or reduce water needs via awareness-raising campaigns (Lavie and Beltrando, 2013).

2 The volumes taken by water managers are quite large, particularly during the agricultural growing season (from October). The peak is reached in summer, when both agricultural and domestic uses soar. From March, the food-processing industry (fruit canning and wineries) is a big consumer. The three oases do not have the same needs but, for all of them, the withdrawals are so great that the discharge drops downstream of the oases for the four rivers studied (around 2.5 m^3/s for the Mendoza river for example[3]), while their water flow is 30 to 50 m^3/s upstream of the irrigated areas. Significant waste has been noticed and can be explained by inadequate water management at the fine-scale level. For example, the domestic water cost is fixed and unrelated to consumption, which may induce additional waste; irrigation is being modernised (drip and micro-aspersion) in the new lands settled on the piedmont, but mostly remains gravity-fed, favouring evaporation.

3 Besides these consumption and water management issues, estimating the availability of short-term water volumes, that is to say the supply, is essential for a society based on irrigation.

4 The risk of water shortage in South American oases has been studied for a long time (Leiva, 1999; Cobos, 2002; Corripio *et al.*, 2008; Cossart *et al.*, 2010). Increased melting of the Andean glaciers is seen as a threat for the long-term water availability needed by the piedmont crops (Collin-Delavaud, 1968; Lavie, 2009; Poncet, 2011; Marshall, 2014). However, annual snow is the main source of the superficial water and aquifer recharge (e.g. 85% for the Mendoza river catchment according to Abraham *et al.*, 2007). In fact, interannual variations in the yearly and monthly discharge of ten central Andean rivers (four Chilean and six Argentinian) in 1955-2002 were significantly correlated with variations in the regional snow accumulation, which was aggregated from the ground measurements of snow water equivalent (SWE) at six high-altitude stations located in both Argentina and Chile (Masiokas *et al.,* 2006). Snow

accumulation was also strongly correlated with precipitation west of the cordillera as measured at Santiago, and high accumulation generally (but not always) occurred during *El Niño* events, while half of low snow accumulation occurred during *La Niña* events. Forecasting Cuyo river discharge is thus possible from snow accumulation estimates if they are available but, because snow accumulation depends only partly on South Pacific atmospheric processes, discharge forecasts based on the Southern Oscillation Index (SOI) must be regarded with caution (Compagnucci and Vargas, 1998).

5 Ground measurements of snow cover may be used for forecasting but, because of technical or accessibility issues, such time series of snow accumulation are often incomplete, which is the case in our study area (Masiokas *et al.,* 2006). Thus, satellite remote sensing has often been used to monitor seasonal snow synoptically (Nolin, 2010) and to study the effects of the interannual variability of snow cover on river discharge in other parts of the world (e.g. Immerzeel *et al.,* 2009; Boudhar *et al.,* 2009). Various technologies are available, all with advantages and disadvantages. Active and passive microwave remote sensing can be used to estimate the SWE of the snowpack (Grippa *et al.,* 2005; Kelly *et al.,* 2003; Nolin, 2010), or features like the timing of snowmelt using low-resolution active microwave sensors (Bartsch, 2010). However, passive microwave instruments have a coarse spatial resolution (about 20 km) that prevents a clear understanding of the estimated SWE value, especially in mountainous areas where high altitudinal variations occur within a 20-km range. On the other hand, current high spatial resolution active instruments (synthetic aperture radar) do not yet operate at the appropriate wavelength and suffer from topography effects on the backscattered signal. Moreover, SWE estimation by both types of instrument requires the snowpack to be dry. Optical remote sensing offers the possibility of monitoring the snow cover fraction within the pixel (Hall *et al.,* 2006; Salomonson and Appel, 2004; Chaponnière *et al.,* 2005), or providing a binary classification of it (covered or not in snow), but does not give any information on SWE or snow depth. At medium spatial resolution (250 m or more), images are available daily enabling seasonal changes in the snow cover to be monitored, but only if the cloud conditions are good.

6 In a previous study, we confirmed the clear link between the river discharge and the snow cover estimated using such medium spatial resolution remote sensing in a large portion of the Andean mountains (Delbart *et al*., 2014). In particular, we explored the relationships between the snow cover surface area each week and month and the mean discharge in the high-water season (September-April) of the four Cuyo rivers considered. We found that the mean discharge correlates particularly with the September and October snow cover. Here, we refine the analysis of the link between the seasonal and interannual variations of the mapped snow bed extent and those of the discharge of the four rivers, this time at each basin scale separately and not at the regional scale, in 2001-2014. From this analysis, we evaluate the possibility of using this optical remote sensing of snow to forecast water shortages.

Material and methods

7 Our study aimed to analyse the relationship between four river discharges, measured daily, and the snow cover estimated by remote sensing every eight days, at the scale of each watershed, delimited using a digital elevation model (DEM). All data are easily and freely available.

Watershed delimitation

8 The watersheds were extracted through an automated procedure implemented under ArcGis© Spatial Analyst applied on the Shuttle Radar Topography Mission DEM available from http://earthexplorer.usgs.gov/. The procedure consists of:

1. Filling the potential basins present on the DEM. These anomalies could distort the analysis.
2. Analysing the slope direction on each pixel.
3. Determining flow accumulation on each pixel to align drainage points on the DEM hydrographical network (shown in Fig. 2D for the Mendoza river watershed), which groups points showing large flow accumulation.

4. Using a slope direction raster, automatically identifying ridges and watersheds uphill of drainage points.

9 The four resulting watersheds are shown in Fig. 2B. Surface areas of watersheds upstream of the first dams are 7,108 km² (Mendoza), 2,460 km² (Tunuyán), 2,762 km² (Diamante), and 3,035 km² (Atuel).

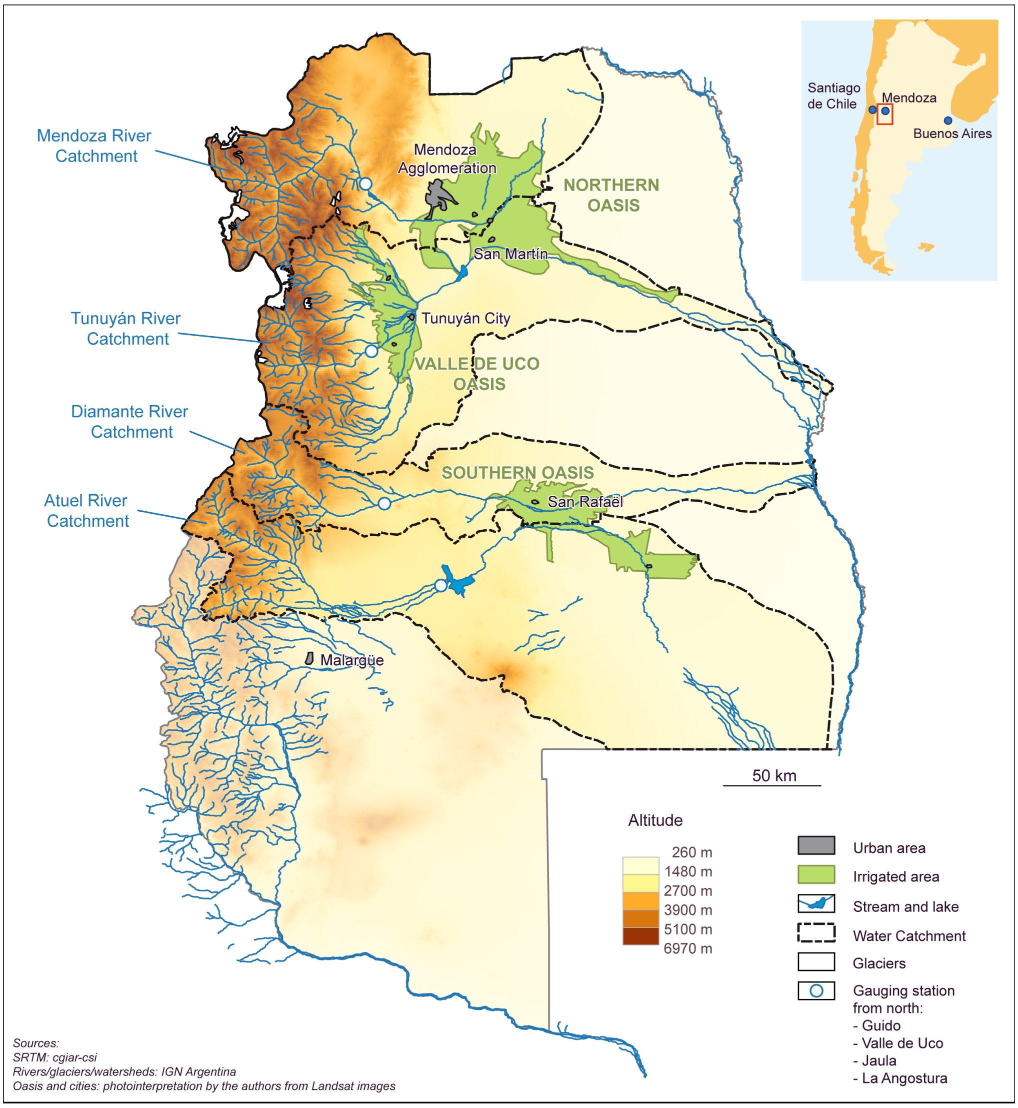
River discharge

10 Water discharge data come from an open database managed by the National Under-Secretary for Water Resources. Various resource managers contribute to this on-line database, such as the DGI for the Province of Mendoza. Amongst these data, we chose to use the daily discharge in m^3/s because the dataset is complete from the 1930s or the 1950s (depending on the river) until June 2014. Flows are measured at noon for three rivers and at midnight for the Diamante river.

11 In order to evaluate the natural discharge for each catchment, the gauging stations located just upstream of the first reservoirs (see Fig. 1) were chose, that is to say:

- on the Mendoza river: Guido station (32°54’55’’S - 69°14’16’’W), upstream of Potrerillos Lake,
- on the Tunuyán river: Valle de Uco station (33°46’36’’S - 69°16’21’’W),
- on the Diamante river: Jaula station (34°40’06’’S - 69°18’59’’W), upstream of Aguas del Toro Lake,
- on the Atuel river: Angostura station (35°05’59’’S - 68°52’26’’W), upstream of Nihuil Lake.

Figure 1: Watersheds studied within the Province of Mendoza



Sources:
SRTM: cgiar-csi
Rivers/glaciers/watersheds: IGN Argentina
Oasis and cities: photointerpretation by the authors from Landsat images

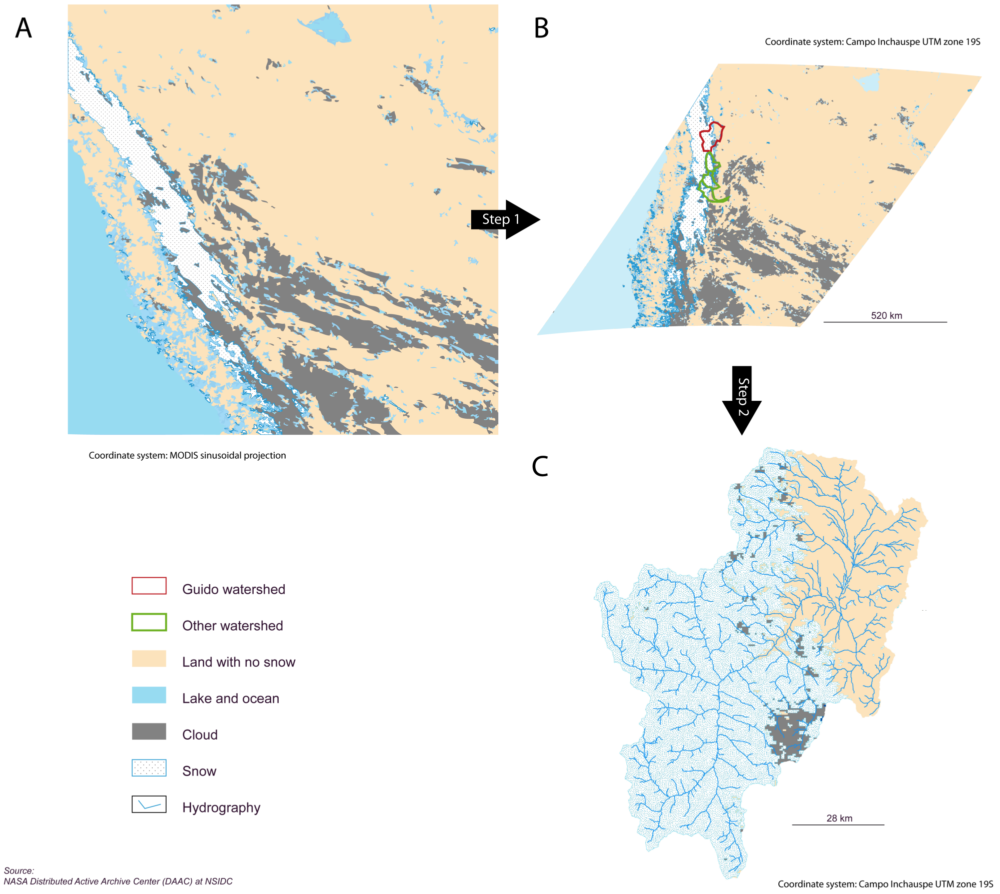
Snow surface estimation

12 Snow cover maps are provided every eight days by the remote sensing MODIS MOD10A2 product, available from http://reverb.echo.nasa.gov/reverb/. The absence or presence of snow is derived for each 1-km² pixel from the Normalised Difference Snow Index (Salomonson and Appel, 2004). This is a spectral index that combines green and short-wave infrared reflectances estimated from satellite measurements; it is close to 1 when snow covers a large fraction of the pixel surface, and close to -1 when snow is absent. We used the MODIS tile h12v12 (Hall *et al.*, 2006). Each MOD10A2 8-day image is a composite based on all satellite observations available during one eight-day period: for each pixel, the best observation is used to detect snow, this selection being made to minimise clouds and other atmospheric effects. Despite this compositing procedure, some pixels can still be classified as "cloud", meaning that they were cloudy during the whole 8-day period. Thus, we used the cloud mask provided to exclude "cloud" pixels. This product has been evaluated; for example, it was compared with about 6,000 ground observations of the presence or absence of snow in Xinjiang (Wang *et al.*, 2007). This revealed that snow is correctly detected in 94% of cases when the snow bed is deeper than 4 cm, the absence of snow is detected in 99% of cases, but snow detection accuracy drops to 7% when the snow cover is patchy and the snow bed is thinner than 1 cm. For our study, this lower accuracy for a thin snow bed may not greatly impact our results as it represents a small amount of water.

13 From this dataset, the surface area of the snow cover and cloud for each 8-day period was estimated within each of the following watersheds: Mendoza, Tunuyán, Diamante and Atuel river catchment areas.

14 To extract the snow coverage of each watershed at each available date, a Python script was developed to execute automatically the 3 steps represented in Fig. 2. Firstly, it re-projects all the MODIS dataset from the MODIS specific projection to the UTM 19S coordinate system using the PyModis module (http://pymodis.fem-environment.eu/). Then, it vectorises the re-projected images and calculates the area of each coverage type (snow, cloud) using GDAL/OGR (http://www.osgeo.org/gdal_ogr) for each watershed. This script was used to analyse the 674 images available at the time of this study.

Figure 2: From original data to useful maps



Source:
NASA Distributed Active Archive Center (DAAC) at NSIDC

A: MODIS data in sinusoidal projection. B: MODIS data re-projected in the UTM 19S coordinate system, and converted from raster to vector format. C: Clipped MODIS data on the Mendoza river watershed, and estimation of the snow and cloud surface areas.

Time series analysis

15 The time variations in snow extent and discharge of the four river catchments during the 2001-2014 period were analysed both qualitatively and quantitatively. In winter, clouds cover a significant part of the watershed areas. For example, up to 25% on average of the Tunuyán watershed is covered by clouds in the MOD10A2 image (Table 1) despite the compositing procedure that aims to reduce the cloud cover in the image. As clouds may hide the snow, snow cover estimates when more than 5% of the watershed was covered by clouds were rejected in order to keep only the time variations that are related to snow cover, leading to a reduced amount of data, especially in the months from June to August. Then, the time series of the daily discharge of each river and the snow surface area for the corresponding watershed were visualised in order to verify whether a link exists between the snowmelt timing and that of the beginning of the yearly increase in discharge, and whether the maximum discharge is directly linked to the maximum snow cover recorded in the previous winter.

Table 1: Cloud cover fraction (%) averaged monthly in 2000-2013 for each watershed

	January	February	March	April	May	June	July	August	September	October	November	December
Mendoza	0.0	0.0	0.0	0.2	7.0	16.5	9.0	5.9	1.9	0.4	0.2	0.0
Tunuyán	0.1	0.0	0.0	2.1	15.8	25.3	17.1	12.1	4.0	1.0	0.4	0.1
Diamante	0.0	0.0	0.0	1.0	8.5	12.2	8.0	7.3	2.0	0.5	0.1	0.0
Atuel	0.0	0.0	0.0	0.2	5.7	7.5	4.9	4.7	1.4	0.2	0.1	0.0

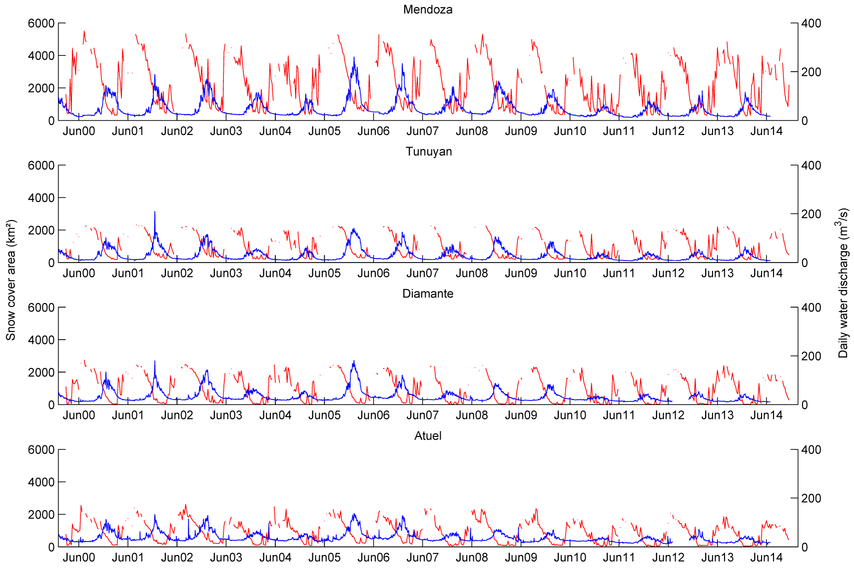
16 Next, we analysed quantitatively how the total amount of water discharged during the high-flow period, i.e. during September-April, is controlled by the snow cover of the previous winter. Thus, the 8-day snow data were summarised in several parameters: annual maximum recorded snow surface area and monthly average snow surface area, for each year separately. The discharge during the September-April period was also averaged. Lastly, the linear relationship between each snow parameter time series and the average discharge was analysed.

Results

Daily discharge and eight-day snow cover time series

17 Each year, discharge clearly starts increasing from the beginning of the snowmelt period (i.e. in late September-early October, Fig. 3) as expected for these snow-glacier regime rivers. From the hydrological seasons of 2000-01 to 2008-09, hydrographs highlight a first flood of 2 to 4 weeks in spring, then the discharge plateaus, and a second flood occurs in early summer corresponding to both snow and ice melt. Each year, the peak, due to both snow and ice melt, occurs from mid-December to mid-January, within the same 48 h for the four rivers.

Figure 3: Relationship between snow cover surface area (red) and water discharge (blue)



Daily water discharge measured on four rivers upstream of dams. Eight-day snow cover surface area was estimated from MODIS MOD10A2 data in each watershed. No data are shown when more than 5% of the watershed surface was covered by clouds.

Sources of data: DGI / NASA LPDAAC for NSDIC (https://nsidc.org/data/modis/data_summaries/index.html).

18 Since summer 2009-10 (December 2009-February 2010), dry years (until then quite exceptional, e.g. in 2003-04) have become more common. On one hand, annual volumes have decreased (i.e. for the Mendoza river, the mean discharge was 27.3 m^3/s in June 2010-July 2011 compared to an average discharge of 49.4 m^3/s for the decade 2001-2012). On the other

hand, the seasonal behaviour has changed: no plateau can be seen between the spring and summer floods. In other words, the regime seems to have changed from snow-glacier to snow, maybe even to snow-rain, but firstly, climate data are needed to validate this hypothesis, and secondly, the period concerned is too short to confirm a significant regime change.

19 The Atuel river time series displays additional behavioural features: while the high-level period is similar to the northern rivers, it presents erratic variations out of this season, with flood peaks during the snow jam period. Two hypotheses can be proposed: 1) some rainstorms occur when floods appear in the autumn; 2) a rapid fresh-snowmelt during the foehn wind days. The Mendocinian foehn (named *Zonda*) creates high daily temperature amplitudes, especially in winter: temperatures can rise to 30 to 40°C in a few hours (Norte, 1988). This hypothesis is the most plausible, as the rises in the discharge are always simultaneous with a decrease in the snow bed extent in the same week (Fig. 3).

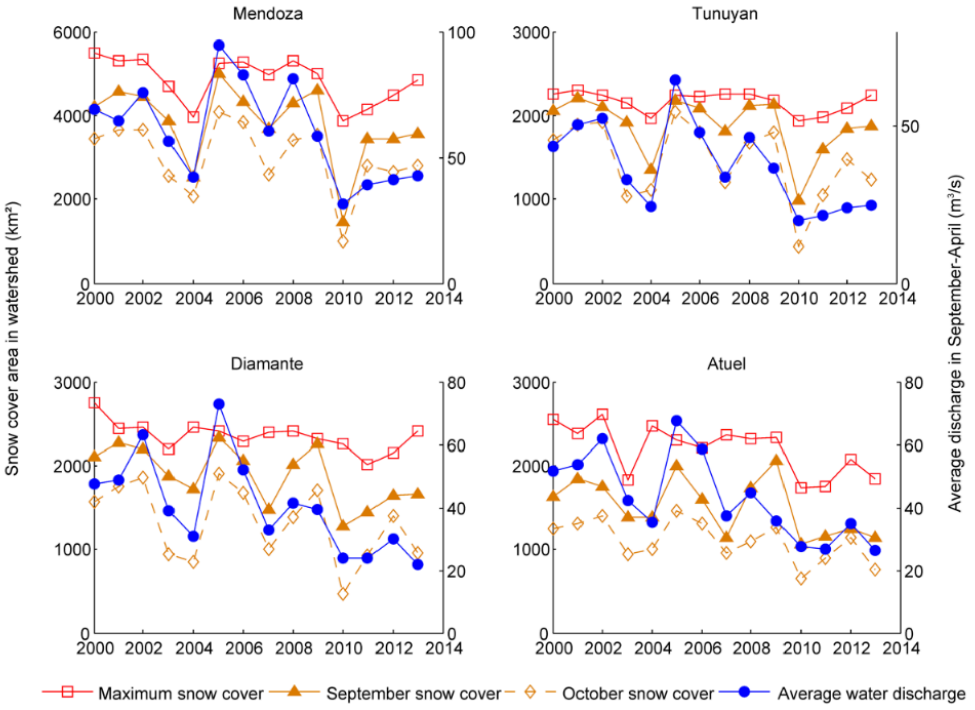
20 The large differences in discharge between the rivers match the large differences in total snow cover area between watersheds, these being linked to watershed dimensions. Interannual variations in the annual discharge appear for the four rivers, partly related to those of the snow bed. For example, for the Mendoza river, the relatively small snow extent over its watershed in June-September 2004 and June-September 2010 was followed by a relatively small water discharge peak in the next high-water period (September 2004-April 2005 and September 2010-April 2011, respectively), whereas the large snow extent in June-September 2005 was followed by a large water discharge in the September 2005-April 2006 period. In order to highlight this relationship between snow cover and discharge, we now focus on the average discharge over eight months, from September to April, i.e. the high-water level period.

Effect of winter snow cover on average discharge during the high-water period

21 The September-April average discharges of the four rivers present largely similar interannual variations, although some differences occur: for example, in 2008 the discharge was higher than average for the Mendoza river but close to average for the other three rivers. The September-April average discharge is poorly correlated with the monthly snow extent for the months of January to August (not shown, see Delbart *et al.,* 2014), and weakly correlated with the maximum recorded snow extent (Fig. 4). This prevents concluding that there is a direct relationship between the total winter snow falls and the river discharge. Nevertheless, for each river, the average water discharge is strongly correlated with the snow extent in September (Figs. 4 and 5, Table 2) and October (Fig. 4, Table 2). This indicates that the total discharge is directly related to the area of the snow bed extent at the beginning of the snowmelt period.

22 For each watershed, the average discharge in September-April and the snow cover in September and October display relatively similar temporal interannual variations and their correlation is around 0.8 (Figs. 4 and 5, Table 2). The linear model parameters are almost the same for two rivers (Tunuyán and Diamante), which differ slightly from those of the Atuel, and greatly from those of the Mendoza river. These differences indicate that one snow surface unit does not translate into the same amount of water discharge for the Mendoza river as for the other rivers. Discharge residuals of the linear regression are generally slightly smaller for the October snow surface area than for the September snow surface area (Table 2).

Figure 4: Snow cover surface area and average discharge of the rivers in the high-water level period (September-April), in 2001-2013



Sources: DGI / NASA LPDAAC for NSDIC (https://nsidc.org/data/modis/data_summaries/index.html).

Figure 5: Average discharge in September-April versus snow cover in September

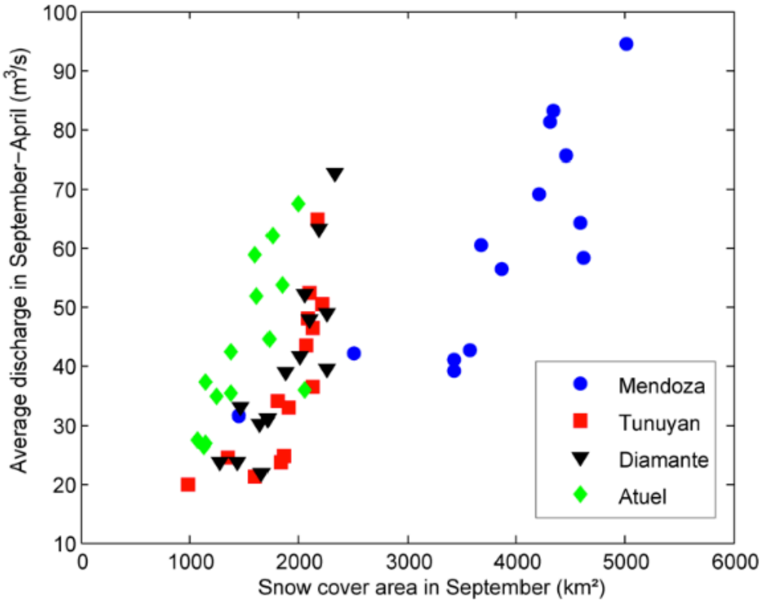


Table 2: Parameters of least square regression linear modelling [Average discharge] = a * [Monthly snow cover] + b, correlation, average absolute residuals, and (in brackets) average residuals relative to mean discharge

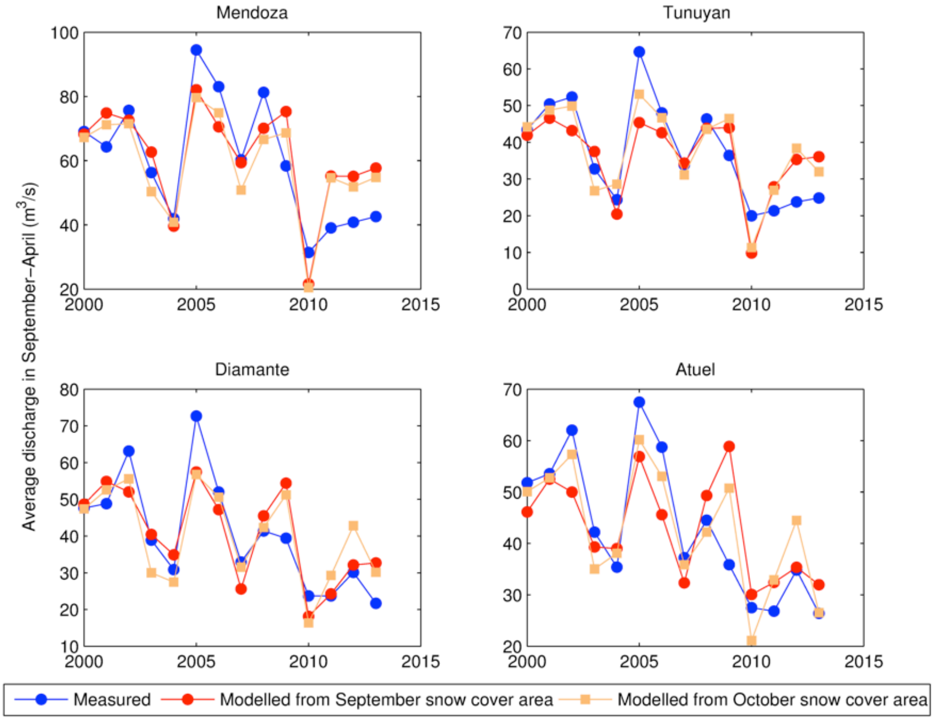
		Correlation	Slope (a) ($m^3s^{-1}km^{-1}$)	Intercept (b) (m^3s^{-1})	Mean absolute residuals (m^3s^{-1}), (relative average residual)
Mendoza	September	0.81	0.017	-3.8	9.5 (15.9%)
	October	0.84	0.019	1.7	9.1 (15.1%)
Tunuyán	September	0.77	0.03	-20.0	7.0 (18.7%)
	October	0.85	0.026	-0.2	5.7 (15.2%)
Diamante	September	0.84	0.037	-29.0	6.4 (15.8%)
	October	0.84	0.028	3.5	6.4 (15.8%)
Atuel	September	0.73	0.029	-0.96	6.9 (16.0%)
	October	0.87	0.048	-10.0	5.1 (11.8%)

Discussion

23 The annual precipitation in the mountain areas is between 300 and 600 mm in the Mendoza river catchment and from 500 to 800 mm in the other watersheds studied, mostly in the form of snow, whereas the precipitation is from 150 to 250 mm at lower altitude where the oases are (Norte, 2000). Agriculture and human activities in these oases depend on the river discharge, which clearly depends on the snow extent at the beginning of the snowmelt period. We did not find a direct strong link with the maximum snow surface area during winter. This may be due to the persistent cloud cover from June to August that led us to reject a large amount of data within this period. Thus, what is called “maximum snow cover” is in fact the maximum snow cover observable under the constraint of cloud cover.

24 Our results indicate that it is possible to use remote sensing to forecast the average discharge in the September-April period from MOD10A2 images, e.g. from images during the September period (Fig. 6). MOD10A2 data are freely available 10 days after acquisition and thus it is possible to anticipate in late September or early October the risk of a water shortage in the following summer. As regression residuals are smaller when the discharge is modelled from the October snow extent, a second and more precise estimate can be provided in early November.

Figure 6: Comparison of the September-April discharge values modelled from remote sensing of snow extent with measured values



25 Unfortunately, large deviations occur between the modelled and the measured discharge, for example for the Atuel river in 2009, thus our forecasting method must be backed-up by other methods. Our method is based on the linear regression between the interannual time series of snow surface area and discharge, thus deviation means that a snow surface unit does not always translate into the same amount of water every year. First, like any other remote sensing-based product, the MOD10A2 snow bed area displays some uncertainty, especially when the snow bed is thin as described above. Moreover, the most obvious explanation for the deviations from the linear model is that interannual variations in the snow depth were not considered. Snow bed SWE variations inferred from passive microwave remote sensing (e.g. Grippa *et al.*, 2005; Kelly *et al.*, 2003) may help to refine our forecasting method, although, as mentioned before, the 20-km spatial resolution makes it very uncertain. Other explanations are that the interannual variations in liquid precipitation and in the annual amount of water from ice melt were not considered. These are potentially major effects, linked to interannual variations in temperature. In particular, changes in the ratio between liquid and solid precipitations, or in the altitude of the transition between rain and snow, may significantly alter the empirical models proposed in this study. Finally, we cannot exclude interannual variations in the amount of sublimation. At the time of this study, we cannot provide an order of magnitude for these effects.

26 The linear relationships between discharge and snow surface area differ from one catchment to another. Compared to our previous study (Delbart *et al.*, 2014) carried out at the scale of the Province of Mendoza, here we could highlight these differences because the catchments were treated individually, which leads to new questions but still represents significant progress. Several explanations are possible, starting again from the differences in snow depth between the watersheds as they may not receive the same amount of precipitation. Secondly, horizontal snow surfaces were considered and not topography. Differences in the slope distribution between watersheds may impact the potential snow accumulation. Moreover, north-facing slopes receive more solar radiation than south-facing ones, and thus the aspect distribution within each catchment may also explain some of the differences between the four empirical linear relationships found here.

27 By adding MODIS snow cover and precipitation data to a hydrological model, under the constraint of the measured discharge, Immerzeel *et al.* (2009) suggested a contribution of glacier melting to the water flow of several rivers in the Himalayas. In addition to the data-based analysis of topography, snow depth and rain variability effects on the discharge and its relationship to snow cover, such a model-based approach may help to establish better the water budget of the four catchments studied here, but this requires reliable meteorological data (Pellicciotti *et al.*, 2012), which are not yet available.

Conclusion

28 Despite the limitations discussed above, the snow surface area estimated by optical remote sensing at the beginning of the snowmelt period explains the average discharge in the high-water level period, while the decline in September and October snow surface areas largely explains the decrease in the four river discharges observed in 2000-2014 (Fig. 6). Correlations of about 0.8 were found, which enabled us to propose a discharge forecasting method that explains over 60% of the interannual variation, which is better than the previously proposed forecast methods based on South Pacific climatic indices (Masiokas *et al.,* 2006, Compagnucci and Vargas, 1999). Our method displays an average error of around 15% and the forecast can be provided early in spring as the data are rapidly available. Thus, although imperfect, our method may contribute to anticipating the available water volumes for Northern and Southern oases whose water flow is managed via reservoirs. This should help the DGI to improve water storage in the lakes/reservoirs. Indeed, forecasting in early spring the available water during the flooding season may prove a valuable tool for managers.

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Notes

1 : The Province of Mendoza also has 2 small mountain oases (Uspallata and Malargüe), but their challenges are not comparable with the three big ones.

2 : For further information on water management according to supply and demand, see Turton and Meissner 2002; Blanchon and Maupin, 2009; Maupin, 2015.

3 : There is no official monitoring, but we estimated it once a month from 2003 to 2010.

Pour citer cet article

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Droits d'auteur

Résumé

In the Argentinian Dry Andes, although the melting of glaciers is seen as a threat for the long-term water availability needed by the piedmont crops, the annual snowmelt is the main source of superficial water and aquifer recharge. In this study, we analyse the link between the seasonal and interannual variations in the discharge measured upstream of the first dams on four rivers (Mendoza, Tunuyán, Diamante, Atuel) of the Argentinian Cuyo region (in the Federal Province of Mendoza) and those of the snow bed extent as mapped by optical remote sensing (MODIS MOD10A2 product) on a weekly basis in the 2001-2014 period, at the scale of each watershed.

For the four snow-glacier regime rivers, seasonal variations in the discharge appear directly related to those of the snow bed surface area in each watershed, as shown previously (Masiokas *et al.*, 2006). We observed that the high-water period (September-April) discharge is directly related to the snow extent at the beginning of the snowmelt period, i.e. in September and October, as revealed by a correlation of about 0.8. Moreover, the decreasing trend in the winter snow bed extent from 2001 to 2014 clearly explains the observed decreasing trend in the annual water discharge.

Agriculture and human activities in these oases mostly depend on river discharge, which from our results clearly depends on the snow extent. Our research indicates that it is possible to use remote sensing to forecast the average discharge in the September-April period (high-water season) from MOD10A2 images with an average uncertainty of 15%. As MOD10A2 data are freely available ten days after acquisition, it is possible to anticipate in early October the risk of water shortages in the coming summer.

Entrées d'index

Keywords : discharge, rivers, snow, remote sensing, MODIS, Andes, Mendoza, Argentina