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Some scientific challenges in the development of South America's water resources

CARLOS E. M. TUCCI

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CARLOS E. M. TUCCI
Institute of Hydraulic Research, Federal University of Rio Grande do Sul, Rua Lavradio 150, 90690-370 Porto Alegre, RS, Brazil
e-mail: carlos.tucci@ufrgs.br

Abstract The natural environment of South America is enormously variable. It includes the tropical forests of the Amazon basin, the rich wetlands of the Pantanal, La Plata basin where human influences are predominant, the semiarid regions of Brazil, Argentina and Peru, as well as the high-altitude lakes of Bolivia. It is difficult to deal in depth with all aspects related to such a diversified environment. Consequently, a few selected topics concerned with water resources, economic development and scientific challenges are discussed. They are: (a) climatic variability and its effects on hydropower production and land use; (b) environmental management of the urban environment; and (c) sustainable water management in semiarid regions.

Key words climate; urban water; semiarid regions; South America

Quelques défis scientifiques pour le développement des ressources en eau en Amérique du Sud

Résumé L'environnement naturel de l'Amérique du Sud est énormément variable. Il comprend les forêts tropicales du Bassin de l'Amazone, les riches marécages du Pantanal, le Bassin de La Plata où prédomine l'influence humaine, les régions semi-arides du Brésil, de l'Argentine et du Pérou, ainsi que les lacs de haute altitude de Bolivie. Il est difficile de traiter en profondeur de tous les aspects concernant un environnement aussi diversifié. Ce travail discute donc de quelques questions choisies au sujet des ressources en eau, du développement économique et de défis scientifiques. Il s'agit en l'occurrence de: (a) la variabilité climatique et ses effets sur la production hydroélectrique et l'utilisation du sol; (b) la gestion environnementale en milieu urbain; et (c) la gestion durable de l'eau en régions semi-arides.

Mots clefs climat; eau urbaine; régions semi-arides; Amérique du Sud

INTRODUCTION

The principal points of concern relating to water resources and the environment have evolved according to themes that touch upon society as shown in Table 1. This compares the status of developed countries with that of Brazil (a developing country with about 50% of the population and area of South America). It can be seen that concern about the environment grew strongly from 1970 onwards. With the 1980s marked by the accident at Chernobyl, society came to see that climate and the factors which influence it must be considered at large, even global, scales. The result was worldwide concern about climate and the effects of human activities on it. The 1990s were marked by the search for sustainable development, and in the decade that we are now entering, there is widespread concern about water, its uses, and the consequences of the way it is used.

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Table 1 The main issues for water resources and the environment.

Period	Developed countries	Brazil
1945–1960 *Large investments in hydraulic works*	Water resources uses: navigation, irrigation, hydropower, potable water supply, recreation, etc.	Watershed inventories, potable water supply; start of small-scale hydropower works and some important projects.
1960–1970 *Environmental impacts*	Urban development and industrial impacts; non-structural measures for flood control.	Start of large-scale water resource projects; improvements to water supply systems.
1970–1980 *Pressure for environmental control*	Urban waste control; introduction of environmental legislation; source control in urban drainage; groundwater contamination and impacts.	Emphasis on hydropower and water supply projects; start of environmental pressure; deterioration of surface water quality due to increased industrial use and discharge of untreated wastewater.
1980–1990 *Interactions of world environment*	Global climate impacts; forest conservation; disaster prevention; rural nonpoint sources of pollution; urban control: drainage, sediments, and rainwater quality.	Reduction in international loans for of hydropower; deterioration of urban conditions: floods and water quality contamination; drought impacts in the Brazilian northeast; environmental legislation.
1990–2000 *Sustainable development*	Sustainable development; improved knowledge of environmental behaviour and the changes caused by human activities; environmental control in large metropolitan areas; gas emission control; preservation of the ozone layer; pollution of aquifers; nuclear waste; increasing impact of nonpoint sources and their control.	Legislation on water resources management; increased investment on sanitation control in major cities; increased impacts of floods and water quality problems in cities; environmental conservation efforts and development of the Amazon, Pantanal and coastal areas; beginning of privatization of the energy sector and of obtaining thermal energy from gas.
2000– *Water issues*	World water vision for development of water resources; integrated water resources development; improvement in water quality from non-point sources: rural and urban; improved transboundary water use in conflict areas.	improved institutional aspects of water management through implementation of the water law; privatization of the energy sector and increase in the thermal capacity; privatization of the sanitation sector; improved water availability for the northeast; development of urban drainage and sanitation plans for the cities.

The technological developments of recent decades have resulted in a significant increase in the quality of life for one part of the world's population. Most of the remainder have yet to benefit from these developments and the thrust of international assistance is to bring this about. Some of the main challenges to society arising from the evolution of technology are discussed in the following sections.

The pressure that society exerts on the environment

Development tends to exert pressure on natural resources particularly when (a) the control of human activities is ineffective, and (b) the impacts of development are not understood. The first of these occurs most often in poor and developing countries, where the need for growth and improvement in the quality of life takes precedence over environmental considerations. The second is much more a problem of more advanced societies, where a great range of products (especially chemical) continues to emerge without sufficient understanding of their complex interactions with the environment and with their potential to threaten the improved quality of life resulting from the development.

The impacts of climate variation on society

As the demands for water resources of an increasingly sophisticated society increase, together with its requirement that such resources be sustainable, climatic fluctuations can bring about conditions which prejudice this sustainability in the medium term.

In South America, where all countries can be regarded as being in the course of development, the principal challenges are: (a) how to develop and acquire the quality of life desired by the population without damaging the available natural resources; and (b) how variations in climate might affect the environment, which, in turn, will impact upon the planning for growth.

CLIMATE VARIABILITY AND ITS EFFECTS

La Plata River basin

The 3 million km^2 of La Plata basin (Fig. 1) produce more than half of the gross national product (GNP) of South America. In terms of area, the drainage basin of La Plata River is second only to that of the Amazon in South America, and it is the fifth largest in the world. It is shared among five countries—Argentina, Bolivia, Brazil, Paraguay and Uruguay—through the principal sub-basins of the rivers Paraná, Paraguay and Uruguay. La Plata basin is important in different ways for the economy of each; about 70% of the total GNP of the five countries combined is produced within the basin, which is also inhabited by about 50% of their combined population.

The hydrological behaviour of the main rivers draining La Plata basin is the product of basin topography—itself a product of geology and climate—and human activities within its boundaries. Natural conditions vary greatly from north to south (the general direction of drainage) and from west to east. In the eastern half of the basin, the basin boundary is clearly defined with a mean altitude of 1000 m; however the water divide can reach 1500 m in the extreme eastern part, but falls to as low as 200 m in the south. On the western boundary, the Andean cordillera reaches altitudes of between 1000 and 4000 m, although there are stretches of this western basin boundary, notably in the northwest and southwest, where altitudes reach only about 500 and 300 m, respectively.

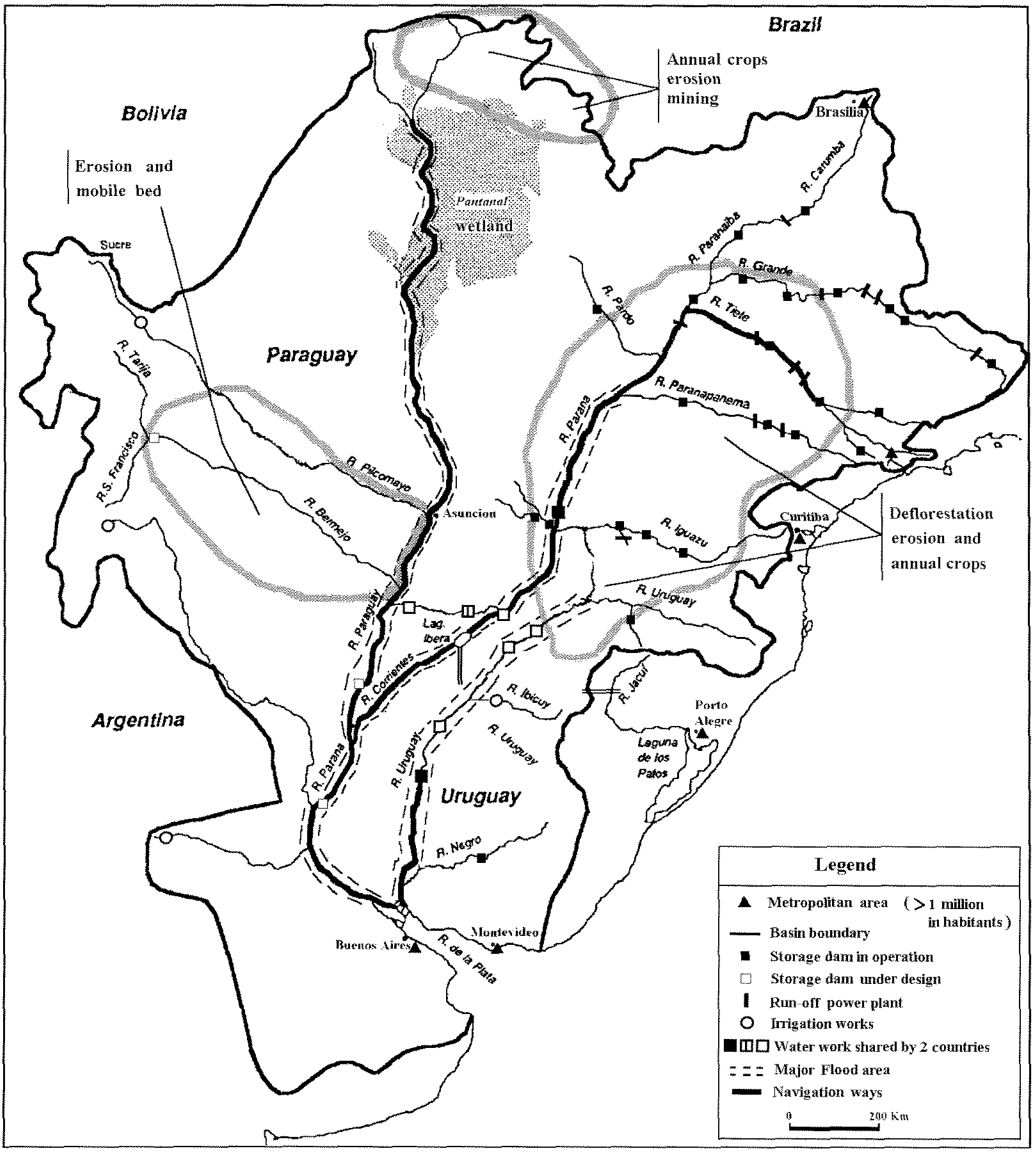

Fig. 1 Water resources development in La Plata basin.

The mean annual rainfall decreases both from north to south, and from east to west; rainfall in the maritime uplands along the Brazilian coast reaches about 1800 mm, but falls to 200 mm along the western boundary of the basin. Rainfall is greatest in the upper parts of both the Paraguay and Paraná river basins. The specific yield of the Paraguay is 2.47 $l\ s^{-1}\ km^{-2}$, compared with 11.72 $l\ s^{-1}\ km^{-2}$ for the Paraná. The difference (a factor of 4.75) can partly be explained by high evaporation losses in the wetlands lying in the upper reaches of the Paraguay, particularly the Pantanal wetland described below.

Impacts

Some of the main issues related to water resources in the basin, shown in Fig. 1, are (Tucci & Clarke, 1998):

- deforestation and intensive agriculture in the Paraguay, Paraná and Uruguay basins: the agricultural expansion since the 1960s, mainly in Brazil, has left some areas with only 5% of natural cover;
- developments of many hydropower projects in the Paraná River: most of the hydropower of Brazil, and indeed of South America, comes from this basin: dams have modified the regimes of rivers and environmental conditions both upstream and downstream;
- climate variations: hydrological records show increases in both rainfall and runoff after 1970: the increases have had important impacts in areas such as the Pantanal, in the the River Paraguay basin, and in the River Paraná basin;
- environmental degradation in the main cities: the population of the region is highly concentrated in urban areas; in the Brazilian State of São Paulo, 92% of its 36 million population is in cities—urban development has affected the environment severely;
- proposed improvements to navigation in the Upper Paraguay will have grave consequences for the Pantanal wetland; and
- the floods in the main rivers have resulted in extensive damage, particularly since the 1980s.

Climate variations observed in La Plata basin have affected the economy and the well-being of its population. Table 2 shows that, since 1970, flows have been about 30% greater than in the previous period. The same effect was observed in the River Paraguay, which flows through the Pantanal region, one of the great wetlands of the world with an area of about 140 000 km^2. Over much of this region, significant changes in land use have occurred, as well as a small increase in rainfall. It is interesting that in sub-Saharan West Africa the effect was the opposite, with above average rainfall occurring before and below average rainfall after 1970. What are the causes of such climate variation? Are the processes in the two continents related? The main consequences of the increased flow are discussed below.

Table 2 Mean annual discharge in m^3 s^{-1} (Tucci & Clarke, 1998).

River section	Before 1970	1970–1990	Increase (%)
Paraná at Jupiá	5 852†	6 969	19.1
Paranapanema at Rosana	1 057†	1 545	46.2
Paraná at São José	6 900†	8 520	23.3
Paraná at Guaira	8 620†	11 560	34.1
Paraná at Posadas	11 600*	14 255	22.9
Paraná at Corrientes	15 265	19 510	27.8

* series from 1901 to 1970.
† series from 1930 to 1970.

Hydropower Much of the hydropower produced by Brazil (>70%), all the hydropower generated by Uruguay, and a significant part of Argentina's hydropower is produced in the Paraná basin. In the case of Brazil, 93% of its energy comes from hydropower, and the proportion is also significant for Uruguay. Because average flow has increased, generating plants have increased their output, the production representing an important economic gain for the sector. The following question therefore arises: Is this gain permanent? If the increase results from changes in land use, the gain is permanent, in spite of silt deposits in reservoirs reducing their useful life. If it results from climate fluctuation, the gain may be transient, so that if investment in energy production is made on the assumption that the increase is permanent, the system will eventually enter a critical state when it will be unable to meet demands.

These countries are at present in the process of privatizing their electric power systems. For a system that is strongly based on hydropower and with private investment, there is a natural equilibrium between supply and demand. The possibility therefore arises of a potential economic imbalance between supply and demand, since sequences of years with below-average flow could result in an exaggerated increase in the cost of energy.

In the Paraguay and Paraná basins, extensive areas that were formerly free of flooding became flooded for 7–9 months of the year for many years, disturbing the economic balance between the natural environment and the flood-plain population, which lived by cattle ranching. A part of this population has moved to the cities, and now lives in poor conditions.

Challenges

Faced with such problems, the scientific challenge is to find answers that will benefit society:
- to develop tools that allow changes in hydrological processes to be identified, as a consequence of land-use change and other human activities, in large basins greater than 30 000 km^2;
- to improve the precision of medium- and long-term climatic and hydrological forecasts (up to 6 months) in order to minimize the impact of climate on the development of society; and
- to improve the long-term evaluation of yield for water resources risk analysis used in water planning.

URBAN DEVELOPMENT

The countries in South America are usually classified as *developing,* based on social economic indicators. The continent has experienced widespread urbanization in recent decades. In most countries, the urban population is more than 75% of the total. In developing countries the population increase is still high and the trend to stabilization is forecast to be reached after 2150. Figure 2 shows some of the important cities of the continent. Among the twenty largest cities in the world South America has three (Table 3).

Urban development in developing countries creates a dense population in small areas, poor public transport, lack of some water facilities, and polluted air and water. Such poor environmental conditions are the main concern for the quality of life in these areas.

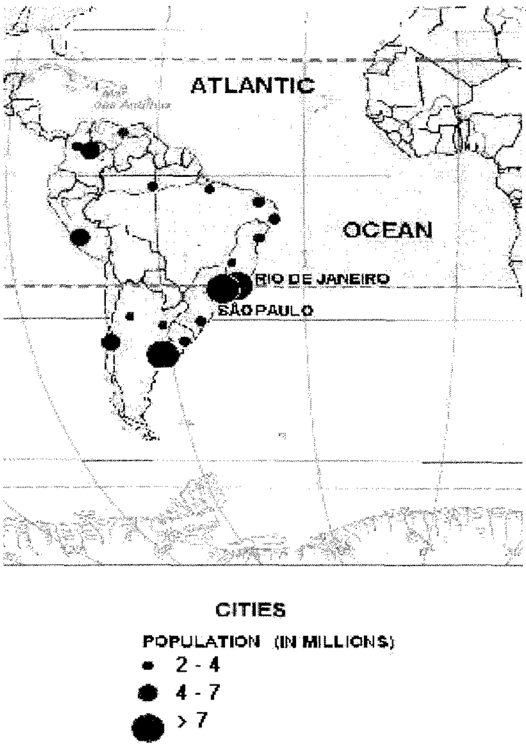

Fig. 2 Some of the major cities in South America.

Table 3 The world's largest cities.

City	Population (millions)
Tokyo	27.8
Mumbai	18.0
Sao Paulo	**17.8**
Shanghai	17.0
New York	16.6
Mexico City	16.3
Beijing	14.2
Djakarta	14.0
Lagos	13.5
Los Angeles	13.0
Calcutta	12.6
Tianjin	12.0
Karachi	12.0
Seoul	12.0
New Delhi	11.6
Buenos Aires	**11.3**
Manila	10.8
Cairo	10.7
Osaka	10.6
Rio de Janeiro	**10.2**

(South American cities are in bold type).

Table 4 Water aspects in urban areas of developing countries and the main alternatives and issues.

Water	Alternatives	Main issues
Resources	Surface flow Groundwater	Contamination from domestic, industrial and agricultural waste
Water supply	Treatment plants and water supply network Supply from wells with some treatment	Water losses due to network leakage Water contamination by chemical compounds
Sanitation	Network and major treatment plants Condominium waste treatment Well disposal without treatment Network and disposal without treatment	Sewer networks without waste treatment Groundwater contamination Lack of waste treatment
Drainage	Separate sewers Combined sewers No storm sewer	Overflow of combined sewers; In separate systems part of the sewage flow is linked into the storm sewers Lack of flow control when urbanization increases
Flood hazard	Structural Non-structural	Flood plain occupation with urbanization Lack of law enforcement in flood zoning

A major part of this urban population lives in squatter settlements (*favelas* in Brazil or *barrios* in Venezuela). Caracas has over 50% of its population in this type of settlement. These slums are built out of cardboard and scrap material in areas which can be flooded, or are located on steep hillsides. After a few years, this kind of construction improves and better materials are used, but the settlements are labyrinths of small streets without any planning for water supply, waste disposal and drainage (The Economist, 1998).

Table 4 presents the main problems related to water in urban areas in developing countries and the control alternatives. These conditions are highly interrelated, since sewage is usually the main source of contamination of water sources.

Because the process is uncontrolled and the public response to it inconsistent, urban development has had significant impacts both on the natural environment and on the human population. The principal impacts have been:

- contamination of urban water supply with a reduced supply of water of acceptable quality;
- lack of adequate treatment and disposal of industrial and domestic wastewater and solid residues;
- increased flooding and contamination from urban runoff; and
- settlement on areas at risk from flooding.

Wright (1997) evaluated the approach used in developing countries for sanitation and his main conclusions are:

- The *supply driven approach*, in which planning and construction methods are based on practices in developed countries, do not take full account of user needs. This often results in a poor return on investments, failure to recover costs and undermining of prospects for new investments. In Accra, Ghana, for example, after 20 years, only 130 connections had been made to a sewage system designed for 2000 connections.

- *Lack of management*: difficulties in financing, little contact with customers, too much centralization;
- *Macro vs micro projects*: an abundance of high-cost projects in which the cost cannot be recovered from a poverty-stricken population;
- *Poor system performance*: the system operation and maintenance do not present an appropriate performance.

Wright's suggestions were: a broader choice of technology options; recognition and analysis of consumers' willingness to pay for perceived benefits; optimum coverage with economic efficiency; innovative financing mechanisms and institutional frameworks; capacity building at all levels; and increase of user participation.

Challenges

The principal challenge in this field is to search for solutions that are economically viable in a context where large numbers of the population have low incomes and live in poor conditions.

At first sight this may not appear to be a scientific challenge; however, good water resources planning and management require not only the application of mathematical, statistical, physical and biological techniques, but also the growth of appropriate management institutions that make service to society possible.

SUSTAINABILITY IN SEMIARID REGIONS

The Brazilian Northeast

In semiarid regions, the long-term sustainability of water resources is generally fragile. A sequence of years in which water supplies are adequate results in a certain population stability, but if this is followed by long dry periods, the consequences are serious and there is migration to other regions. As the population becomes poorer, adverse health impacts are inevitable.

Sixty percent of the Brazilian Northeast (about 0.9 million km^2) is semiarid. This area is about 10% of Brazil and 5% of South America. Over an extensive area of northeastern Brazil, a combination of the following unfavourable conditions occurs frequently:

- annual rainfall is below 600 mm;
- annual evaporation is above 2500 mm, with high temperatures throughout the year;
- the soils are shallow with low storage capacity;
- the mean annual specific flow is below 4 l s^{-1} km^{-1};
- there are no permanent rivers; and
- in most of the area there is only rock and, even where soil does exist, the water is frequently saline.

Water is the fundamental factor for development. People can live with a seasonal dry period each year, but when these extend over several years they have a destabilizing effect on the population.

There are difficulties in regulating flows using traditional techniques: evaporation is very high, greatly reducing the storage volume of reservoirs, which is not great at the outset. The most critical conditions occur when there is a sequence of dry years. Although the solution generally attempted is to build reservoirs to control flow over a period longer than a year, severe problems of high evaporation losses and salinization due to long residence times are encountered. Furthermore, there are problems in addition to salinization when underground storage is used, even where sub-soil exists.

The consequences of these physical and climatic limitations are severe, resulting in significant disadvantages for health, education and sustainable development.

Challenges

The challenges that nature presents in regions where insufficient water severely limits social and economic development require scientific and technological solutions, for which the following are needed:

- an understanding of the main hydrological processes operating at the sub-basin and basin scales;
- technical solutions that allow the population to sustain itself in the critical years of drought, at different scales of water-resource usage, water availability and improvement in socio-economic conditions; and
- adequate management of water resources at short, intermediate and long time scales. These challenges require the interdisciplinary application of scientific knowledge for the benefit of society as a whole.

CONCLUSIONS

A series of problems faced by South American society has been described requiring an innovative input from the hydrological sciences that is aimed at improving the quality of life, whilst conserving the environment. The main conclusion to be drawn from this analysis is that, when dealing with water resources, it is not possible to import solutions that have been developed under different conditions. The interacting factors of natural resources and human activity involve such a large number of cross-disciplinary components that each problem requires a separate approach. It is therefore essential to train professionals to have the necessary broad approach to enable them to work in these regions, with the ability to identify their problems clearly and to find solutions relevant to the regional realities. The innovative capacity of the researcher and of his or her science must be the basis on which such solutions can be sought and from which society can develop.

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