Risks in water management associated with changing climate systems: reflections and case analysis

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Abstract Climate variability, climate change and hydrological variability are distinct phenomena whose effects on water resources can mean, among other consequences, changes in the conditions originally assumed in the design of hydraulic facilities. Hydrological variability takes place when there are changes in the main inputs and/or outputs of a hydrological system (precipitation, evapotranspiration, flows). This paper presents some considerations concerning the hydrological behaviour of river basins in situations associated with climate change, climate variability and hydrological variability. Several case studies in the central region of Argentina illustrate the issues discussed. The considerations presented are intended to contribute to the awareness of new risks that arise in operational water management.

Key words hydrological variability; climate change; climate variability; Argentina

INTRODUCTION

Climate variability, climate change and hydrologic variability are three distinct, but interrelated, phenomena. However, for a proper treatment they should be clearly differentiated. Climate variability is understood as climate variations based on natural conditions of the globe and their interactions. Climate change, meanwhile, is understood as changes of climate variability product of human action, or due to natural variations, e.g. solar activity. Hydrological variability is reflected when changes occur on the main entrances and/or outputs of hydrological systems (precipitation, evapotranspiration and/or discharge). Among its causes are: (a) the natural variability of climate processes, (b) the impact of climate change, and (c) the effects of land use and other anthropogenic alterations of water systems. Therefore, it can represent changes on the conditions originally assumed in the design and operation of water facilities.

This paper presents some considerations about the behaviour of river basins in situations associated with climate change and climate variability. Several case studies, mainly for the central region of Argentina, illustrate the considerations presented.

HYDROLOGICAL AMPLIFICATION OF CLIMATE CHANGE

Usually the relationship between the input and the output hydrological variables of a basin has a nonlinear behaviour. Usually the precipitation, P, is the input with greater spatial variability; in comparative terms evaporation and evapotranspiration often have closer values, mainly in humid regions. Therefore, a change in precipitation is not reflected in the same way over the flow, Q. Hydrological data demonstrate that in those years with extreme values (floods and droughts), the basin response is amplified with respect to the dimensionless variation of P. This phenomenon occurs due to the different relations of proportionality between the values of P and Q (Tucci, 2002). Berbery & Barros (2002) point out that in some cases changes of 1% in P result in changes of 2% or more in Q. Figures 1 and 2 illustrate the hydrological behaviour of the Quinto River Basin (San Luis, Argentina) in the Vulpiani station (5000 km^2). For the period 1971–1989 the areal average rainfall was 678 mm and the annual average runoff was 43.4 (mm year). Figure 1 shows the relationship between P and Q (in dimensionless terms), with a nonlinear hydrological behaviour. The mean linear trend can be interpreted as indicative of the behaviour observed in average years, with differences between extreme years. Figure 2 shows the dimensionless variability of precipitation (P/Pm), flow (Q/Qm) and loss (E/Em). It shows the amplification of the response of the basin with respect to the dimensionless variation of precipitation.

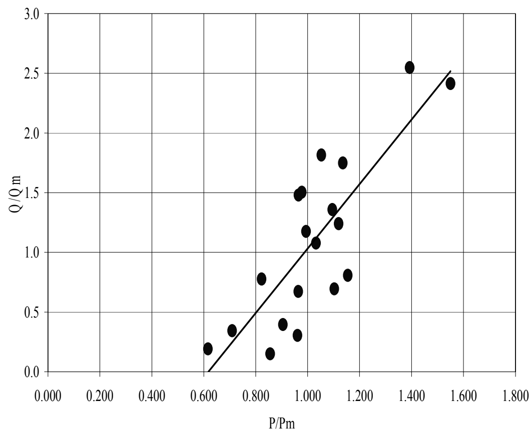

Fig. 1 Dimensionless ratio between runoff and precipitation in the Quinto River basin, Argentina.

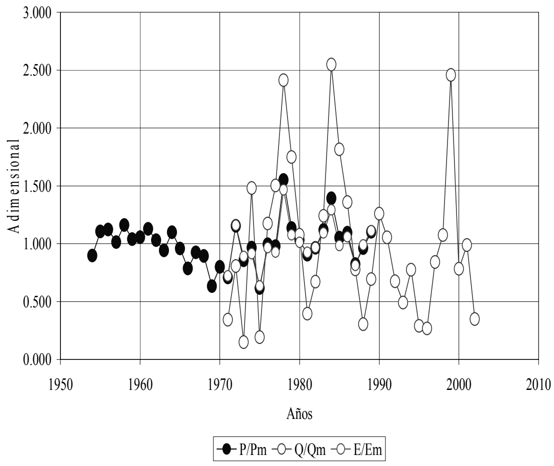

Fig. 2 Dimensionless variability of precipitation (P/Pm), flow (Q/Qm) and loss (E/Em) in the Quinto River basin.

HYDROLOGICAL SPATIAL SCALE AND THE IMPACT OF CLIMATE CHANGE

Often the estimates of climate change and/or climate variability are synthesized as the likely variations of the precipitation. However, the impact of climate variability also depends on the hydrological spatial scale that is considered. This has implications in the field of planning and managing water resources. An increase in annual total rainfall can be significant for large rural catchments as soil moisture increases. Therefore, the likelihood of generating major flooding increases together with the threat associated with the occurrence of the type “riparian” flooding. Nevertheless, in the case of small basins (such as those considered in urban areas), the change in annual total precipitation may not have a substantial practical significance. Instead the intensity of precipitation is of greater interest. Consequently, in the case of large basins, one of the more advisable non-structural measures would be to take action to improve the climate forecast, based on global phenomena. Meanwhile, in small watersheds, specifically urban areas, the major interest should focus on weather forecasting, particularly in the very short term forecasting (nowcasting). In recent years some methods have been proposed for the weather forecast with ranges up to 2 weeks (Collier & Krzysztofowicz, 2000; Golding, 2000). The nowcasting has been promoted from the greater global availability of weather radar data. In Latin America, this trend is beginning to take shape after the installation of equipment and the gradual cooperation between the actions of the national meteorological services and the corresponding agencies responsible for the water resources management.

In several countries of Latin America it is possible to observe a trend of spatial extrapolation of hydrological forecasts, especially for purposes of planning and management of water resources. Often this derives from the lacks of hydrological data. When the extrapolations correspond to basins of different sizes, uncertainties must be considered about the fact of contemplating dissimilar hydrological scales.

The observed variability in hydrological processes at different spatial scales should not be associated, therefore, with that resulting from the climate change and/or climate variability. For example, a soil management practice that tends to reduce surface runoff in a small basin, such as direct seeding, can have a different effect on larger scales. The reduction in runoff in headwater catchments due to increased infiltration and surface storage, can lead to enlarged flow into the larger basins that are located downstream (due to increased base-flow in streams). Tucci (2002) showed these behaviours for some humid basins of Brazil. Extrapolation of specific flows corresponding to different spatial scales may also lead to erroneous estimates, which are sometimes incorrectly associated with the climate change and/or climate variability.

HYDROLOGICAL VARIABILITY FROM CHANGES IN LAND USE

The major changes observed in the behaviour of the hydrological output variables (flows, levels, sediment yield, etc.) usually come from changes in land use such as cutting of trees, changing of crops and/or tillage methods, infrastructure works, etc. Variations in physiographic features also result in changes in the hydrological variability. The cutting of trees tends to decrease the potential evapotranspiration, reduced infiltration and increased runoff flows.

With the increased market value of agricultural commodities, especially soybeans, several countries in South America (particularly Brazil and Argentina) have undergone a major expansion of agricultural frontiers. The central region of Argentina is characterized by its flat relief (Pampa) and it has been typically used for agriculture. Based on data from a peripheral sector of the Pampa, Aoki (2002) showed that changes in surface runoff coefficient for native forest and soybean crop were above 10%; the reductions of base infiltration were of the order of 60 to 5 mm/h. Minor changes were also observed by changes of farming methods.

The physiographic characteristics of watersheds are another distinct factor of the hydrological behaviour. In plain water systems the vertical hydrological processes (precipitation, storage, evapotranspiration, seepage and percolation) are dominating. These systems are characterized by areas with diffuse surface water boundaries and the generation of surface runoff occurs more or less slowly, from the threshold of accumulation.

In Argentina they are called “No Typical Hydrologic Systems” (NTHS), to differentiate them from those “typical” (THS) in which the dominant process is predominantly rainfall–discharge. The NTHS are sensitive to changes caused by human actions, mainly to changes in land use and to alteration produced by roads or artificial drainage channel systems. The typical effects result in delays, diversions and accelerations of runoff. Usually the artificial drainage channels are facilities strongly required by the population (including urban areas) during wet periods. However, the drainage channels systems systematically cause a faster displacement of the natural flood to downstream. Generally, when a channel is designed, the topographic conditions for its realization are checked, but the hydrological consequences of its implementation are rarely analysed. Therefore, there is not always a general overview of the hydrological impact that a drainage channel system can cause.

The lower basin of the Salado River, located in the central region of Argentina (55 950 km^2; 1150 mm mean annual precipitation), is a NTHS that resembles a slightly inclined plane, with regional slopes varying from 0.01 to 0.05%. The implementation of artificial channels has led to a systematic increase in the density of courses capable of draining urban and rural areas. Bertoni *et al.* (1998) estimated that in central and northern regions of Santa Fe State, the artificial channel length was increased by about 42% from its natural condition. This percentage has continuously increased to the present. The relevance of these actions is associated with the fact that, depending on the artificial increase in the capacity of surface drainage, the NTHS may respond as a THS, especially during the occurrence of extreme humidity and rainfall conditions. Consequently, a mathematical hydrological simulation of a NTHS, usually performed with models of cells, distributed algorithms and multiple vertical storages, can be simplified.

In the region the summer period of 2003 was preceded by a stage of extreme humidity and was highlighted in April by three rainy days throughout the SHNT, with an average precipitation of 120 mm (up to 380 mm in some stations). The corresponding flood had extreme characteristics (peak flow: 3950 m^3/s, the highest historic recorded, estimated time to recurrence: 800 years) and resulted in the catastrophic flooding of Santa Fe city, with 400 000 inhabitants, located just off the basin. This was the largest urban flooding in Argentina's history, with loss of human lives and material damage in the region estimated at about US$ 1000 million (CEPAL, 2003).

Bacchiega *et al.* (2004) realized a study to define the consequences caused by the artificial increased of the drainage basin of Cululú Creak, identified the most probable cause of the occurrence of a sudden peak flood over the city. The authors concluded that the increase in flow magnitude was of the order of 30% and the reduction in the arrival times was around 20%, corresponding to a 12 h reduction. The tendency of the NTHS to act like a THS was verified by the hydrological simulation of flood forecasting with the well-known HEC-HMS program calibrated on the base of a prior extreme event. This allowed correct estimations of the order of magnitude of the 2003 flood with the advantage of having the results three days in advance. Thus, the hydrological forecasting was simulated using public free available tools that in critical or risky situations can be converted in appropriate tools.

Actions such as the reduction of vegetation and paving surfaces tend to alter the natural hydrological processes of production and transfer, leading to an increase in volume and runoff flows. These effects are particularly evident in South America, since the region has 77% of its population concentrated in urban areas, with an annual growth rate of 1.5%. In particular, Argentina has 90% of urban population, one of the highest percentages in the region, and it is expected that this percentage will increase to 94% by 2015. As indicated by the World Bank (2000), Argentina occupied the 14th position of countries affected by catastrophes related to urban and rural floods, reaching losses above 1.1% of the Gross National Product (GNP).

Among the main parameters used to represent hydrological conditions of urbanization there are: (a) the percentage of impervious areas of the basin understood as the ratio of surface area through which precipitation enters directly into the drainage system, and (b) time concentration, Tc. Bertoni (2001) analysed the relationship between the percentage of impervious areas and the population density for several Argentinian cities. This relationship is useful for planning purposes. The results allowed the conclusion that, on average, Argentina has a *per capita* percentage of impervious surfaces higher than several Brazilian cities. This is due to the larger number of high buildings in the Brazilian cities and, therefore, the increased concentration of people per m^2. However, Bertoni *et al.* (2000) analysed the variation of Tc in three semi-urbanized basins of the central region of Argentina, two of them located in the city of Rafaela (4.8 and 13.6 km^2) and the other in Villa Carlos Paz city (0.58 km^2). The two Rafaela basins were nested basins. Data from the larger Rafaela basin covered two wet periods, while those from the smaller basin covered only a period of rain. Figure 3 shows the Qmax–Tc relationship for the three basins. It is possible to deduce: (i) the variation of Tc as a function of the magnitude of flow, according to a mean gradient similar in all three cases, and (ii) the effect of flow acceleration produced in the lower basin of Rafaela in relation to total basin as a result of their greater degree of urbanization. The relationships presented have a trend similar to that proposed by SCS (1986) for the graphical version of Tr-55 method.

Hydrological impact of long-term climatic variations

Long-term variations of climate variables (wet or dry anomalies) are important for their effects on hydrological variability. In Argentina, when droughts occur that mainly affect the most humid region of the country, the situation becomes more complex, with serious socio-economic consequences. Argentina has the highest percentage of land in arid and semi-arid areas of South America (66%). Nonetheless, in this country the droughts do not receive proper attention, mainly related to planning actions for the public and private sectors and during formulation of the corresponding contingency plans.

In practical terms, the major hydrological impacts of droughts are related to: (a) drinking water systems, and (b) hydropower systems. Both types of system are intended to address both seasonal as well as short-term variations (2–4 years). However, the biggest impact occurs when there are long-term inter-annual variations (5–10 years or more), with effects that tend to collapse the systems.

In the central region of Argentina the phenomenon of drought has occurred in recent years, after a relatively wet period that extended from the 1970s. A typical case related to inter-annual climate variations is observed in the operation of water supply to the Metropolitan area of the city of Córdoba (MCC). Vicario *et al.* (2009) characterized the drought that occurred in the region based on data from the period 1943–1999 in San Roque station, as being representative of the climate of the main contribution basin for the supply system. The results represented short-term inter-annual variations, and have already put the supply system in critical situations. Figure 4 illustrates the precipitation index variations (SPI), which considers the probability of occurrence of precipitation for a given period.

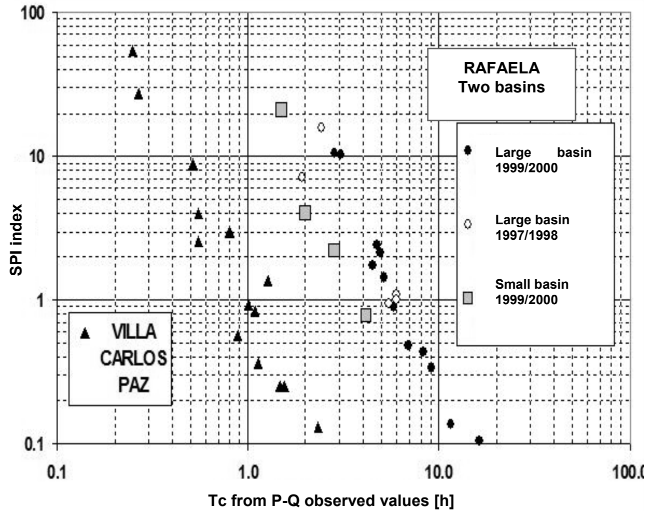

Fig.3 Specific Qmax–Tc ratio in three semi-urbanized basins (central region of Argentina).

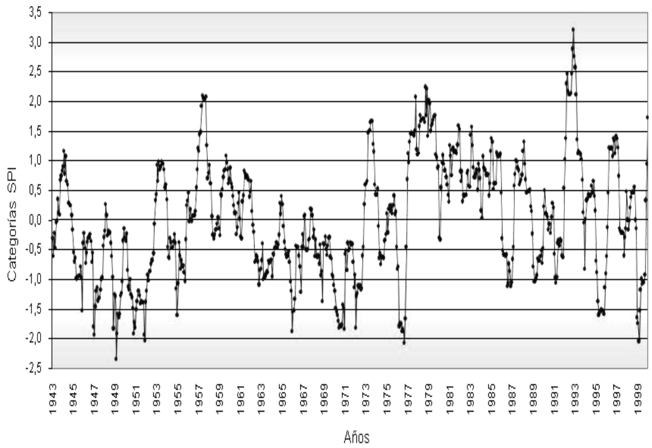

Fig. 4 SPI index applied to San Roque station (1943–1999 period; Cordoba, Argentina).

The study led to an estimate that the multi-annual period with severe and extreme droughts alternated in a cyclic manner every 10 years. Intense and prolonged droughts occurred in the second half of the 1940s and between the late 1960s and early 1970s; since then there has been a trend with wet periods. Moreover, in the case of the water supply system of MCC, additional factors complicate the picture, among these: (i) the substantial increase in population, (ii) the absence of a policy aimed to achieve a greater efficiency with the sources already available, (iii) lack of management of demand, and (iv) lack of investment in new storage dams (partly due to environmental pressure).

With regard to long-term variations of climate and it impacts in hydropower systems, it is worth mentioning that in recent years the pressure from environmental groups has been reflected in the adoption of new criteria for the proposed dams. One of these is to circumscribe the upper bound of the new reservoirs to the maximum flood line caused by the largest historical floods. This reduces the size of the dam, and therefore, to produce the equivalent energy the number of dams should be increased. The adequacy of the proposed Garabí Dam project, in the shared sector of Uruguay River between Argentina and Brazil, includes this restriction. If this trend continues the hydropower systems will grow in terms of energy generated, but not in regulatory capacity. Then, their vulnerability to the occurrence of long-term variations of climate, especially during prolonged drought, will be more important.

CONCLUSIONS

Changes in climate, natural or man-made, results in effects on hydrological variability. The hydrological effects of changes in the input variables can be different depending on the hydrological spatial scale considered. The same applies with regard to mitigating measurements. In countries such as Argentina, long-term variations of climate are especially important because they can cause critical situations linked to increased social vulnerability. Among the more predictable are river flooding, problems related to water supply, and hydropower system reliability. The above aspects are important in the field of planning and management of water resources as they can provide a basis for identifying areas where it would be essential to address specific contingency plans based on the risks associated with climate variability, change climate and hydrological variability.

REFERENCES

Aoki, A. (2002) Characterization of hydraulic properties as quality indicators of a Haplustol typical soil from Central Cordoba State, Argentina. Master's thesis. FCA, UNC-UNRC. Argentina (in Spanish).

Bacchiega, D.; Bertoni, J. C. & Maza, J. A. (2004) Hydraulic expertise relating to the Judicial Process no. 1341/2003. Juzgado de Instrucción Penal de la 7ma. Nominación. Poder Judicial de la Provincia de Santa Fe, Argentina (in Spanish).

Berbery, E. & Barros, V. (2002) The hydrologic cycle of the La Plata basin in South America. *J. Hydromet.* **3**, 630–645.

Bertoni, J. C. (2001) Etude hydrologique et analyse des incertitudes sur trois bassins versants semi urbanisés de la région centrale d'Argentine. These de Doctorat. École Doctorale Sciences de la Terre et de l'Eau. Université des Sciences Montpellier II, Montpellier. France.

Bertoni, J. C., Zucarelli, G. V., Morresi, M. V. & Rodríguez, D. (1998) Physiographic and hydraulic aspects related to the drainage network of Santa Fe State. *XVII Congreso Nacional del Agua* **2**, 364–373. Santa Fe, Argentina (in Spanish).

Bertoni, J. C., Chevallier, P., Bouvier, C. & Desbordes, M. (2000) Analysis on the estimation of concentration time: application to three semi urbanized basins of the central region of Argentina. In: *Proc. XIX Congreso Latinoamericano de Hidráulica, II*, 349–359 (in Spanish).

CEPAL (2003) Assessing the impact of flooding due to Salado River in the Santa Fe State, Argentina, 2003. Naciones Unidas. CEPAL/ LC/BUE/R.246 (in Spanish).

Collier, C. G. & Krzysztofowicz, R. (2000) Quantitative precipitation forecasting. *J. Hydrol.* **239**, 1–2.

Golding, B. W. (2000) Quantitative precipitation forecasting in the UK. *J. Hydrol*. **239**, 286–305.

Soil Conservation Service (SCS) (1986) Urban hydrology for small watersheds. In: *Tech. Realease no 55 Revision.* Water. Resources Publ., Colorado, USA.

Tucci, C. E. M. (2002) Impacts of climate variability and land use on water resources. Agencia Nacional de Aguas, ANA. Forum Brasileiro de Mudanças Climáticas, Brazil (in Portuguese).

Vicario, L., Ravelo, A., Bertoni, J. C. & Rodríguez, A. (2009) Frequency analysis of intensities of drought in the San Roque dam basin. Córdoba State, Argentina. In: *Memorias del XXII Congreso Nacional del Agua* (Chubut, Argentina) (in Spanish).

Work Bank (2000) Argentina: Management of water resources. Elements of policy for a sustainable development in the XXI century, vol. I. Report no. 20729-AR.