Influence of the acequias in the hidrology and hidrogeology of Sierra Nevada: Cañar case

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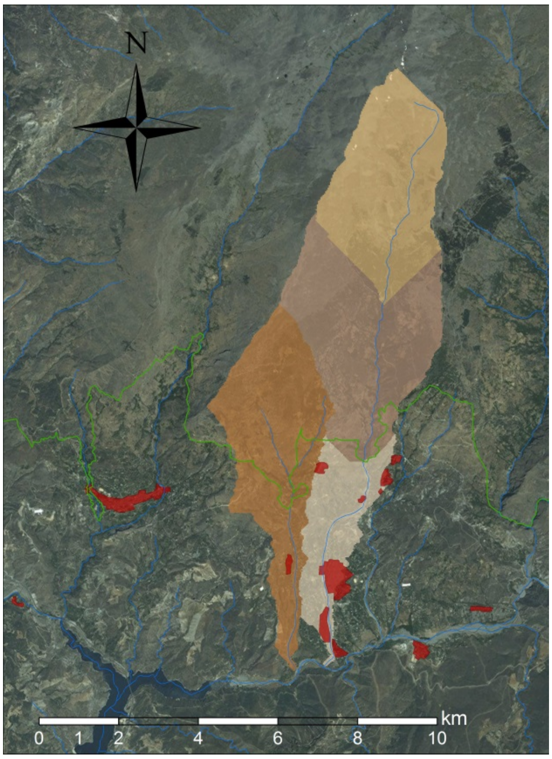
1. Introduction

This natural regime has been historically altered by a well-distributed irrigation channel system ("*acequias"*) on both banks of the main river that makes possible the deviation of water from the main channel and from the ephemeral mountain creeks ("*barrancos*") as they are intercepted along the hillslopes. Six main *acequias* deviate water for direct irrigation and for aquifer recharge ("*careo*") in the steepest parts of the basin. These *careos* allows water to flow slowly towards downstream areas through springs, what supplies with water resources well below the snowmelt areas during late spring and early summer. This creates a new human-driven natural regime that has supported for centuries the sustainable development of a rural society in an area very sensitive to water scarcity and has generated some singular and high value agroecosystem services in this mountainous region.

In this project we have worked to characterize the influence of these *acequias* in the hydrology and hydrogeology through several actions that involve measurement and modelling: 1) Continuous measurement with a capacitance water level logger of the volumes of water taken by the Barjas channel, those recharged at Cerro Man and those drained by the Pueblo Alto spring. 2) Differential measurement of the water flow along the *acequia* of Barjas together with the characterization of its bed material and measurement of its detailed topography and geometry. 3) Periodical monitoring of the river flow at the outlet of the basin directly affected by the *acequia* de Barjas, located under the bridge of Bayacas. Simultaneous measurements in the main river and *acequias* were also made to take a still photograph of the distribution of water within the basin at certain times. 4) Hydraulic modelling of the water routing along the *acequia* of Barjas using the Muskingum-Cunge method, including an infiltration term. 5) Hydrologic modelling of the basin, including snow processes, for the period 1950-2017 using WiMMed, a fully distributed hydrological model that has a physical basis.

2. Study Site

Upper Chico river basin (25.7 km²) is located on the southwestern face of the Sierra Nevada Mountains and is characterized by steep slopes and high altitudes, with important influence of the snow. The vegetation is a mixture of reforested pines with some terracing, a valuable non-dense oak forest (Q*uercus Pyrenaica*), and crops. Above 2000-2500 m we can only find high mountain pastures and shrubs. A hydrological restoration in hillslopes and in the main reach was applied to the basin in the first half of the XXth century, which reduced significantly some serious problems of torrential flooding and erosion and soil loss. From a geological point of view, Chico River basin is framed within the Internal Zones of the Betic cordillera. Hydrogeologically speaking, three aquifer formations can be differentiated: cracked aquifer (*“nevadofilábrides”* and *“alpujárrides”* shales), carbonatic aquifer (carbonates outcrops sets) and detrital aquifer (recent detrital materials). The natural hydrometeorological regime is characterized by a great variability between years, with concentrated storm events unevenly distributed through the year, and periodic torrential events with high flood risk tempered by the important presence of the snow above 2000 m. The shallow high-mountain aquifers mainly follow the topographic flow but at the same time they are sufficiently developed to maintain, with the help of the delayed snowmelt, some evidence of baseflow even during the warmer periods of the year.



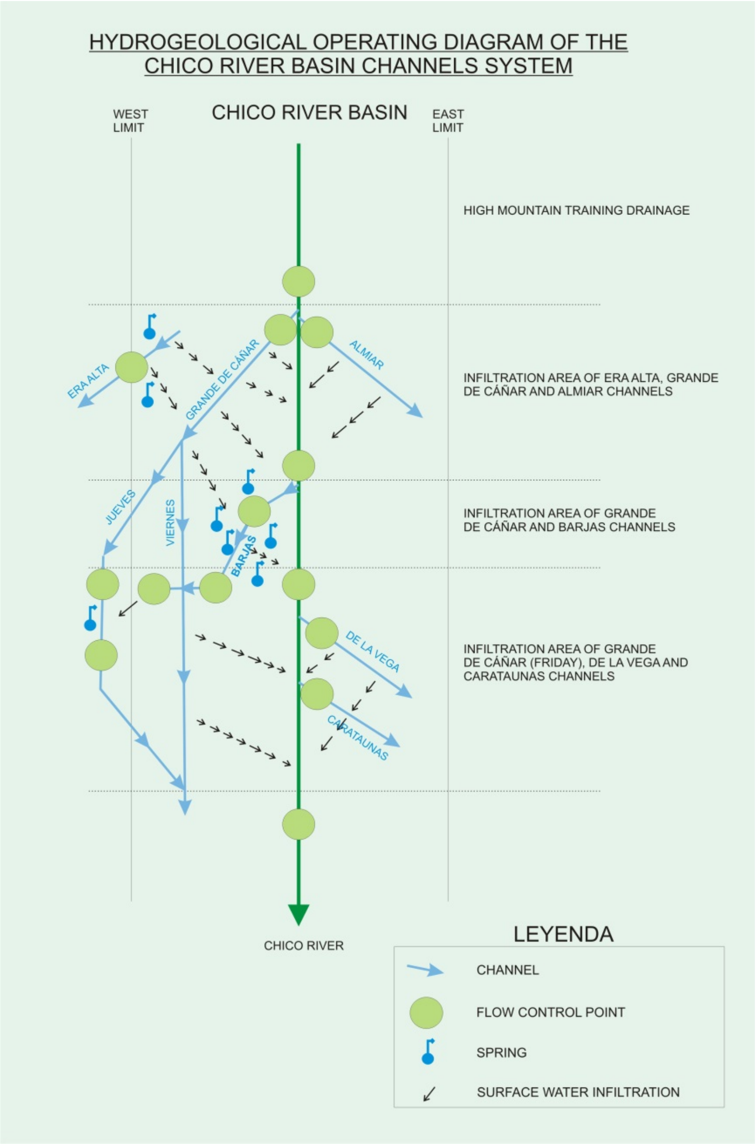
This area matches exactly within the limits of the Natural Park of Sierra Nevada. The outlet of this basin is located under the bridge of Bayacas, the point where the road from Orgiva to Pampaneira crosses the Chico River. This basin has a great influence of the snow, with elevations above 3 thousand meters high. And steep slopes very prone to erosion. That is why an important hydrological restoration with reforestation in the hillslopes and little dams in the main stream was applied in the first half of the XXth century. It reduced significantly some serious problems of torrential flooding and erosion. The acequia of Barjas (which can be seen in yellow in Fig X) is completely contained within this basin.

But the area of influence of our basin extends beyond its limits, to the lower Chico River and to the Sucio River, because they are also affected by the irrigation and cropping system of the town of Cañar and the water extracted from the upper chico river. In this study we are going to focus on the upper basin as we could isolate much better the influence of the acequias over the hydrology.

3. Methodology

NET OF ACEQUIAS

The ideal hypothesis is to think of the acequia like an artificial river forced to run through a defined path, with a constant infiltration rate as this particular acequia is mainly made directly on the soil with no seal.



The reality was that there were so many water inflows and outflows along the course and so many changes in slope, geometry, and channel bed materials and properties of the acequia that is very difficult to give a meaningful value for infiltration. There is a constant hydraulic interaction of the acequia with the surrounding terrain.

So, we can find

- water coming from the ephemeral creeks, part of which is incorporated to the acequia, but returned a few meters away in a diffuse way by overflow in a natural spillway.
- We can also find hidden wells of the uphill subsurface water that raise the level of the acequia in a given section from the bottom
- Or sections with increased infiltration
- And, of course, we have Artificial Diversion of water through secondary branches of the acequia for irrigation to lower plots.

Not to mention that infiltration changes with the flow rate as well as with time because of the process of consolidation or sealing of the bed materials of the acequia.

MODELLING

This monitoring work develops at very local scale, and goes on with the intrinsic difficulties of the field work. In the case of Cañar these difficulties are highest because of the heterogeneous nature of the hydrological processes, the difficult access to most of the monitoring sites, the low magnitude of the flows in the ditches, creeks and main reaches, and even the human intervention of the local people, sometimes suspicious of the matters related to water.

To overcome this and to gain a global vision over the hydrology at a basin scale, we use models. Specifically, we have set up a hydrological model called WiMMed.

- It is physically based, which means that needs fewer data to work as it is calibrated in other neighbor and similar basins in Sierra Nevada.
- It is distributed, which means that uses inputs and offer outputs in the form of map at a resolution of 30x30 m.
- It deals with snow and with high mountain shallow aquifers, as it was specifically design to work properly at Sierra Nevada.

WEATHER DATA

The model uses as inputs all the meteorological data available from weather stations in the region from 1950 to the present. These data only offer daily precipitation and temperature during the first years, and only in the XXI st century when we can use subhourly data as well as data obtained at high altitude stations. Of course than these two aspects are very important:

- subhourly data is essential in a torrential weather
- As well as high elevation data is essential in a basin with such elevational gradients and with such an important presence of snow.

But from the relationships established with the present data that comes from a much better distributed and equipped meteorological network, we can infer the data from the past, at least until 1950.

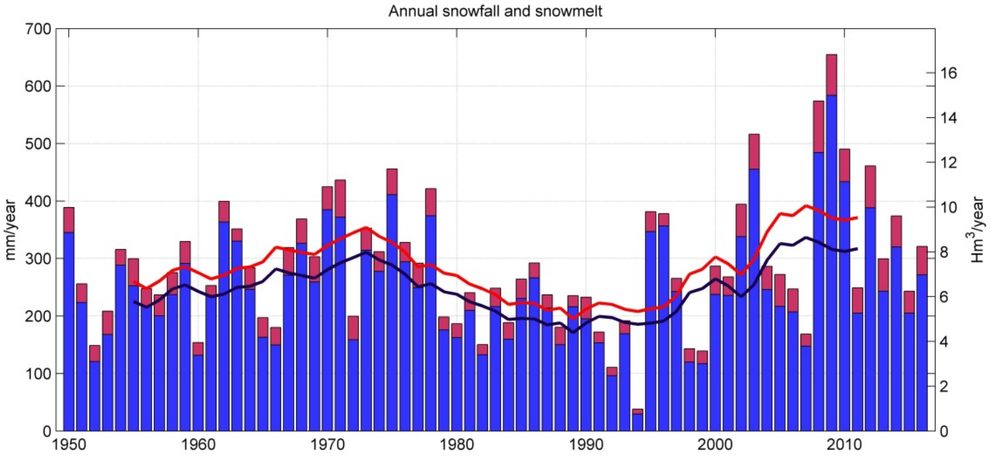
4. Results

PRECIPITATION/SNOWFALL

So, the model allows us to calculate, in first place, the average precipitation and temperature in the basin for the last 65 years. In this way, we can actually see how the changes that are happening in a framework of global warming are affecting the hydrometeorology in this particular basin.

As for precipitation, we can see here the annual average precipitation and the fraction of it that is snowfall (in white). Each bar is the total value for one year. The lines represent the moving average for 10 years. These lines are very useful because here we come across with the Mediterranean nature of the climate of Sierra Nevada: a great variation between years, with alternation of dry and wet years within cycles acting at different time scales that overlap.

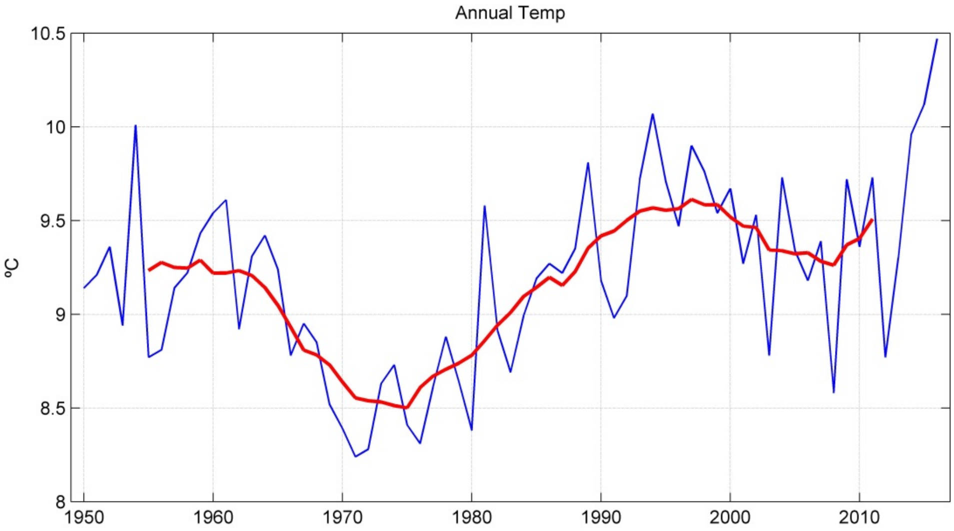
In general, the precipitation reached a minimum during the 1980's and remained stable in average, but with an intensification of the difference between dry and wet years. Increasing of the torrential nature, as it is usually presented.



However, it is curious to notice that the total amount of snowfall don't follow exactly this pattern. There is a clear minimum in the exceptionally dry year of 1994. But after that, the average snowfall reaches the maximum of the series. This is due to the timing of the storms. As they are more frequent during the winter period of are associated to cold front storms, the fraction of snow has increased, as well as the total amount of snow has also done it. Snowmelt follows exactly this same interannual pattern as the snowfall.

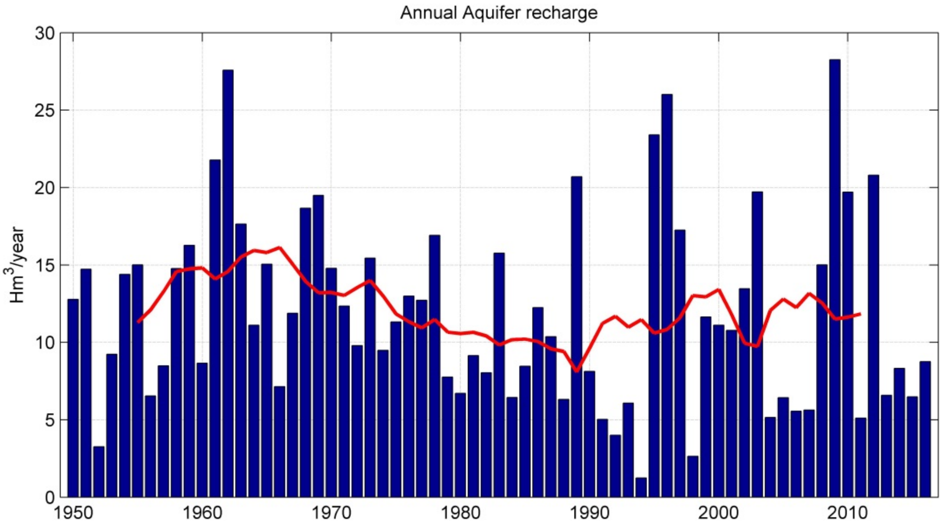
TEMPERATURE

The evolution of the temperature is clearer. Here, the kind of anomaly of the last 3 years draws a lot of attention, since the three maximum temperatures of the series have been reached consecutively.



AQUIFER RECHARGE

However, and this is an important factor for the management of the water, this rise in the snowmelt doesn't compensate in the drop of precipitation. And in this way, the deep percolation, that is the total recharge to the shallow aquifers of the basin, follow the downward trend.



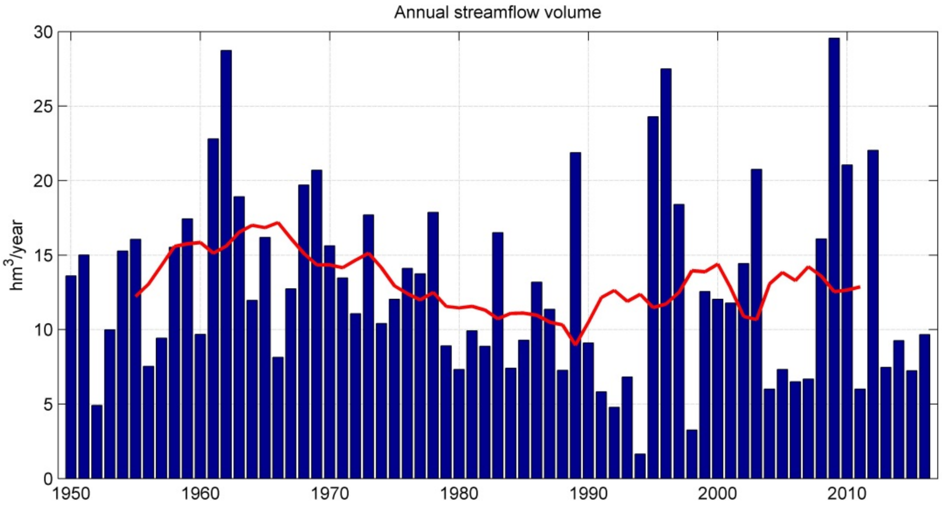
This means that snow itself cannot compensate for the effects over the hydrogeology of a dry year. Obviously it helps, and can change the fraction of the recharge for a particular year, but it is not enough in the general trend. As in the case of precipitation, this recharge is extremely variable between years.

From the previous graphic and this one, is important to take note of the total volume of water that is available in the basin. If the average precipitation is actually about 15 cubic hectometers per year for the whole basin, snowmelt produces 7 cubic hectometers and the aquifer recharge hardly reaches 8 cubic hectometers.

So taking use of the fraction of the snowmelt that is not reaching the aquifer and infiltrating it by artificial means as the acequias do, really implies a difference in the overall balance of the hydrology at a basin scale.

RIVER FLOW

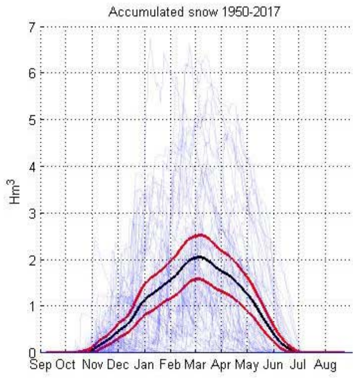
The shape of the graphic of the aquifer recharge is almost identical to the final streamflow in the outlet of the basin. The direct runoff only appears in some particularly intense events of specific years, but the annual river flow is dominated by the baseflow.

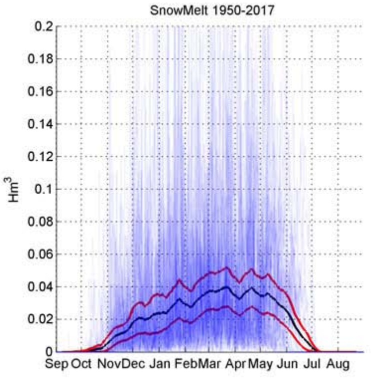


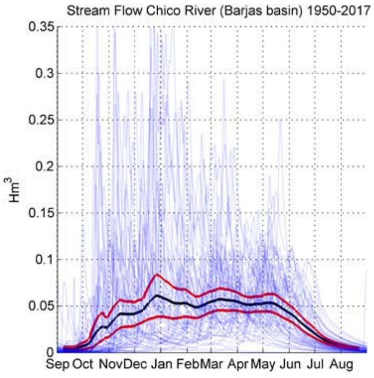
ANNUAL DISTRIBUTION

If we look at these variables from the perspective of the distribution throughout the year, we obtain graphic like these.

These are examples for snow water equivalent, this is, volume of water stored at a specific date as snow, snowmelt and stream flow, which “proceed” in sequence .





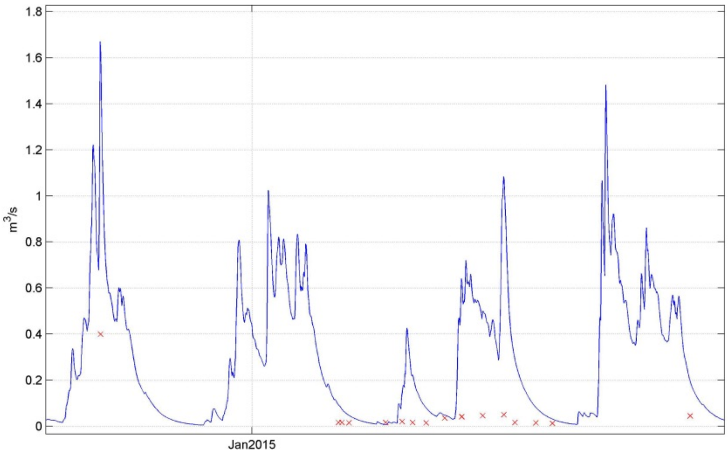


The only thing that we can assure from these graphics is that we are not expecting any snow until November and it won't last beyond June (in significant amounts hydrologically speaking) and that we will have a low-flow summer months. For the rest of the months the variability is huge. As an average, there is a clear maximum of accumulated snow at the beginning of March, a small maximum of snowmelt at the beginning of April (30 days later) and the average stream flow remains almost constant at maximum value from December to the beginning of May (with another 30 days of delay) with a mean value of 0.6 cubic meters per second

MODEL VS MEASUREMENTS

And as a final graphic, we can plot together the hindcast of the model for the past 4 years for the barjas basin, and the actual measurements made at this same outlet. These measurements were developed especially during the hydrological year 2015-2016, with at least one measurement per month.

In these measurements we find a remarkable stability at the base flow level, in such a way that they don't show any sign of the expected flow according to the model.



During the last field campaign, we measure the total flow derived by the acequias in the basin. The total deviation of water from the main course was that day of 0.14 cubic meters per second. That value matches the gap between the measured and the simulated value for that day. This means that, during the other measurements, the net of acequias was always extracting the maximum flow available from the system up to 0.4 cubic meters per second. And that probably that measured base flow corresponds with the flow generated in the last course of the river, from the last of the acequias for each river side

The return of these acequias to the hydrological-hydrogeological system takes place downstream this point, or even in different basins. This is the reason why we cannot measure them at this point. This makes the basin of rio Chico, at this point, clearly in a negative balance.

5. Conclusions

We are dealing with an extremely complex system, very difficult to analyze according to the classical methods used in hydrology, hydrogeology and hydraulics. In the acequias, even the hydrological effect at the hillslope scale in the very proximity of the channel is not clear due to the continuous inflows and outflows of surface and subsurface water with the hillslopes along the acequia through its porous bed, not always easy to locate or justify. At a basin scale, we deduce that the acequias system in upper Chico River are capable of diverting and getting out of the system up to 0.4 cubic meters per second. An important value if we take into account that the mean flow from december to may is 0.6 cubic meters per second. But the role of Barjas in this system is modest, since it is not working at full capacity yet.

There is a three-way interconnection between the shallow aquifers baseflow, the accumulation and melting of the snow, and the acequias themselves that is very difficult to unravel. They affect the hydrological processes at a similar 1-month timescale, what makes it very difficult to distinguish which part of the effects is due to each of them. This timescale has been encounter both in the measurements, like in the baseflow at the Pueblo Alto spring discharge, as in the simulations of the snow processes performed with WiMMed.

The direct impact of the acequias over the river flow may be notorious, as they have the ability to deviate most of the flow at least during dry and moderate years. The spatial redistribution of water will determine which courses of the river are more or less affected by this human impact. In the case of the upper Chico river the impact is maximum for the natural outlet, reaching almost to dry the river during most of the not wet years

Even so, we can affirm that, for example, and considering an irrigation return of 80% of the water used, the annual volume that is incorporated to the aquifer by the surface water use with the Barjas channel will be about 85,000 m3/year. The careo effect results in an increase in Pueblo Alto spring discharge, located out of the upper Chico river basin, with a residence time of approximately 30 days. Besides, the analysis of the values of electrical conductivity of the water perfectly locates the arrival of the artificial contribution of snowmelt water through the *careo* (“*careada”*).