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Sustainable Groundwater Management
Lessons from Practice

Case Profile Collection Number 9*

The Guarani Aquifer Initiative for Transboundary Groundwater Management

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This case profile provides a summary and vision of the GEF-funded Guarani Aquifer Program for groundwater resource sustainability and environmental protection (Proyecto para la Proteccion Ambiental y Desarrollo Sostenible del Sistema Acuifero Guarani), which is valued at US $26.7 million with 50% from GEF. The project was launched in May 2003 by the Mercosur nations of Argentina, Brazil, Paraguay & Uruguay under the supervision of the World Bank, coordination of the Organization of American States (OAS) and with support of the International Atomic Energy Authority (IAEA). GW•MATE has been involved throughout the detailed project preparation process (which commenced in May 2000) and continues to provide services in support of project implementation, with special reference to (a) the evaluation of regional aquifer development and management issues and (b) the promotion of sustainable management and protection measures for groundwater at local level through a series of 4 pilot aquifer management projects and (c) the application of the existing legal and institutional framework to deliver effective transboundary groundwater management in the two international pilot projects. The factual information in this case profile is a synthesis from a wide range of sources, and the academic institutions of the region have figured prominently in local data collection to date.

CHARACTERISTICS OF GUARANI AQUIFER SYSTEM

Hydrogeological Structure

- The Guarani Aquifer is a huge hydrogeological system that extends over an area of at least 1,200,000 km^2 of Brazil (with about 70% of its known area), Paraguay, Uruguay and Argentina (Figure 1). It has an average thickness of 250 m and reaches depths in excess of 1,000 m. The total volume of freshwater in storage is estimated around 40,000 km^3 (equivalent to 125 years cumulative flow in the Paraná River). Most of this is believed to be of potable quality, although at certain depths in some areas it can have excess fluoride concentrations or high salinity.

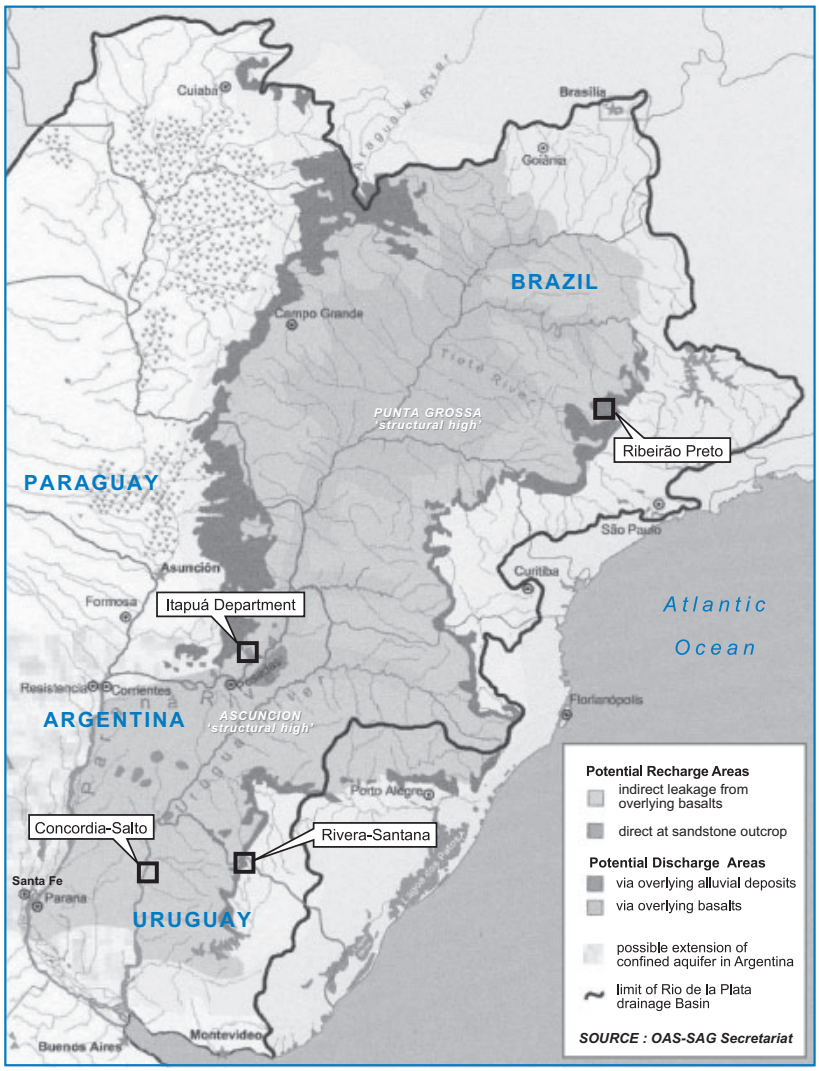
- The aquifer occurs in two major semi-independent structural basins – the Central Paraná (which is relatively well known) and the south-western Chaco-Lower Paraná (whose geology and freshwater distribution is much less understood). These two basins are separated by the pronounced Asunción-Rio Grande arch (Figure 1), and this, and other 'structural highs' (such as the Ponta Grossa in Brazil-Paraná State), appear likely to affect aquifer structure generally, to control the presence of magmatic intrusions, and thus have a strong influence on the groundwater flow regime.

- The Guarani Aquifer System (known as the SAG in Spanish and Portuguese) comprises a sequence of aeolian and fluvial weakly-cemented sandstones of Upper Jurassic-Lower Cretaceous age, extensively overlain by Upper Cretaceous sheet basalt flows (Figure 1). The geological continuity of this sandstone was only recognized in the 1990s, following the drilling of some oil exploration wells and subsequent stratigraphic interpretation by academic researchers, who named the associated aquifer system the 'Guarani' in homage to the indigenous population of the area concerned.

- Prior to this the SAG was known locally by various names :
  - the Tacuarembó Formation in Uruguay and Argentina
  - the Botucatu Formation in Brazil
  - the Misiones Formation in Paraguay.

  Some underlying formations (such as the Pirambóia Formation in Brazil) are sufficiently permeable to form the lower part of the SAG, although being more of lacustrine and fluvial origin tend to be lower yielding and may contain groundwater of unacceptable quality.

Figure 1: Hydrogeological map of Guarani Aquifer System showing the location of pilot management area



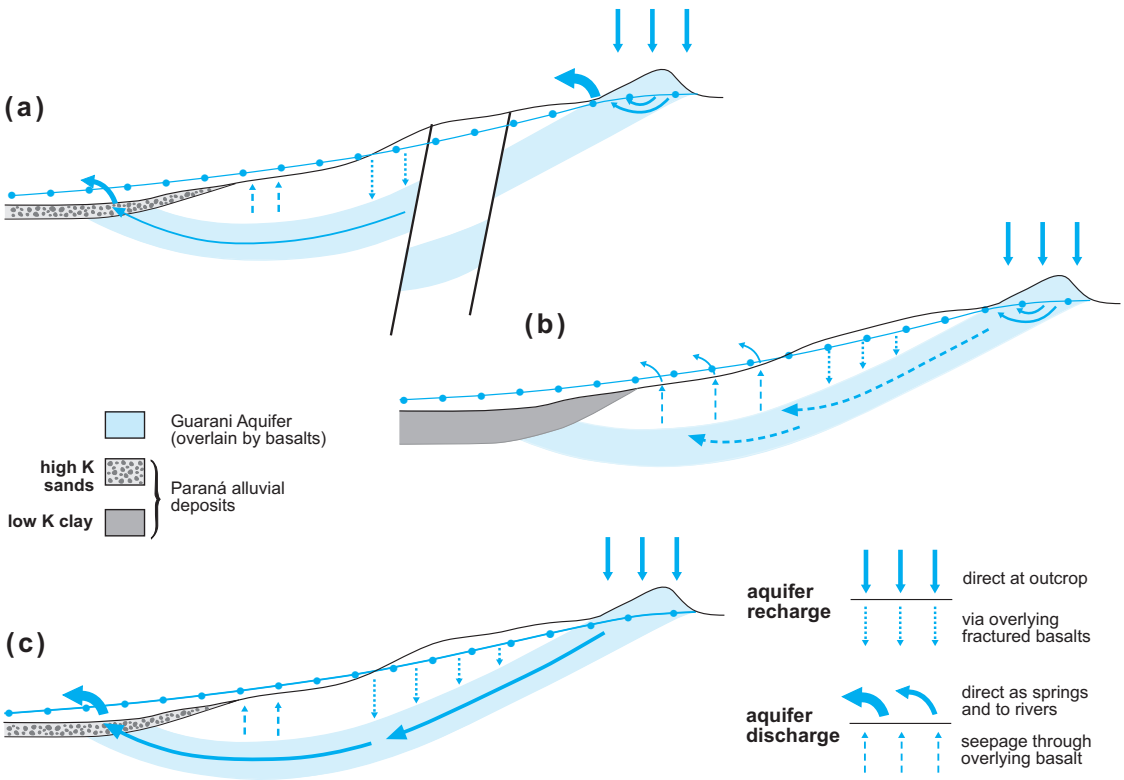
Groundwater Flow & Quality Regime

- Replenishment of the SAG occurs by infiltration of excess rainfall and stream-flow across the so-called 'recharge area' – which is considered to comprise both the sandstone outcrop (limited to about 150,000 km^2) and the more extensive adjacent zone where sandstone is covered by relatively thin and well fractured basalt (Figure 1) – the overall rate of recharge has been preliminarily estimated at 160 km^3/yr.

- When traced towards the center of the structural basins, SAG groundwater becomes progressively more confined by the thickening overlying basalts and exhibits an artesian overflowing head over large areas (Figure 1). With increasing depth and confinement the groundwater temperature also increases substantially (Table 1), such that it widely exceeds 40°C, and more locally reaches 60°C, although the controlling mechanisms are not yet fully understood. There will also be a marked temperature effect on the aquifer's hydraulic conductivity (permeability) as a result of changing kinematic viscosity.

- The natural discharge of the SAG is also still poorly understood. In the 'undeveloped condition' a considerable amount of 'locally rejected recharge' appears to occur in many locations adjacent to the aquifer recharge area, with the component of natural deep groundwater flow into the confined aquifer section being limited by the geological structure (compare Figure 2a-b to 2c). However, some areas of 'regional aquifer discharge' may possibly exist (Figure 1), especially as base-flow to the middle sections of the Uruguay River (in southern Brazil) and as up-flow to the Esteros de Ibera wetland (in extreme northeastern Argentina), but the groundwater flow lines into these features are not yet confirmed.

Figure 2: Hypothetical cross-sections of Guarani Aquifer System showing possible structural controls on the groundwater recharge, flow and discharge regime



- Natural groundwater chemistry shows marked changes when traced downdip from the aquifer outcrop (Table 1) including:
  - cation exchange reactions with Na replacing Ca in solution
  - some increases in F and/or overall salinity, probably associated with upward seepage or diffusion from the basal SAG formation
  - increasing $\delta^{13}C$ due to dissolution of CO_2 and under closed conditions
  - much lighter $\delta^{2}H$ and $\delta^{18}O$ suggesting the presence of palaeo-groundwater recharged under colder wetter climatic conditions.

  The apparent presence of a marked modern recharge 'cut-off', with much older water at only modest distances downdip, suggests either a long (arid and/or cold) period with little recharge or absence of flow in the deep aquifer with rejection of recharge.

Table 1: Typical chemical and isotopic changes in Guarani Aquifer groundwater when traced westwards down-dip from Ribeirao Preto (São Paulo) – Brazil)

PARAMETER (units)		OUTCROP BOREHOLES	DOWNDIP BOREHOLES (distance from outcrop) 30km	150km
Chemical Characteristics				
T (0C)	temperature	24	26	42
pH	acidity	6.5	8.5	9.5
Ca (mg/l)	calcium	30	20	2
Na (mg/l)	sodium	1	5	90
HCO_3 (mg/l)	bicarbonate	15	75	160
Cl (mg/l)	chloride	1	2	10
F (mg/l)	fluoride	< 0.1	0.2	> 1.0
SiO_2 (mg/l)	silica	15	20	30
Isotopic Indicators				
δ 2H (0/00)	deuterium	- 50	- 70	- 65
δ 18° (0/00)	oxygen-18	- 7	- 9	- 10
δ ^{13}C (0/00)	carbon-13	18	- 10	- 8
14C (pmc)	carbon-14	> 80	30	< 5

(data selected from Silva, 1983; Kimmelmann et al, 1989; Sracek & Hirata, 2002; Silva et al, 2002)

- There are also some concerns that the deep confined groundwater might contain significant levels of the soluble U isotopes, radium and radon gas, and in general the trace element hydrogeochemistry merits more detailed investigation.

Current Exploitation & Development Potential

- Although a comprehensive waterwell inventory does not yet exist, the current level of SAG exploitation is relatively modest. There are estimated to be around 1,000 operating deep production wells, although the number may reach 3,000 or more if wells in the overlying basalts that may just reach the sandstone are included. Most are capable of producing at least 600 m^3/hr (and some over 1,000 m^3/hr) if pumped, but less than 500 m^3/hr where overflowing.

- Total groundwater production has been estimated to be in the range 1,000-3,000 Mm^3/yr and mainly concentrated in Brazil – with 80% of this for public water supply, 15% for industry and 5% for spa tourist use. Its growing importance in the potable water supply of many towns with population in the range 50,000-250,000 needs to be emphasized (examples include Tacuarembo and Rivera in Uruguay, Caaguazu and Ciudad del Este in Paraguay, (in Brasil) Livramento and Caixias do Sul in Rio Grande do Sul, Londrinha in Parana, Uberaba and Uberlandia in Minas Gerais, and Campo Grande in Matto Grosso Sul).

- The population of the extensive area overlying the SAG is 15 million, and this increases to more than 50 million when immediately adjacent areas are included. The climate is mainly sub-tropical, and the area has abundant (but often polluted) surface water resources, which experience a significant dry season and occasional drought. Thus the need for reliable potable water supply sources (of low-treatment cost) could grow considerably, and a demand for high-value agricultural and industrial uses is also likely to increase substantially.

- The SAG also represents a major, widely-distributed, low-enthalpy, geothermal resource (often with overflowing artesian head) of numerous potential applications. These include:
  - expansion of spa facilities in northwestern Uruguay and neighboring parts of Argentina, and possibly also further north in the Iguazu international tourist area
  - numerous agricultural and industrial applications
  - low-enthalpy energy generation.

Existing Institutional & Legal Provisions

- Both Paraguay and Uruguay are unitary states, and responsibility for groundwater resources rests with the respective national governments:
  - in Uruguay, the main laws relating to groundwater are to be found in the water code, but a specific decree was adopted in 2000 to regulate exploitation of the Guaraní aquifer — groundwater management functions are mainly vested in the Dirección Nacional Hidrográfica (DNH) (under the Ministerio de Transporte y Obras Pública) for water quantity aspects, and the Dirección Nacional de Medio Ambiente (DINAMA)(under the Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente) for water quality aspects
  - in Paraguay, a few provisions relevant to groundwater are scattered in different pieces of legislation, but a comprehensive water law is currently being studied – the Secretaría del Ambiente (SEAM) is in charge of water resources, while the Empresa Reguladora de Servicios de Saneamiento (ERSSAN) is responsible for the regulation of water services.

- In contrast, both Argentina and Brazil are federal countries in which water responsibilities are vested by Constitution in the provinces/states through more-or-less developed provincial/state legislation
  — although minimum management standards are provided for in the national/federal legislation. The administration of groundwater resources has been largely delegated to state or provincial government
  — but not all states/provinces have yet evolved adequate institutional capacity and/or are active on implementation.

  In spite of the existence of a legal and institutional framework for water resources in the countries involved, there are no clearly-defined mechanisms in the interest of groundwater protection:

- to influence agricultural policy decisions which have a major effect on rural land-use
- to stimulate, through economic instruments, a shift to groundwater-friendly land use practices
- to ensure that municipalities consider groundwater vulnerability when controlling urban land-use.

REGIONAL OBJECTIVES OF THE INITIATIVE

Scope & Structure of the Program

- The Guarani Aquifer Program is not just a scientific investigation, but more the development of a comprehensive management framework, where sustainability and environmental concerns figure prominently, especially those with transboundary repercussions. The project is essentially preventative in character – anticipating potential problems associated with future expansion in the use of Guarani Aquifer groundwater for public water-supply, hydrogeothermal applications and supplementary irrigation, and with significant land-use changes that could impact aquifer recharge rates and/or quality.

- During the preparation phase of the project a list of key technical issues were identified:
  - insufficient baseline information on SAG groundwater, and its users and uses, due to disperse and incomplete data and inadequate data compilation and dissemination
  - potential conflict due to localized excessive or indiscriminate pumping, and lack of pollution protection in aquifer recharge areas
  - the influence on groundwater quality of the major changes of rural land-use that have affected substantial tracts of the SAG recharge area in the last 30 years

Table 2: Summary of Principal Guarani Aquifer Project Components

COMPONENT	PROPN. OF TOTAL COST	OUTPUTS
Expansion & Consolidation of Scientific Knowledge	33%	· definition of aquifer geometry and properties · evaluation of aquifer structural compartmentalization · groundwater quality / isotopic signature / pollution risks · evaluation of aquifer recharge mechanisms and rates · survey of aquifer discharge mechanisms and functions · regional/local aquifer numerical management modeling · specification of norms for well design and construction · evaluation of hydrogeothermal resources and applications
Development of Legal & Institutional Framework	12%	· review of existing legal/institutional framework · assessment of future legal/institutional requirements · negotiation of coordinated management framework · identification/implementation of priority management actions
Stakeholder Participation & Public Awareness	8%	· development of a strategic plan for participation · initiation of participatory management process · development of a plan for public education · initiation of school, society and media campaigns
Groundwater Pilot Management & Protection Projects	41%	· critical component in terms of overall program objective (described in detail in subsequent section)
Program Administration, Monitoring & Dissemination	6%	· normal program management arrangements (not specified in detail here)

- concern about the possibility of extensive but subtle pumping interference effects in the highly-confined aquifer system threatening reductions in artesian head and overflow, reductions in dry-weather river base-flows and groundwater discharge-dependent wetlands.

- Significant socio-cultural and political-institutional challenges to implementing groundwater management and protection measures on-the-ground were identified in project preparation as needing to be addressed:
  - despite well-developed and widely-distributed scientific expertise in groundwater, a lack of capacity in practical resource management and protection, socio-political risk assessment and conflict resolution
  - little public awareness of groundwater in general and of the SAG in particular, and insufficient stake-holder participation in resource management and environmental protection
  - absence of national and transboundary groundwater development and management policy, especially in terms of 'operating rules' and 'decision-making protocols' at local level, with diverging standpoints (between national/federal and state/provincial governments) as to the required character of institutional arrangements for water resources
  - a legal framework for groundwater governance (especially procedures for allocation and use licensing) and the relationship with surface water resource administration at sub-basin level that required varying levels of development and improvement in the different nations/states/provinces
  - no enforced code-of-practice for well design, construction and operation.

- Components of the SAG Program (which will be of 4 years minimum duration) were designed to address these deficiencies (Table 2). It is hoped that these, together with 4 pilot groundwater management and protection projects, will provide the stimulus to generate a shared vision of Guarani Aquifer groundwater resources, and the necessary synergy between the project partners to generate an appropriate level of local and international resource administration.

Scales & Levels of Aquifer Management Need

- The process of program preparation and initiation revealed widespread misconceptions about the SAG – and in particular the character of its groundwater resources, the scale of problems with which it could be affected and the most appropriate level of management for resolution of these problems. Because of this an indicative framework has been elaborated (Table 3) to provide a realistic and balanced summary in this regard.

- This framework, which has been carefully drawn-up and critically reviewed, shows clearly that:
  - the SAG Program is 'preventative' in character – there being no major 'crisis issues' to resolve and many benefits potentially accruing from cooperation – although the rapid and major land-use changes occurring in many parts of the aquifer's recharge area (deforestation, intensification of livestock grazing, pasture conversion to intensive soya/maize cultivation, eucalyptus reforestation, etc) do give rise for concern
  - current transboundary groundwater issues do not have major 'upstream-downstream implications', but are strictly limited in distribution and essentially local in character, requiring resolution through agreement and action at the corresponding scale
  - only with extensive change in agricultural land-use and/or intensive groundwater use for irrigation – and under a specific combination of hydrogeological conditions (which are not yet proven) – are any potential transfrontier effects on groundwater likely to grow from local to catchment scale.

Table 3: Framework of groundwater management needs for the Guarani Aquifer System and their appropriate scales of resolution

COOPERATIVE ACTIONS OF LOCAL APPLICATION WITH MUTUAL BENEFITS	ACTUAL & POTENTIAL SITUATIONS WITH LOCAL TRANSBOUNDARY EFFECTS	POSSIBLE SITUATIONS WITH SIGNIFICANT IMPACTS AT CATCHMENT SCALE
• evaluation of incidence/ control of natural groundwater contamination (F, U, Rd, Rn) affecting use for potable water supply	• contamination of potable waterwells due to inadequate urban sanitation and uncontrolled urban land-use	
• definition of strategies for efficient groundwater resource development and sustainable management • assessment of aquifer pollution vulnerability and appropriate protection measures for aquifer recharge areas	• wetland* impact and river baseflow* reduction as a consequence of potential intensive groundwater resource development for agricultural irrigation • deterioration in the quality and rate of aquifer recharge as a result of extensive changes in agricultural land use and crop cultivation	the adjacent problems could grow if regional agricultural policies and markets favour the intensive and extensive use of local soils and/ or groundwater resources — but only if current field investigations confirm (a) the present ecological role of aquifer discharge and (b) the hydraulic continuity of the aquifer system in the corresponding areas
• evaluation of economic and efficient options for the use of the aquifer's geothermal resources	• reductions in the artesian and geothermal characteristics of the aquifer due to uncontrolled exploitation by geothermal wells	
Appropriate Level of Resolution		
SAG-P and CSDP in service of the national and state organizations involved	SAG-P through intervention of CSDP with the countries and local institutions involved	CSDP in consultation with supra-national organizations and with support of the SAG-P

(source : OAS-SAG Secretariat & GW•MATE)

*principally the Esteros de Ibera (Argentina) and Niembucu (Paraguay), and the Rio Uruguay respectively

- An interrelated issue is that of selection of an acceptable physical model on which to base further development of an appropriate international legal framework for aquifer management, and various analogues are from time-to-time referred to :
  - an 'underground river' in the guise of 'water flowing to a common terminus', by implication with limited residence time since flow dominates over storage
  - a 'hydrocarbon reservoir', which is completely isolated from surface processes and without resource replenishment
  - an 'underground lake', in which storage dominates but with immediate propagation of physical perturbations.

- But none of these is really appropriate to many aquifers, and certainly not to the SAG – which possess huge storage (compared to its annual replenishment) and very long residence times, and whose natural flow directions can be modified, at least locally, as a result of groundwater extraction. Like all 'granular aquifers' it also tends to localize the impacts of abstraction and pollution, and in addition has a significant (but not well understood) degree of compartmentalization with uncertainty over groundwater flow

paths and discharge regime. It is much more appropriate to identify 'groundwater bodies' (as used in the EC Water Framework Directive, 2000) as sub-units of the SAG for groundwater management purposes, and improved definition of these will be possible once the 'basic study component' has advanced understanding of the groundwater flow and storage regime.

From Program Implementation to Transboundary Aquifer Management

- There is a long-standing history of Mercosur environmental cooperation with a complex web of multilateral and bilateral treaties in existence from the 1970s onwards, and these impinge upon and could help to underpin the present initiative on SAG groundwater resource management.

- The formation of an semi-independent 'transboundary aquifer commission' was not favored from the outset, because of the implied high transaction costs and danger of losing contact with national and state groundwater management issues, capabilities and procedures. The preferred initial institutional model was the creation of a Guarani Aquifer Steering Council (CSDP), supported by a 'slimline program secretariat' (developed through the vehicle of the present 4-country project) and involving the persons nationally responsible for groundwater resources (or their representatives) directly.

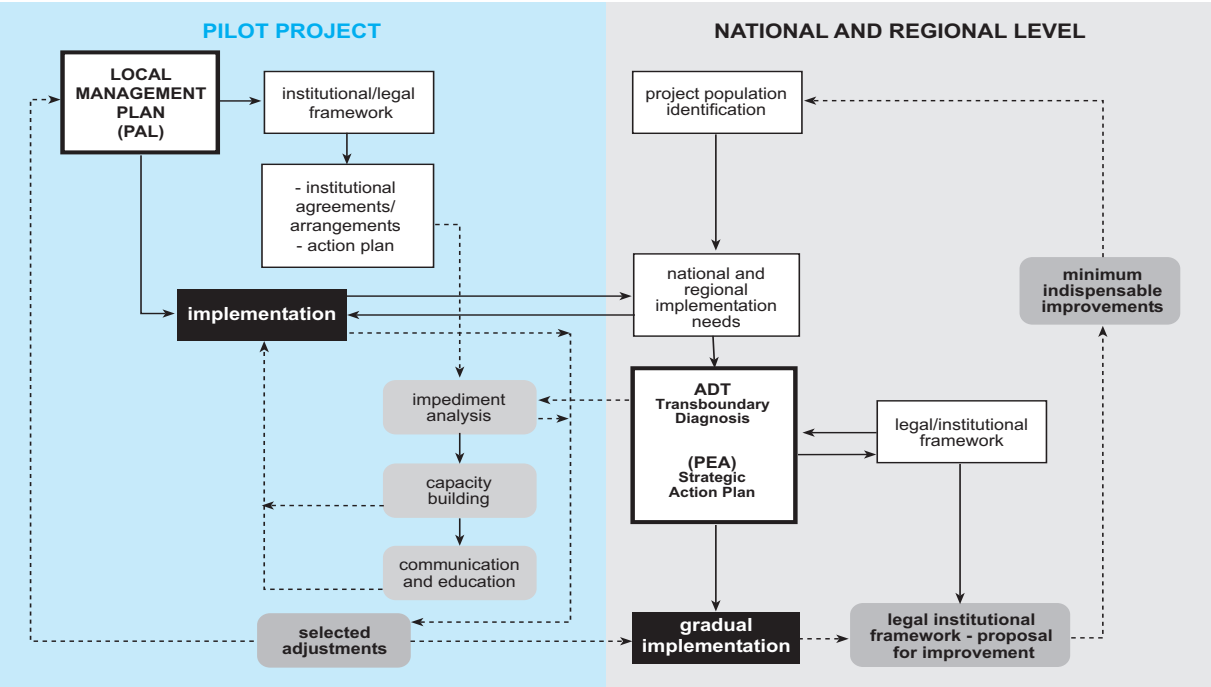
- Eventually, in order to contribute to sustainable outcomes, the CSDP could evolve into a more permanent structure and provide a mechanism to:
  - consult upon, co-evaluate and negotiate major aquifer development with potential transfrontier effects
  - mobilize investment for local groundwater development and management institutions
  - develop a 'shared vision' of resource status, aquifer potential and management needs, and promote local action through appropriate management interventions and day-to-day management procedures
  - keep the SISAG (the shared aquifer information system) updated
  - to implement a long-term social communication and participation program.

  It would thus hopefully tend towards making resource-allocation decisions by a pragmatic risk assessment and impact based approach, rather than more arbitrary decisions based on force majeure, supposed equity relating to population, aerial extension, etc.

- The key to developing a 'shared vision' and the foundation for cooperative management will be the development of a common knowledge base, shared information systems and agreed (target-oriented) monitoring protocols, underpinning aquifer numerical modelling at different scales (but with compatible boundary conditions) to evaluate actual linkages, present dependencies and potential impacts, and to predict development and management scenarios

- Successively improved versions of the Local Management Plan for each Pilot Project (Figure 3) are being prepared and a Transboundary Diagnostic Analysis (ADT) following the 'prevention philosophy' suggested by Table 3 has been completed following wide stakeholder consultation. The Strategic Action Plan (PEA) (Figure 3), informed by experience in the Pilot Projects, will define groundwater management and protection measures to be taken at 'aquifer level'. This process, carried out under the existing legal institutional framework, will indicate where further strengthening of the framework is required.

Figure 3: Flow chart detailing SAG Program structure and the dynamic relation between the national /regional and local pilot components



Management in Practice – Role of the Pilot Projects

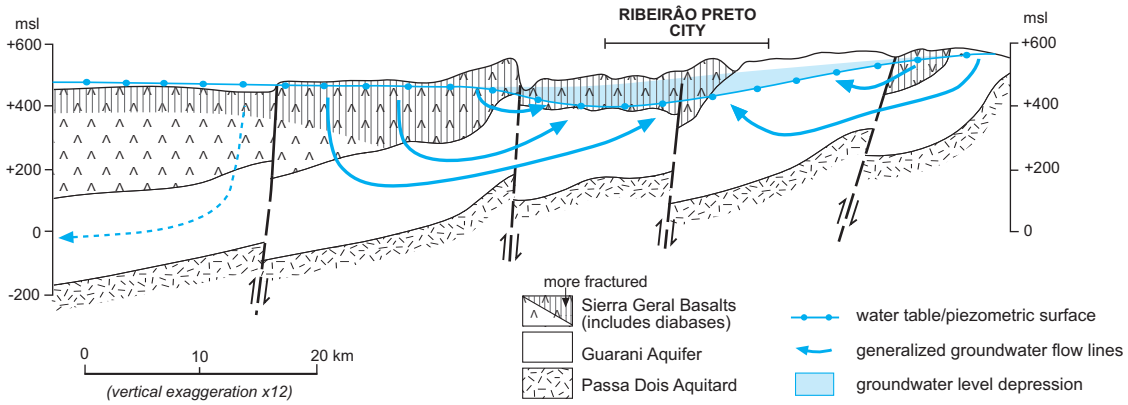
- Four groundwater management pilot projects are being promoted through GEF-Project Local Facilitators. They are aimed at identifying and implementing local agreements and actions on specific 'type problems' of SAG groundwater management and protection – two of these are transboundary in character and the other two restricted to a single country and state (Figure 1). The preferred scheme of interaction between the 'pilot projects' and the overall program is given in Figure 3.

Ribeirão Preto, Brazil

- The Ribeirão Preto (RP) Pilot Project is centred around the municipality and city of the same name in the northeastern part of São Paulo State, which has a population of 505,000. The pilot project comprises an area of 651 km^2, including 137 km^2 of the Guarani Aquifer outcrop but spreading mainly across the overlying Serra Geral Basalts (Figure 4), and includes territory which falls under the local jurisdiction of various neighboring municipalities.

- Groundwater recharge occurs when rainfall excess to plant requirements on the sandstone outcrop infiltrates during November-March at rates believed to be around 135 mm/yr – but the recharge area of the Guarani Aquifer extends considerably beyond its outcrop, because where the overlying Serra Geral Basalts are thin, they are densely fractured and allow downward seepage from their phreatic zone (Figure 4), probably at rates of around 50 mm/yr.

Figure 4: Hydrogeological section of the Ribeirao Preto Pilot Project Area



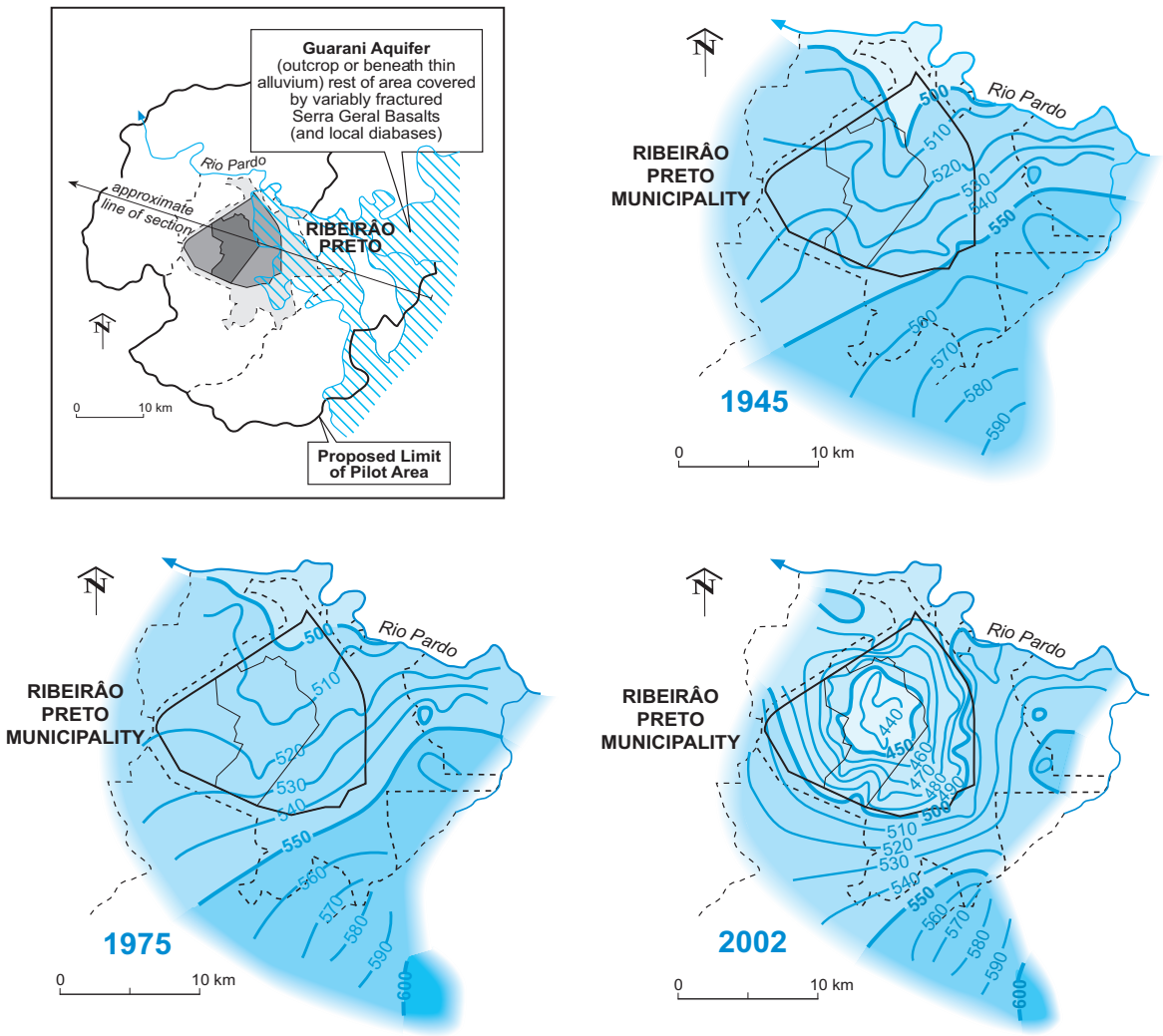
- The Ribeirão Preto area is one of major agricultural production, with sugarcane (for alcohol distillation), coffee and oranges (for fruit juice production) being the dominant crops. The city is also a major industrial centre – with fuel-alcohol distilling, agro-industrial products and services, and a wide variety of manufacturing enterprises being very active.

- The SAG is exploited by more than 1,000 wells in the general area – DAERP (Departamento de Águas e Esgotos) have about 90 that are currently in active operation with a potential yield of about 3,700 l/s and an estimated actual production of around 65 Mm^3/yr. However, there is a significant degree of uncertainty about the total level of actual groundwater abstraction, which is estimated to have grown from 45 Mm^3/yr in 1976 to 96 Mm^3/yr in 1996.

- The process of groundwater resource development and water-table lowering has reduced and largely eliminated natural groundwater discharge to streamflow (and replaced it in large measure by waste-water discharges). Contemporary groundwater recharge is exceeded by abstraction since, over a large area across the city, groundwater levels have fallen since the 1970s by an estimated 30-40m (Figure 5). Amongst the side-effects experienced have been:
  - increases in operational water-supply costs, due to falling water level and decreasing well efficiency with loss of upper well-screen sections
  - loss of groundwater confinement in some boreholes
  - previously effluent watercourses becoming influent and increasing groundwater pollution risks.

- Groundwater quality is reported to be good, with excellent microbiological results, exceptionally low total salinity, slightly acidic pH (6.0-6.5) and nitrate concentrations not exceeding 10 mg/l in DAERP water wells. Mobile herbicides (such as tebuthiuron, diuron, ametrine, etc) widely-applied to sugarcane, have not yet been detected in groundwater samples. But the vadose zone is thick (often 30-60m), and has increased as a result of falling water-table, and these water wells also have deep screen intakes – and groundwater pollution by persistent contaminants from sanitation practices, industrial effluents and agricultural cultivation would take many decades to reach such depths. Thus the need to take some timely preventive measures must be assessed.

Figure 5: Evolution of groundwater table decline in the Ribeirão Preto Municipality during 1945-2002



- São Paulo State Law and Ribeirão Preto Municipal Decrees make various provisions for groundwater resource management and protection, which are at least partially implemented but require more integration, application and enforcement through institutional cooperation and stakeholder involvement. In addition various local initiatives are contributing towards developing a more holistic vision for the future:
  - the Comitê da Bacia Hidrográfica do Pardo (CBHP) is promoting action to constrain water demand in the urban population
  - the Instituto Geologico de Sao Paulo (IGSP), with German technical cooperation, has undertaken aquifer vulnerability mapping, groundwater pollution risk assessment and source protection zone definition at pilot level.

- The pressing issues that must be addressed by the Pilot Project are:
  - first and foremost, to promote land-use planning on the Guarani Aquifer recharge zone compatible with its primary function as a low-cost, high-quality source of potable municipal water supply – this should be based rationally on aquifer vulnerability mapping and groundwater supply protection area delineation

- second, to appraise the risks to existing municipal groundwater sources posed by current urban sanitation measures, industrial activities and agricultural practices, and to promote action to manage any significant risks identified and confirmed – in particular the urban water cycle needs to be better understood and managed from supply sources to wastewater reuse
- third, current average water production is very high (350 l/d/person), with total municipal demand predicted to rise 65% to 105 Mm^3/yr by 2020 as a result of population growth to 830,000 – measures need to be identified and taken to bring down this demand by 20-30% to relieve pressure on aquifer resources and keep to a sensible minimum the land area that will need to be specially protected in the interest of municipal potable water supply
- fourth, systematic consideration will probably need to be given to the possible development of some municipal groundwater production capacity in well fields in the more protected (confined) sections of the aquifer system, in part to replace any existing sources found to be at greatest risk of pollution and in part to meet the increasing water demand.

- Some important advances have already been facilitated by the project including:
  - the issuing of strong constraints on water well drilling and/or replacement within Ribeirão Preto Municipality for a period of up to 4 years and awaiting definition of a resource management policy, as a result of an agreement reached between DAEE and the Municipal Government
  - the progressive installation of a network of observation boreholes (through conversion of old water-wells) by DAERP.

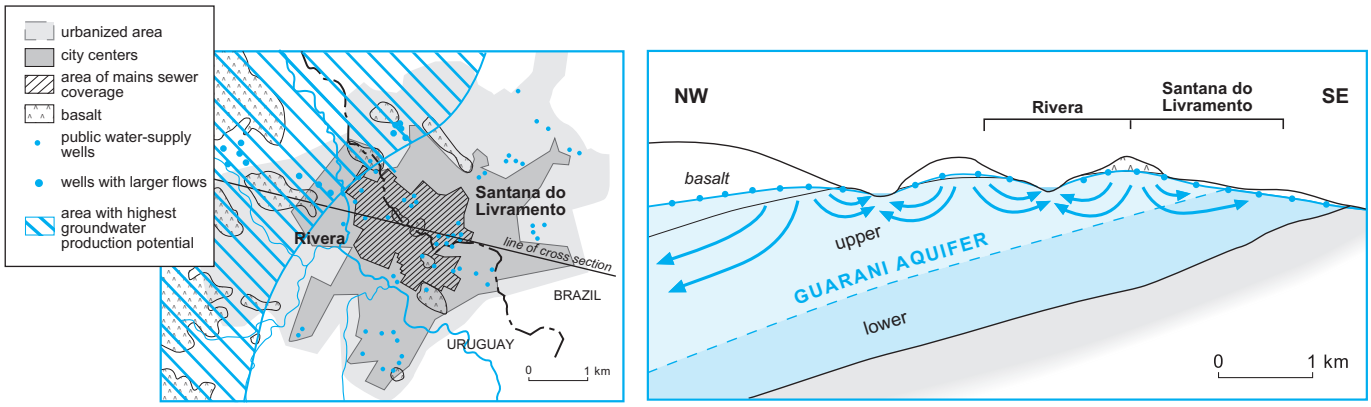
- Despite calibration limitations and potential difficulties of defining boundary positions/conditions, the construction of a numerical aquifer model will serve as a rigorous tool to integrate all existing data and challenge the existing conceptual model, to identify key groundwater investigation and monitoring needs and to evaluate possible aquifer development and management scenarios and to facilitate dialogue with stakeholders and municipal authorities. A corollary to this type of aquifer modeling will be its application to improve the definition of capture and flow zones around individual municipal wells and wellfields needed as an input to land-use planning.

Rivera-Uruguay / Livramento–Brazil

- The Rivera/Livramento Pilot (Figure 6) comprises an area of 750 km^2, straddling the frontier of Uruguay (Departamento de Rivera) and Brazil (Estado de Rio Grande do Sul), which follows a low but hilly surface water-divide and is underlain by the Guarani Aquifer with a groundwater table at shallow depth. Groundwater flow is concentrated in the most permeable aquifer horizons in the depth range 40-80 m, and is naturally in a north-easterly direction but modified by abstraction which has depressed groundwater levels by about 5-10 m in the last 10 years (Figure 6).

- The towns of Rivera and Santana do Livramento have a combined population of approaching 200,000, divided almost equally and growing rapidly, and in many ways live and act as a single continuous urban area with common electricity supply system, emergency services and freedom of movement. The principal economic activity is based upon agriculture (cattle and sheep for wool, leather and meat production, grapes, maize and increasingly soya-bean cultivation – and on the Uruguayan side forestry with wood and pulp production). There are some potentially-polluting facilities such as livestock slaughterhouses and timber yards.

Figure 6 : Sketch map of water infrastructure and hydrogeological section of the Rivera-Santana do Livramento Pilot Project Area



- The Guarani Aquifer outcrops across much of the pilot project area, and elsewhere is covered by a thin capping of Sierra General (Serra Geral) Basalts. The SAG is the principal source of water supply there being in the order of 300 water wells, including those of Obras Sanitarias del Estado (OSE) in Rivera and the Departamento de Agua y Esgoto (DAE) in Livramento (Figure 6), which provided some 5.1 and 8.7 Mm^3/yr (about 70% and 100% of the total public water supply) respectively in 2002 (OSE also operate a small surface water impoundment and treatment plant built by the British in the 1940s).

- The coverage of mains water-supply is more than 95% of the population – but it is not clear to what extent multi-residential buildings and larger single-family residences also operate groundwater self-supply from private boreholes to mitigate against discontinuity of mains service or to reduce the overall cost of water-supply. Such practice was in fact prohibited in all towns of Rio Grande do Sul by a Sanitary Declaration (1974), because it was feared that use of shallow groundwater from inadequately constructed wells could present a serious health hazard – but this regulation proved difficult to enforce (especially with the advent of mobile rapid drilling rigs).

- Natural groundwater quality is excellent with a low level of CaHCO3 mineralization (and Cl > 10 mg/l, SO4 > 5 mg/l, Na > 10 mg/l) – but low pH (less than 6.0) and elevated NO3 concentrations (over 50 mg/l) have been reported on the Uruguayan side. The main groundwater management problem relates to the lack of mains sewerage, which results in a substantial load of wastewater to an aquifer of relatively high pollution vulnerability either directly from cesspits or indirectly from polluted streams. The past history of land tipping of solid municipal waste, the infiltration of a variety of industrial effluents and the presence of a substantial number of poorly-maintained gasoline filling stations represent further hazards to groundwater quality.

- The coverage of the main sewerage system is restricted (being available to 30% and 40% of the Rivera and Livramento population respectively), with the implication of a substantial subsurface loading of wastewater from in-situ sanitation units over extensive areas of the city. There is also overflow of numerous in-situ sanitation units in certain areas of the city (due to improper construction, insufficient space for soakaway construction and locally inadequate soil infiltration capacity) leading to unsanitary conditions at street level. Both towns are striving to amplify their mains sewer system – and OSE in particular are in the process of increasing coverage from 30% to 50% or more in the coming years.

However, this process is complicated by a number of factors:

- the very hummocky terrain which usually necessitates a large number of local sub-stations for pumping sewage and causes a major increase in capital cost and operational problems
- the relatively low population density in the outer urban areas, which considerably increases the unit cost of connection and operation
- unwillingness of some of the population to meet the capital cost of linking their properties to the main sewer when provided and to pay the annual charge for mains sewerage provision once connected
- a considerable number of illegal connections of roof and patio drainage from residential properties to main sewage collectors, causing system overload, heavy sediment load and treatment plant by-pass during frequent episodes of intense rainfall.

The prevailing situation means that, even with increased investment in the provision of mains sewerage, it is not certain that the full benefits will be realized – either in terms of public (especially child) health or of aquifer protection.

- Both OSE and DAE have a group of higher yielding water wells (yields greater than 100 m3/hr) in two restricted areas west of the city and close to the foot of the basalt escarpment, where the full thickness of the Guarani Aquifer is present (including the more transmissive parts of the Tacuarembo/Botucatu Sandstone Formation). In both cases the supply derived from these areas appears already to represent more than 30% of the total.

- These locations, which are at or beyond the current limit of urbanization, would appear to be well suited to the drilling of more urban water-supply wells and the establishment of special protection areas for potable groundwater capture. This approach would provide a more secure water-supply for the city and reduce dependence on the numerous water wells dispersed throughout the urban area which are at greater risk of pollution irrespective of decisions on extension of the coverage of mains sewerage.

- A question arises of if and where the legal and institutional powers lie in relation to the possible declaration of potable groundwater supply protection areas (of various km^2 extension) for which significant land-use constraints would apply. It is clear that such powers are not held by MOPT-DNH or OSE in Uruguay nor SEMA-DRH or DAE in Brazil, and it is likely that such a protection action would have to be through petition to municipal or local government.

- In the main urban areas (which still include some operational OSE and DAE water wells) the Guarani Aquifer probably exhibits only moderate pollution vulnerability as a result of the pumping depression of the water-table to below 10m below surface and the nature of the (only slightly consolidated) sandstones – but they must be expected to experience pollution by nitrate, chloride and persistent organic compounds in the longer run if these continue to be discharged to the subsurface.

- A Comisión Transfronteriza del Acuífero Guaraní (COTRAGUA) has been formed to promote the pilot project by representatives of 5 local stakeholder organizations on each side – including the local government offices, the corresponding water utilities (OSE and DAE), water well drillers, NGOs, agricultural, hydrological and public health organizations. Its functions will include:
  - assist in the collation of relevant technical, economic and legal materials, and in the dissemination of information to the community
  - focal point for required social surveys and promotion of community participation in groundwater

management decision-making, including denouncing illegal well construction and polluting discharges
- coordinate local efforts for capacity building amongst stakeholders.

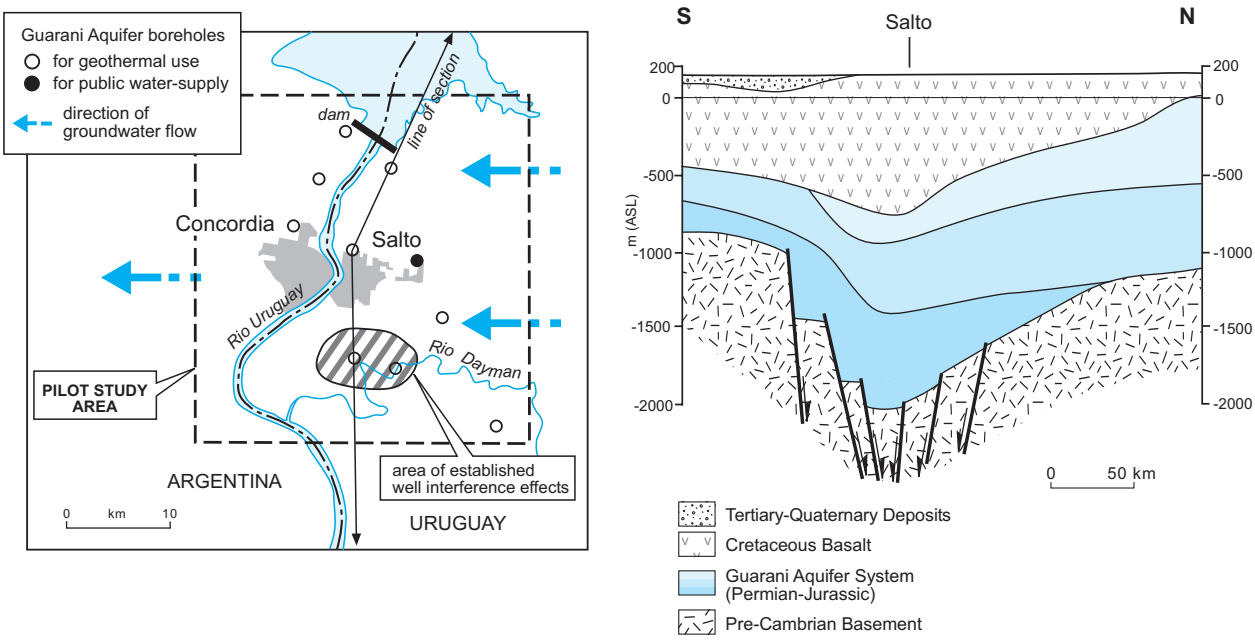
- Some international legal agreements already exist locally, most notably the 'Acuerdo sobre Cooperación Brazil-Uruguay en Materia Ambiental de 1992', and these, along with the long-standing cooperative environment between the two cities, should provide an excellent starting point for the present initiative.

- The main outcomes desired of the Pilot Project are to:
  - establish protection zones/perimeters around the more important sources of public water-supply, with appropriate land-use planning controls (both urban and rural), to ensure their sustainability and protect investments in the sources themselves and their associated infrastructure
  - mobilize a joint investment and action plan to improve urban sanitation both as regards sewage effluent and solid waste elimination – including where appropriate and feasible improved coverage of mains sewerage and other pollution prevention measures in vulnerable aquifer zones in the communal interest of conserving groundwater quality.

Concordia-Argentina / Salto-Uruguay

- The Concordia / Salto Pilot occupies an area of 500 km^2 on either side of the Rio Uruguay (Figure 7), which forms the international frontier between Argentina and Uruguay. In marked contrast to the other 'pilot management areas', the Guarani Aquifer is here found beneath 800-1000 m of volcanic basalt flows (Figure 7) and its groundwater exhibits overflowing artesian heads and marked geothermal potential (temperatures of 44-48 °C). Geothermal borehole yields are normally in the range 100-300 m^3/hr with drilling depths up to 1400 m.

Figure 7: Hydrogeological sketch map and section of Concordia-Salto Pilot Project Area



- In this area the SAG is not significantly developed for public water supply – with treatment plants on the Rio Uruguay providing the bulk of the supply. This is supplemented by mainly shallow water wells in the thin Tertiary / Quaternary deposits and fractured upper part of the Sierra General (Serra General) Basalts as a complementary 'cold water' source used for public supply and small-scale irrigation.

- The pilot project comprises the most populated area of the Argentina-Uruguay frontier region with a total of about 200,000 inhabitants, split approximately equally on either side of the border. The major sources of income in the area are an expanding citriculture and horticulture industry, together with an important development of hydrogeothermal tourism. Salto (Uruguay) is the most developed area of thermal spa tourism in the Mercosur with a history of more than 10 years development – in the late 1990s the annual number of tourists reached 368,000 generating an income of about US$ 58 million/yr and producing (directly and indirectly) 3,500 employment jobs. In contrast Concordia (Argentina) has only recently initiated its first thermal tourist complex.

- Environmentally the SAG is well protected by the thick cover of overlying basalts and its high degree of confinement, and the main potential groundwater problems are:
  - hydraulic interference between neighboring wells (already 8 geothermal boreholes exist in a relatively restricted area), which reduce (and may even eliminate) the overflowing artesian heads which are a special tourist attraction and might also reduce groundwater temperatures
  - a risk of saline intrusion from the south-south-east, where the SAG contains thermal groundwater of high natural salinity.

  Generally SAG groundwater is of the Na-HCO_3 type, and an increment in Na from 135 to 205 mg/l has been observed during the period 1992-2000 in the Termas de Dayman. Increased Na and Cl are observed in wells which draw groundwater from the greatest depths, with increases of Cl from below 100 to above 200 mg/l in some instances.

- Many thermal spas do not yet have adequate water demand and use management, and there is a communal need to develop and disseminate more efficient geothermal water-use practices, including water recycling for the cultivation of exotic gardens, space-heating of hotel installations and greenhouses, and fish farming, with safe discharge of effluents (especially if their salinity is elevated), and to combine this resource as appropriate with shallow groundwater for 'non-spa uses'.

- A local committee (Comité Local de Apoyo al SAG – Proyecto Piloto Concordia/Salto) has been constituted comprising representatives of local government and the municipalities, the provincial and federal agency for water resources respectively for Argentina and Uruguay, geothermal water users associations and universities with the following functions :
  - assist in the collation of relevant technical, economic and legal materials, and in the dissemination of information to the community
  - focal point for required social surveys and promotion of community participation in groundwater management decision-making, including denouncing illegal well construction
  - coordinate local efforts for capacity building amongst stakeholders.

- The present institutional arrangements for groundwater management are distinct on either side of the international frontier – with the Secretaria de Recursos Hidricos-Entre Rios and the federal departments Departamentos Nacionales de Hidrografica & de Medio Ambiente (DNH & DENAMA) being respec-

tively responsible in Argentina and Uruguay. But the respective legal provisions have many points in common and could readily be the platform for the development of a 'set of parallel legal regulations'.

- The Pilot Project has the aim of laying the scientific and institutional foundation for the sustainable and efficient use of SAG hydrogeothermal resources in an area of the highly-confined aquifer. Important progress has already been made in respect of the joint adoption of:
  - an appropriate standard for geothermal well design, construction and operation so as to avoid unnecessary loss of geothermal water or of artesian pressure and ingress of shallower groundwater of low temperature
  - an interim minimum separation of geothermal wells of 2 km, pending more accurate specification by the current project.

Itapua - Paraguay

- The Itapua Department Pilot involves a predominantly agricultural cropping and livestock-rearing area of 800 km^2 in the extreme south-east of Paraguay, including the districts of Bella Vista, Jesus, Trinidad, Hohenau and Obligado, with an average rainfall of about 1,600 mm/yr. The area was originally populated by indigenous Guarani, and includes important Spanish colonial sites (ruined Jesuit missions), but today has a cosmopolitan population of 45,000 with immigrants from more than 10 countries.

- The outcrop of the Guarani Aquifer forms about 40% of the area and in the rest it is covered by a variable thickness of volcanic basalt flows (Figure 8). Some 60 water wells have been registered by the Servicio Nacional de Agua y Saneamiento (SENASA), and inspected by an on-going German technical assistance project with the Secretaria del Ambiente (SEAM). These mainly vary between 70-120 m in depth but reach to over 300m in areas of thick basalt cover – a few of the shallower wells show signs of incipient NO_3 contamination.

- Southeastern Paraguay has witnessed major changes of rural land-use in the last 30 years:
  - first during 1975-80, rapid deforestation for wood production and cattle ranching, facilitated by the construction of the road-bridge over the Parana River to allow exportation
  - second during the 1990s, the rapid expansion of the area under arable cultivation due the widespread introduction of soya-bean and sunflower or maize rotations which provide much higher farmer incomes than ranching (especially on the excellent lateritic soils of the Alta Parana Basalts whose land price has risen steeply to about US$ 4,000/ha in recent years)
  - third in the last 5 years or so the widespread introduction of seed-sowing by direct drilling on arable land to reduce soil erosion, but that requires heavy applications of herbicides such as glyphosate.

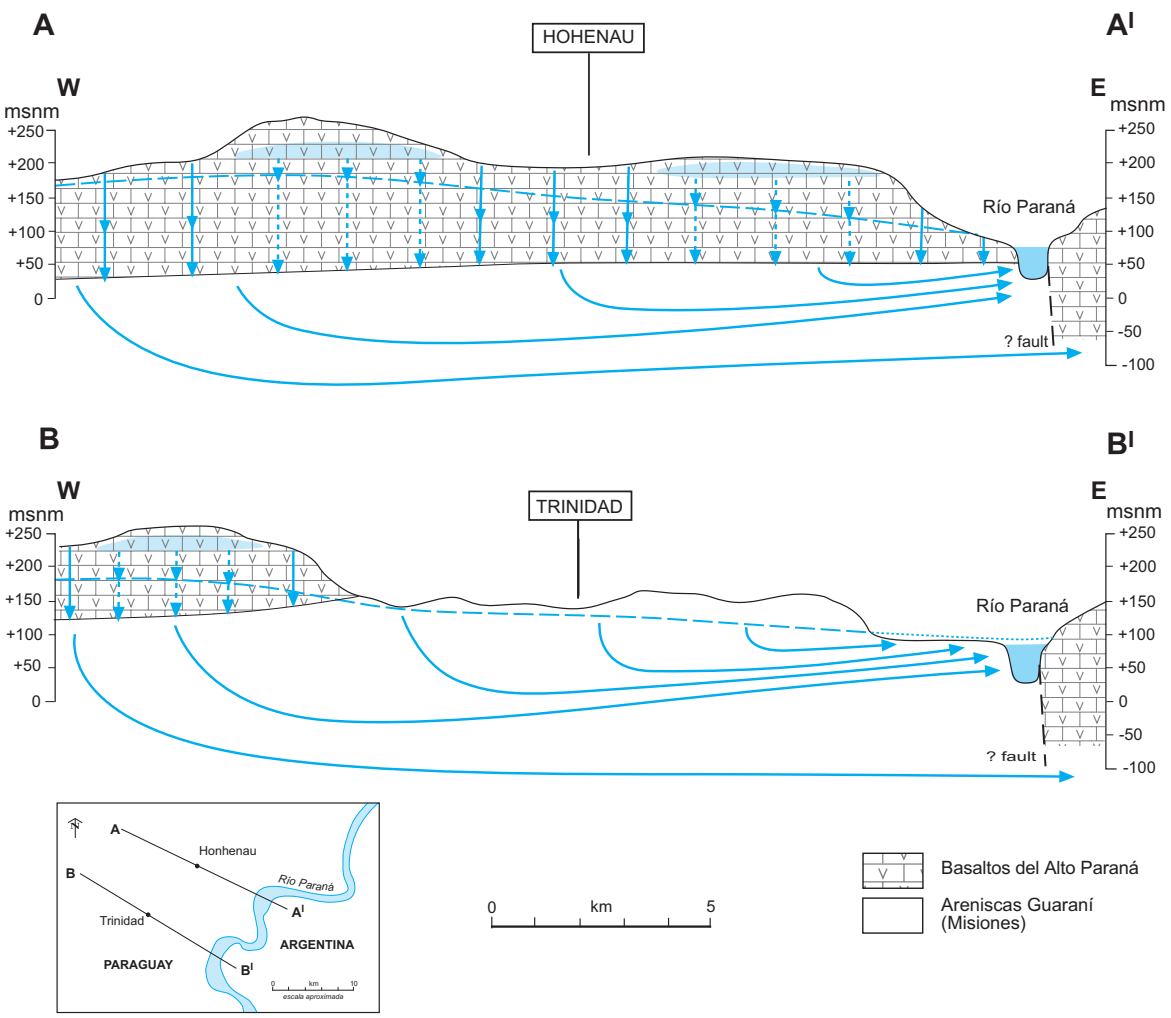
  While these changes have caused important hydrological impacts as registered by macro-monitoring of surface water systems, their effect on groundwater is not yet known.

- This pilot project, whose main objectives are listed below, will thus be of relevance to land-use planning, agricultural production and water resource management both at Paraguayan national level and to much larger areas of the Mercosur:
  - review the socio-economic and agricultural evolution of the area since 1960, including the mapping of the changes in land-use and agricultural cropping, to confirm the trend in the amplification and

intensification of soya-bean cultivation in relation to hydrogeologic and pedalogic conditions

- classify the more heavily applied pesticides on the basis of their water solubility and soil mobility, and then evaluate (using data on typical rainfall intensities at their time of application) the likelihood of their being leached to groundwater in the typical soil profiles developed on the sandstone outcrop and on the basalt cover
- establish a network of relatively shallow groundwater monitoring piezometers and wells (including some drilling at carefully selected sites) in the Guarani Aquifer Sandstones and overlying Alto Parana Basalts, and undertake sampling and analyses to determine the extent of past and current agrochemical leaching to groundwater
- establish the hydrogeologic and socio-economic potential of the SAG to support supplementary agricultural irrigation as an insurance against crop yield reductions associated with droughts even of short duration, especially in the soya-bean cultivation cycle
- a critical evaluation of the procedures used to develop and protect groundwater sources used for public water-supply and the design and operation of sanitation systems in small rural towns

Figure 8: Hydrogeological cross-sections of the Itapua-Paraguay Pilot Project Area



- predict future trends and identify needs for management action to ensure groundwater resource sustainability and environmental protection, and develop the necessary local institutional and stake-holder capacity for an adequate level of soil and groundwater resource management

It is clear that it will be necessary to mobilise the participation of 'key actors' from both the agricultural and water sectors, together with representatives of local government and community leaders, for the project to be a success.

Final Remarks

- The character of this GEF-funded initiative on the transfrontier Guarani Aquifer System (SAG) is special because of its preventative and cooperative objectives. Two aspects warrant brief recapitulation:
  - the importance of addressing the lack of adequate and common understanding, since it represents a threat to cooperative conservation, protection and sustainable use of groundwater and geothermal resources
  - that concrete management actions need to be promoted at the appropriate (mainly local) scale, with the necessary level of transboundary integration, so as to generate best-practice experience which can be replicated over much larger areas as found necessary.

Publication Arrangements

The GW•MATE Case Profile Collection is published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwpforum.org).

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