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GROUNDWATER/SURFACE-WATER CONJUNCTIVE USE, MENDOZA PROVINCE, ARGENTINA: I. PHYSICAL AND HYDROGEOLOGICAL SETTING

Timothy D. Steele [1], Jaime Suclla F. [2], and Armando A. Llop [3]

ABSTRACT: Groundwater resources of the Mendoza Province region of Argentina are derived and are replenished by streamflows largely originating from the Andes Mountains from the west and are generally conveyed through rivers and arroyos. This surface-water conveyance process affects groundwater through diversions, irrigation, and subsurface infiltration from channels, canals, and irrigated lands. By means of engineered structures (dams, channel diversions, and canals), surface waters are conveyed to irrigated lands, the principal basis of the regional economy of the Mendoza Province. Although relative intensive irrigation development has been achieved in the Mendoza River/lower Tunuyán River systems, increased irrigation through conjunctive-use strategies are being promoted in three other regions – upper Tunuyán River, the Atuel-Diamante Rivers, and the middle-valley region (Atuel-Salado-Malargüe Rivers) to the south

For aquifer systems, recharge by water percolation general occurs in unconfined zones, tending to be located in the western parts of irrigation oases (regions). Groundwater-flow gradients initial are in an easterly direction, with variations downgradient affected by topography, subsurface stratigraphy, and associated subsurface hydraulic properties. Exception to this general depiction of recharge to shallow aquifer zones occur locally, due to geological anomalies, over-exploitation of groundwater, and infiltrating waters from industrial and municipal/domestic wastewater discharges.

Salinity problems are increasing in the Province, due to growing water demands and poor well construction. Subsurface water movement tends to dissolve salts. Near-surface groundwater, because of evaporation and evaporation, tends to concentrate salts inherent in the water. Aquifer systems in the eastern part of the Province tend to be comprised of multiple zones. This aquifer-zone segregation is impacted adversely in localized subareas by discontinuous interbedded layers and by poorly constructed wells, allowing interzonal mixing of groundwater. In several areas, groundwater pumping has been excessive, resulting in overexploitation. These factors all have aggregated the process of salinization.

This general regional groundwater-resources characterization and groundwater/surface-water conjunctive-use framework are being evaluated for attaining efficient water-resources management and for promoting sustainable economic development. The modernization/rehabilitation components of a major FAO project are critical in achieving these goals in the Mendoza Province.

KEY TERMS: Conjunctive use, irrigation systems, groundwater, surface-water diversions, water supply, salinity, Argentina

INTRODUCTION

Between September 2001 and March 2002, the primary author conducted a consultancy on behalf of the Food & Agricultural Organization (FAO) in Mendoza, Argentina (Steele, 2002). This consultancy focused upon developing a general understanding and a comprehensive characterization of groundwater resources and conjunctive-use practices critical to irrigation and involving four oases (regions) in the Mendoza Province: (1) the North Zone (Mendoza River, including the lower Tunuyán River), (2) the Central Zone (upper Tunuyán River), and (3) two regions in the southern part of the Mendoza Province (the Atuel-Diamante Rivers and the Atuel-Salado-Malargüe Rivers).

A primary purpose of this FAO consultancy was to provide a general framework for groundwater-resources planning and management for the Mendoza Province. This work relied on review of the technical literature, discussions with local professionals, field-site observations, to gain knowledge and understanding of the groundwater resources of these regions. The interrelationship of groundwater resources with other hydrologic components, namely surface-water/groundwater interactions, forms an integral part of water planning, management, and uses in the Mendoza Province.

[1] International Groundwater Consultant, TDS Consulting Inc., 595 West Meadow Road, Evergreen, CO 80439-9745 USA, Phone: 303-674-0266, E-mail: TDSConsult@aol.com; [2] Principal Technical Assessor (ATP), FAO, c/o DGI, Av. España y Barcala, 5500 Mendoza, Argentina, Phone: 54-261-429-2802 or 54-261-420-2117, E-mail: jsuclla@irrigacion.gov.ar; and [3] Director, National Water Institute (INA), Center of Economics, Legislation, and Administration of Water, Belgrano 210 West, 5500 Mendoza, Argentina, Phone: 54-261-428 5416 or 54-261-428-5284, E-mail: celaa@piemza.edu.ar.

Several basic technical issues and concerns involving groundwater-resources management in the Mendoza Province have been identified. Extensive data-collection efforts and interpretative investigations have been conducted by local (Provincial) and national scientists and engineers (Steele, 2002). International donor agencies (UN, The World Bank, FAO, and UNDP) have supported studies addressing water-resources planning and management and aspects applicable to the Mendoza Province. Key concerns address how much groundwater is available, both from a physical and economic standpoint, what are the chemical characteristics, and what role this critical resource plays in regional water uses (predominately irrigation agriculture). Relevant issues include: hydrologic balances, groundwater availability, groundwater uses (past, present, and future), and adverse impacts of groundwater development, such as salinity and changes in groundwater recharge due to increased clear-water streamflow diversions. Pending operations of Potrerillos Dam and current irrigation/drainage rehabilitation efforts by FAO will affect the present conditions of surface-water/groundwater interactions in with regard to water-use management in the Mendoza Province.

The Mendoza Provincial Water-Resources Plan (Government of Mendoza, 1999) includes a compilation of useful information including the physical setting, institutional and water-administrative aspects, and water-policy and payment issues. It is important to assess what are the present and proposed administrative, institutional, and economic factors and regulations for sustainable use and protection of these resources (Contijoch, 2002). Water-policy (including groundwater) statements have been made; however, more critical is how these statements are implemented as a matter of practicality. Issues include: (a) a preponderance of private (unregistered) wells which to date operate without any central controls, (b) lack of coordinated resource management between groundwater and surface-water resources (physically and administratively), and (c) an identified critical need to inventory groundwater use and to monitor groundwater [quantity (water-level) and quality] changes in conditions both in areally and over time. Regarding the second aspect, the role of water-user associations (WUAs), historically having principal concern with surface-water-based irrigation systems, now has to include groundwater use and conditions as well within the overall context of efficient water-resources operations.

Physical Aspects

Groundwater Development and Sustainable Use

Reports summarizing information and data are for irrigation-related regions of the Mendoza Province have been completed by the National Institute of Water (INA) on behalf of the Departamento General de Irrigación (DGI) through a contract with FAO. INA and DGI have conducted numerous field and modeling investigations associated with regional groundwater resources and associated problems and issues related to water quality. Several aspects of water availability, use, and resource management as applicable to the Mendoza Province are given as follows. Basin-specific water-resources allocations of water beneficial uses are given by The World Bank (2000, Annex E-4, Table 3). This regional water-resources beneficial-use distribution is as follows (units of H m^3/yr):

Basin	Agua Potable	Agrícola	Industrial	Riego Público	Total
Mendoza River	192	946	1.8	22	1,161
Upper Tunuyán River	2.8	765	0	13	781
Lower Tunuyán River	0	1,023	0	0	1,023
Subtotals:	195	2,734	1.8	35	2,965
% of Total:	*87*	*57*	*56*	*14*	*57*
Diamante River	29	1,020	0.8	20	1,069
Atuel River	0	958	0.5	0.8	959
Malargüe River	0.2	51	0.1	200	251
Subtotals:	29	2,029	1.4	221	2,279
% of Total:	*13*	*43*	*44*	*86*	*43*
Grand Total:	**224**	**4,763**	**3**	**256**	**5,244**

A similar breakdown of uses by region supplied by groundwater is given in Steele (2002). It should be noted that 91 percent of all water use is attributed to the agricultural sector. Groundwater supplies 7.3 percent of the overall water use, 22 percent of the potable water supplies, and 5.8 percent of the agricultural use. These contributions underlie the critical situation regarding groundwater in overall regional water-resources planning and management and future economic development for the Mendoza Province. With this in mind, the following premises provide the framework to this overview:

- Sustainable groundwater-resources management is more than an institutional or political goal -- it should be understood, be accepted, and have the consensus of the general beneficiaries of this resource -- the inhabitants and visitors (in other words, the beneficial water users) in the Mendoza Province.

- Resource-management decisions have inherent uncertainties. Any implemented water-resources management program should be accompanied by physical monitoring and monetary accountability, in order to insure that anticipated outcomes and benefits in fact are taking place and justify the necessary costs incurred. Moreover, such tracking procedures are used as the basis for modifying the management program to bring it more in line with its long-term objectives -- in this case, encompassing the goal of sustainable water-resources management.

Considering the physical setting in the Mendoza Province, the following basic premises need to be considered:

- Groundwater resources are derived and are replenished by streamflows largely originating from the Andes Mountains from the west and generally conveyed through rivers and arroyos. This surface-water conveyance process affects groundwater through diversions, irrigation, and subsurface infiltration from channels, canals, and irrigated lands.
- The general direction of water movement in this process is from west to east. For aquifer systems, recharge by water percolation generally occurs in unconfined zones tending to be located in the western parts of regions. Groundwater flow gradients initially are in a western direction, with variation downgradient as affected by topography, subsurface stratigraphy, and associated hydraulic properties of the subsurface. Exceptions to this general depiction of recharge to shallow aquifer zones occur in the case of localized infiltrating waters, such as from industrial and municipal/domestic wastewater discharges. The critical issue of increasing salinization in groundwater and soils is discussed below.

This general regional groundwater-resource characterization then is linked to the concept of *sustainable* resource management. The key underlying question is: *How much and how groundwater can be used over time so that no long-term adverse conditions occur over time or in space?*

Water Availability

Using existing studies and data, regional INA studies provided the FAO project with updated information regarding regional estimates of surface-water (in units of H m^3/yr) and groundwater availability(in units of H m^3). For two of the regions (Mendoza River and lower Tunuyán River), apparent trends of reduced streamflows are judged to have occurred.

Region (Oasis)	Surface Water	(period)	Groundwater	[Comments]
Mendoza River	1,471	(1967-1983)	600,000-650,000	total volume in storage
	1,271	(1991-2000)	22,000	economically exploitable
Lower Tunuyán River	989	(1967-1983)		
	954	(1991-2000)		
Upper Tunuyán River	954	(probably recent period)	95,000	*[GW data are limited]*
Diamante River	1,160		32,500	(both areas)
Lower Atuel River	1,095			South Region
Atuel-Salado-Malargüe Rivers	1,710		130,000	*[complex, little GW data]*

In summary, through long-term hydrologic data-collection programs, estimates have been made regarding surface-water inflows to and groundwater storage in the various oases (regions). Time trends of decreasing flows have been documented for only the Mendoza River and Tunuyán River stream systems. Time variability (seasonal and year-to-year) as well as any trend over time has ramifications regarding long-term water-resources availability and sustainable use. Groundwater overexploitation is most prevalent in the Mendoza Norte region and eastern part of the Mendoza Province.

Allocation of Water Uses

It can be presumed that the difference between surface-water availability and total regional water demands are largely fulfilled through groundwater extraction. INA completed a useful summary of water availability versus demand for 12 subregions of the Mendoza River region. In this region, total water demand (1,154 H m^3/yr) exceeds (surface-water) supply (841 H m^3/yr) by an estimated 37 percent. CRAS indicated a total of 17,087 wells in the Mendoza North region (average density of 6 wells per square kilometer). The cultivated area (principally under irrigation) totals nearly 237,100 ha. Groundwater-pumpage extraction in the region has been variable, ranging from between 560 and 600 H m^3 during years of below-average streamflows to less than 100 H m^3 during years of above-normal streamflows. This is, less GW is used if SW supplies are available. The average annual pumpage extraction of groundwater resources in the region was estimated as 380 H m^3. Using inventory data for 1988, CRAS estimated the cultivated areas in the Mendoza Norte region are broken out as follows (units of hectares):

Grapes (vineyards) and fruit	142,221	*83 percent*
Vegetables	21,588	*13 percent*
Hay and pasturelands	5,073	*3 percent*
Woodlands	2,876	*>1 percent*
Total:	171,752	*100 percent*

In general, a system of canals irrigates nearly 156,100 by surface waters: (a) 78,130 hectares (ha) for the Mendoza River region and 77,966 ha for the lower Tunuyán River region. Corresponding average annual streamflow volumes for these two regions are: 512 H m^3 and 361 H m^3, respectively. It is worthy of note that, despite the irrigated lands for the two regions being nearly equal (approximately 78,000 ha), streamflows from the Mendoza River are 42 percent greater than streamflows from the Tunuyán River. This is understandable from a surface-water availability perspective and supports the greater dependency upon groundwater resources in the lower Tunuyán River region.

In 1997, CRAS indicated for the Mendoza Norte region an overall irrigation efficiency of 0.54. FAO has indicated for the Luján Sur subregion an existing irrigation efficiency of 0.36. With implementation with the FAO-developed irrigation/drainage improvements for this subregion, it is estimated that the efficiency may be increased to as much as 0.65.

In summary, water-use estimates have been over recent years for oases the Mendoza Province. Using detailed analyses for the Mendoza River system as an example, most water-use estimates indicate considerable variability. As a result, this situation indicates the need: (a) to qualify any estimate to the year of applicability, and (b) to use longer periods for deriving average uses. Also, it is critical to distinguish between water withdrawals water consumptive-use values.

Regional Hydrologic-Balance (HB) Estimates

Various hydrologic-balance estimates have been made by DGI, INA, and most recently by Arresse (2002). General observations regarding the regional HBs have been noted (Steele, 2002) as follows:

1. The HBs have not taken into consideration the time dynamics of the various hydrologic components. This is the common practice; however, because of inferred time trends in stream inflows (specifically, involving the Río Mendoza and Rio Tunuyán systems), additional assessment needs to be made as to sustainable water-resources development.
2. The aspect of recent or present levels of groundwater extraction (as depicted in the HBs) should be evaluated from the standpoint of what might be the maximum (sustainable) level of groundwater well pumpage to be permitted in the future for any given region. In other words, the results of each HB should be incorporated into the context of future groundwater-resources management.
3. Localized (point values areally and depth) aquifer characteristics need to be generalized to provide regional-aquifer characterization for the oases. Specific aspects of deficiencies in available data (such as lack in aquifer characterization at depth; need and usefulness of geophysical surveys and well logging; and drilling of new wells) should be identified and studies identified to overcome these deficiencies.

Restricted Groundwater-Development Areas

DGI has delineated three areas in the Mendoza Province where groundwater resources are limited and any further groundwater development currently is prohibited. These restricted areas consist of: (1) Pedemonte, highlands just west of Mendoza capital (metropolitan area), (2) the Luján Sur/Margen Derecha area, and (2) the northeastern part of the Mendoza River region. This resource-development restriction by DGI is based upon limited physiographic and hydrogeological information available for each area but uses observations on areal responses by well drilling that has taken place to date as well as aquifer responses (in terms of lowering water levels and/or increases in salinity). DGI has specific proposals for conducting technical field investigations to confirm this institutional stance of localized areal groundwater-development restrictions and plans to proceed with these investigations.

CONJUNCTIVE SURFACE-WATER/GROUNDWATER USE

Irrigated lands throughout the Mendoza Province interactively use surface-water and groundwater resources for cultivation of irrigated crops. Of the estimated 360,000 has of irrigated lands in the Mendoza Province, 80,000 ha currently (The World Bank, 2000, Annex C) are irrigated exclusively by groundwater; the remaining lands receive surface waters or are supplied by conjunctive surface-water/groundwater sources. In some areas, groundwater development and associated well pumpage have increased over time, providing supplemental water at times of critical need when surface-water supply either does not occur or cannot be dependable. In other areas, localized groundwater supplies have over-exploited underlying aquifers; hence, surface-water supplies are sought to help sustain the agricultural-resource base. Conjunctive-use surface-water (SW) and groundwater (GW) estimates were available for two regions, as follows:

	Upper Tunuyán River region		Diamante/Atuel Rivers region	
Water Source	*INA-CRA/FAO (ha)*	*Percent*	*INA (ha)*	*Percent*
Exclusively SW	21,899/20,010	*40/37*	78,200	*80*
Conjunctive SW/GW	13,696/14,602	*25/27*	14,200	*18*
Exclusively GW	18,773/19,470	*35/36*	1,640	*2*
Subtotals:	54,370/54,082	*100/100*	79,840	*100*

The concept of surface-water/groundwater (SW/GW) conjunctive use has to be acceptable and developed explicitly in the institutional framework. DGI, given its mission and responsibility for water-resources planning and management in the Mendoza Province, needs to make sure that its administrative structure and implementation of water policy promotes this concept. Within DGI's institutional framework, the WUAs need to understand and to promote the physical aspects of conjunctive use. This includes enforcement of water-administration policies promulgated by DGI. In addition, costs of water use need to be compatible with promoting conjunctive SW/GW uses throughout the Province.

Upstream (Upgradient) Water-Resources Management

The Potrerillos Dam construction was completed in late 2001; the reservoir began filling in mid-December. Other on-channel surface-water impoundments have been constructed; a prime example is Presa Carrizal on the Tunuyán River, providing surface waters predominately for downstream irrigation lands. Another physical aspect of upstream water-resources development involves the entrapment of suspended sediment (normally conveyed downstream in stream channels) in constructed water-storage reservoirs and the accompanying hydraulic and geomorphological implications of sediment entrapment upstream. The conveyance of so-called "clear water" naturally results in channel and sidebank erosion and in changes in stream-channel slope, channel-bed armoring by sediments, and associated channel-infiltration to either the alluvium or underlying subsurface stratigraphic units (varying with geologic origin and lithologic characteristics).

Salinity and Groundwater Over-Exploitation

Given the semi-arid physiographic setting of the Mendoza Province, increasing salinization of groundwater is of considerable concern (Llop, 1997). Thus, any water-resources development adversely affecting either the quantity of quality of water should be viewed quite critically as it may impact the sustainable livelihood and regional economic conditions in the Mendoza Province. An assessment of investigations and suggested planning/management strategies regarding increasing salinity in the eastern part of the Mendoza Province. Specific focus is on the Mendoza Norte and the lower Tunuyán River regions. Many of the problems related to salinity contamination are caused by poor well construction (inventoried by DGI) and deterioration to well casings over time due to geochemical changes. What now is needed is a program for plugging of these wells and replacement with wells of good construction. Who will pay for well abandonment/plugging or for replacement wells? These considerations are the responsibility of DGI, along with the WUAs.

The problem of cross-contamination of multilayered aquifers has occurred most notably in the lower Tunuyán River region. In these situations, the solution to a large extent depends upon the degree of contamination (that is, how high are the salinity levels). Perhaps there is opportunity for blending of groundwater of high salinity with either groundwater or surface waters of lower salinity. Another alternative is not to use (prohibition or voluntary) of such identified high-salinity groundwater. It is recognized also that irrigation return flows can increase salinity and also contribute agrochemicals. Other types of contamination have occurred or potentially can occur. These are derived from municipal wastewaters, mining, petroleum production and refining, as well as industrial wastewaters and sludges.

Specific recommended actions have included: (a) a well-replacement program, based upon inventories of wells in poor condition, and (b) detailed investigations involving salinity characterization and trend analyses. INA has completed a farmers' guide to help in educating the groundwater users, especially in the east part of Mendoza Province. Meetings with various farmers' groups (water-users associations) have been held by INA, to discuss principles of water use and possible controls over salinization. This critical issue also indicates specific needs in groundwater monitoring.

The topic of aquifer vulnerability is a critical one, relative to this issue. A general map of groundwater vulnerability has been developed for the Mendoza Province. More recent CRAS investigations include evaluation of well-plugging procedures and a study of salinity impacts of well conditions. It has been difficult to assess time trends over the period of these intermittent areal characterizations, due to variability in wells included in any given characterization and possible unsystematic methods of contouring.

Specific network-design documents are available for past or present groundwater-quality monitoring programs for oases in the Mendoza Province. Recommended specific actions include implementation, program evaluation, revisions, if needed. Still needed are details on locations (areal-coverage criterion), scheduling (at least annually, preferred quarterly) and constituents (indicators wherever possible). Interpretation and display of resultant data are critical, and monitoring programs need to be evaluated and modified at 3-5 year intervals (Steele, 2002).

Water Conservation and Re-Use

Useful historical perspectives are available regarding irrigation development in the Mendoza River region between 1890 and 1930. It was during this period that the greatest rate of expansion of irrigated lands in the Province occurred. In recent times, areal extent of irrigated lands has been limited by availability of water. In some areas, limited availability of diverted surface-water resources has led to supplemental groundwater use. The majority of irrigation in the Mendoza Province uses gravity-flow flood-irrigation. Only in selected areas, where water is limited and/or costs can be justified are trickle-irrigation systems being used.

It would seem that current water-administration policies in Mendoza provide minimal incentives for incurring the costs of such water-conservation practices (The World Bank, 2000). The reduction in surface-water availability has resulted in a greater dependence on groundwater resources available throughout the Province. With the onset of supplemental diverted streamflows released to the Río Mendoza from Presa Potrerillos, some relief in groundwater demands for this area should occur. However, if demands increase over time (as expected), then groundwater use may rise again in the future.

An re-use example involves the City of Mendoza's re-use of treated (residual) municipal wastewaters (Campo Espejo facility) located northeast of the City. This facility treats an average of 50.5 H m^3/yr. This facility, with 300 hectares of lagoons, removes solids and sequentially lowers BOD, fecal-coliform, and turbidity levels in the predominately municipal wastewaters. The re-usable resource contains relatively high nutrients of benefit to irrigated agriculture. The linkage of aerated-lagoon treatment with the treated-effluent application to irrigated lands (approx. 2,500 hectares) for Campo Espejo is beneficial. The costs of lagoon treatment of wastewaters have been kept relatively low ($0.045/$m^3$).

SUMMARY AND CONCLUSIONS

1. DGI should develop and implement institutional links between existing irrigation-oriented WUAs to include additional and new responsibilities for groundwater and conjunctive SW-GW uses.
2. More definitive economic analyses are needed regarding possible benefits for controlling contaminant sources.
3. Systematic, long-term regional monitoring networks should be implemented. Network components should include surface waters, groundwater, and water quality. Objectives of the network should be explicitly stated; periodic monitoring-program evaluations are required to measure program effectiveness and to assess the extent to which defined objectives are being fulfilled. Information products need to reach layperson (public) audiences.
4. Water administration, being addressed in more detail by another international consultancy (Contijoch, 2002), is critical. DGI's role should include effective and objective GW-resource management. Of the estimated 18,000 registered wells in the Mendoza Province, about one half (9,000) are privately owned and operated. Administration of these wells (under the responsibility of DGI) constitutes a key management issue.
5. Although initial components for this critical role are already in place, enforcement of resolutions and associated *Normas* as well as explicit acknowledgment of limited regional GW resources need to addressed in the future. Promoting SW/GW conjunctive-use principles is a key consideration.
6. A water-policy strategy is particularly critical in promoting the economic sustainability of the lower Río Tunuyán region in the eastern part of the Mendoza Province. Issues include increasing salinization, poor well construction causing inter-aquifer contamination (requiring plugging), and the limited available groundwater resources.

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