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DEPARTMENT OF TECHNICAL COOPERATION FOR DEVELOPMENT

GROUNDWATER OVEREXPLOITATION IN DEVELOPING COUNTRIES

Report of an Interregional Workshop

Gran Canaria, Canary Islands, Spain
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NOTES

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Water volumes are given in cubic hectometres (hm^3) or million cubic metres (Mm^3).
$1 hm^3 = 1 Mm^3 = 1 \times 10^6 m^3$

The term overexploitation is freely used throughout this report even though many have concluded that the word is ambiguous and confusing, and recommend that its use be limited or avoided altogether. The term is, however, in the formal titles of both the Congress and the Workshop and it is a legal concept in Spain. When reading this report, therefore, care must be taken to distinguish among the terms overexploitation, intensive exploitation, extensive exploitation and unsustainable development, and to recognize that they are not synonymous.

Abbreviations used

DTCD	Department of Technical Cooperation for Development
FAO	Food and Agriculture Organization of the United Nations
g/l	grams per litre
IAH	International Association of Hydrogeologists
L	size (length) of aquifer
l/s	litres per second
MWWA	Metropolitan Waterworks Authority (Bangkok)
NGOs	non-governmental organizations
S	storage coefficient
T	transmissivity
TCDC	Technical Cooperation among Developing Countries
TDS	total dissolved solids
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization

As of 1 March 1992 the functions and programmes of the United Nations Department of Technical Cooperation for Development (UNDTCD) are being carried out by the newly formed United Nations Department of Economic and Social Development (UNDESD).

ABSTRACT

Following a Congress at which 300 groundwater professionals presented technical papers on aquifer overexploitation, 33 representatives, including 21 from 17 developing countries of Africa, Asia, the Caribbean, Latin America, Mexico and Western Asia, spent four days at a United Nations Workshop on the subject. Both the concept and evidence of overexploitation were found to be confusing and ambiguous. The many benefits of extensive groundwater use require that control strategies, prevention of abuse, and remedies for past damage require planning, monitoring, legislation and public awareness. Groundwater mining and water supply for small islands can entail special economic and technical considerations.

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INTRODUCTION

Background and organization

Early in 1990, the United Nations Department of Technical Cooperation for Development (DTCD) was invited by the Organizing Committee of the XXIII Congress of the International Association of Hydrogeologists (IAH) to sponsor and send a representative to attend the Congress, along with other organizations of the United Nations family such as UNESCO, WHO and UNEP. Its theme was Aquifer Overexploitation and the venue was Puerto de la Cruz in Tenerife, Canary Islands, Spain.

The Water Resources Branch of the Natural Resources and Energy Division, in the course of the last 25 years or so, through its advisory missions and field projects, encountered many cases in which groundwater exploitation contributed in an effective, economic and fast way to solve important acute urban water-supply problems and to increase agricultural production. Nevertheless, it also encountered cases of extensive groundwater development leading to a variety of environmental and socio-economic problems, especially in arid regions, coastal areas and small islands.

The theme of the Congress was therefore of great interest. DTCD thus decided not only to arrange for the attendance of one of its technical advisers, in addition to that of national representatives from its water projects (under their fellowship component), but also to propose to the Government of Spain that it convene, in cooperation with the United Nations, an interregional workshop on the subject, to be held in the Canary Islands immediately after closing of the Congress.

The concepts behind the Congress-Workshop project were essentially three-fold:

1. They would allow participants from developing countries to attend the Congress so as to gain state-of-the art knowledge on overexploitation of groundwater (about half the 95 papers contributed to the Congress were from developing countries),

2. There would be a short workshop following the Congress, including the same participants and some from developing countries other than those who had attended the Congress. They were to be selected on the basis of the relevance of the papers they had presented to the Congress. Several senior experts from industrialized countries attending the conference in the capacity of keynote speakers or main lecturers were also invited to attend the workshop.

3. They would concentrate on the problems of management related to extensive groundwater use that are of special relevance for developing regions, drawing useful conclusions from the Congress and the personal experience of the Workshop participants, taking into acccount both detrimental and beneficial aspects. Such problems have been, are or will be affecting hundreds of millions of people.

Combining the congress with the Workshop would, it was hoped, bring together a maximum of expertise at minimum cost.

The Spanish Government, the local Government of the Canary Islands and the Organizing Committee of the XXIII Congress of IAH and the International Course on Groundwater Hydrology jointly with the Polytechnic University of Catalonia, Barcelona, responded positively to the DTCD proposal. A formal project document (INT-90-R43) was prepared by the Water Resources Branch and approved by DTCD in December 1990 and by the Spanish Government in March 1991. The budget provided for services of a consultant, participation of two staff members of the Water Resources Branch, attendance at both the Congress and the Workshop for eight professionals from developing countries, and attendance at the Workshop for eight additional professionals already attending the Congress at the expense of their respective governments. The Water General Directorate of the Government of the Canaries, through the Water Resources Services of Las Palmas, with the help of the Civil Engineering Association of Las Palmas de Gran Canaria, provided funds for servicing the Workshop.

The Workshop and the Congress

Some 300 groundwater professionals attended the Congress in Puerto de la Cruz, Tenerife, while a maximum of 35 participants had been planned for the Workshop, which was held at a different venue. The Spanish Committee selected the facilities of Feria del Atlantico in Las Palmas de Gran Canaria, Gran Canaria island. In Gran Canaria another kind of groundwater resources management and intensive exploitation could be seen, with aspects closer to the participants' interests.

The Workshop was ultimately attended by 33 water resources professionals, of which 21 were from 17 developing countries in different regions: Central America, South America, West Africa, North Africa, the Mediterranean, Western Asia, South-east Asia, Eastern Asia and the Pacific. Unfortunately, although invitations had been sent to the Governments of India and Pakistan, there was no participation from the Indian subcontinent, due apparently to communication problems.

Three high-level senior experts from industrialized countries: France, the United Kingdom, and the United States of America provided guidance, especially with the discussions, and arranged for contributions from the participants in questionnaire form. They were joined by professionals from Spain (peninsular and Canary Islands), some of whom constituted the Organizing Committee.

It was not possible to arrange for a senior United Nations regular programme staff member to act as director of the Workshop. An Interregional Adviser in water resources, however, attended the Congress and acted as general rapporteur. Administrative matters related to the United Nations project were handled by an assistant from United Nations Headquarters. An officer from the UNESCO Division of Water Sciences represented that agency.

The Workshop was conducted in English. Several participants were more at ease in such other languages as Portuguese, French, Spanish, and Russian. Eventually, through voluntary on-the-spot translation, communication with them was easily improved.

The list of participants is presented in annex I. The six topics of the Congress, the programme of which is presented in annex II, were also discussed by the Workshop, but from a different approach. First, the Workshop was organized in the form of roundtable sessions as an exercise in Technical Cooperation among Developing Countries. Second, the topics of the Congress were reorganized into three themes: 1) the concept of overexploitation and evidence of overexploitation, 2) the impact and benefits of extensive groundwater use, and 3) control strategies, prevention and remediation. Third, the Workshop extracted from the abundant and valuable material presented in it and at the Congress, key ideas and concepts that would be of value in the development and implementation of water resources in developing countries.

The Workshop functioned as a somewhat informal, but extremely animated, professional forum. Communications between all attending were greatly facilitated by the roundtable arrangement. The programme of the workshop is presented in annex III.

Owing to the late approval of the project, it was not possible to arrange for many participants from developing countries to prepare papers. They were requested, therefore, to submit notes, including replies to questionnaires, on the situation of groundwater overexploitation in their country, its consequences, and the remedial measures already taken or being considered for the future.

A summary of the contributions to the Workshop is presented in annex IV. DTCD, for its part, prepared a position paper (annex V) which was distributed to the participants. A draft outline for this report was approved by the participants.

The report

The term "overexploitation" and the concepts it implies were widely discussed during the Congress and Workshop. Interesting ideas emerged from those discussions, resulting in much-needed clarification. This matter is dealt with in section I of this report. The factual evidence of overexploitation from hydrologic and other physical data is described and evaluated. Section II reviews the detrimental effects of overexploitation. In section III, the positive aspects and benefits of extensive and intensive groundwater development - or overexploitation by some points of view - are considered as well as situations in which the recharge of aquifers is deliberately exceeded or, in other words "groundwater mining".

Because overexploitation has social consequences and can be seen from an economic point of view, section IV considers these aspects together with legal considerations. Preventive and corrective measures for uncontrolled, unplanned and detrimental extensive groundwater exploitation are described in section V. In conclusion, a short but comprehensive assessment of the overexploitation concept is presented and specific recommendations proposed. Each section contains examples, mainly drawn from the Congress and Workshop papers and presentations, with emphasis in developing countries.

This report includes results from the discussions and a number of concepts, ideas and information contained in papers submitted to the Congress and which were discussed at the Workshop. Those are listed in annex VI and cited in the text by bracketed numbers. A few other references of especial relevance are included. The list of references does not constitute a bibliography on the topic. Readers interested in further information on groundwater overexploitation should contact the International Association of Hydrogeologists, which has published the proceedings of the Conference and is to publish revised versions of selected papers.

It is hoped that this report will help decision-makers in developing countries in their policies for water resources planning and management, targetted at the improvement of socio-economic conditions and also at the preservation of the environment so as to achieve sustainable development in the spirit of the International Conference on Water and the Environment of the United Nations (Dublin, Ireland, January 1992). Also it is hoped that errors already made both by industrialized and developing countries will be avoided in the future, thus obtaining optimum use of perennial and exhaustible groundwater resources.

Acknowledgements

The Host Country Committee spared no effort or resource in organizing the Workshop. Thanks are due the team from the Canary Islands led by the Chief of the Water Resources Service of Las Palmas, Mr. José Jiménez-Suárez. Their outstanding organizational efforts in terms of conference room, secretariat facilities, hotel reservations and transportation between hotels and the venue contributed to the workshop's success. The hospitality provided was extremely generous. Two professors from the Polytechnic University of Catalonia, Lucila Candela and Emilio Custodio were in charge of scientific, technical and part of the organizational tasks.

The excursions covered many aspects of the local geology, water resources and water sector installations, including a wastewater treatment plant with water reuse for agriculture and gardening, and three desalination plants (one for agriculture and two for urban water supply, two using reverse osmosis and one electrodialysis, two using brackish groundwater and one sea water). Mrs. Mari-Carmen Cabrera was in charge of the technical organization.

The United Nations expresses its appreciation to the Government of Spain, the local Government of the Canary Islands, and the organizers of the Workshop, especially for their administrative, substantive and financial support.

I. OVEREXPLOITATION OF GROUNDWATER: AN AMBIGUOUS CONCEPT

A. General

The word "overexploitation" can be found in few dictionaries [1, 4]. In Spain, however, it entered the legal terminology with the 1985 Water Act, although a precise definition is not provided [1]; in fact, the different Water Authorities are giving non-coincident interpretations in the cases of aquifers already declared "provisionally overexploited".

In the few instances groundwater overexploitation is mentioned in the literature it has obvious negative connotations, to the point of some professionals calling overexploitation any situation leading to undesirable effects, even pollution by induced recharge from the surface or other aquifers. This was clearly seen during the Congress and the Workshop, and also in a 1990 meeting in Almeria, Spain [38] that included a first attempt to define the concept. The format of the Congress and Workshop and the way that titles for the topics were formulated contributed partly to this bias. This does not invalidate the results if the point of view is clearly shown.

There are considerations with associated hydrogeologic and hydrologic and even geotechnical detrimental impacts as described in section II. But, in fact overexploitation is more a level of groundwater development which generates physical, chemical, economic and social undesirable effects than a hydrogeological concept. In many cases undesirable effects had not been foreseen due to lack of knowledge of the groundwater resources and aquifer behaviour. Such unforeseen effects often are considered consequences of overexploitation.

B. Hydrogeologic aspects

Because some definitions link overexploitation to aquifer recharge it is worth mentioning that aquifer recharge is one of the most difficult values to obtain. Best calculations may have a wide uncertainty, e.g., between half and double the calculated value, unless careful checking of all reliable observations over a long enough period, generally several years, is carried out by means of adequate observations and simulation models. It is a rare situation to have the necessary data in developing or even industrialized countries. Besides, recharge has a stochastic nature and mean values may be useless for management if representative time-series considering real situations, including abstraction pattern, or likely scenarios are not used. Furthermore, recharge conditions change with exploitation pattern, groundwater reserve depletion, land use (agricultural practices, irrigation, urbanization), river and river channel changes, and so on. The problem is still more complex when only part of an aquifer system is considered, as often happens due to physical, administrative or political limitations. Groundwater transfers from other areas or aquifers are difficult to reckon. It is especially difficult to evaluate adequately contributions from deep, regional aquifers, if they exist. In many cases they are unsuspected or poorly known [41].

An important factor is the time needed for exploitation to cease having recognizable lowering of the groundwater head, when abstraction is maintained constant. This transient stage is related to several parameters including the dimension, transmissivity and storage coefficient of the aquifer (see figure 1). The existence of thick aquitards produce initial aquifer reactions close to that of a confined one and then changes to that of an unconfined aquifer. The higher the vertical permeability of aquitards the earlier the evolution matches that of an unconfined aquifer. For low vertical permeability, changes are initially fast and apparently attain equilibrium, but in the long term a certain rate of groundwater level decline may be seen more likely to happen after an initial period of large and widely distributed drawdown in the permeable layers.

It is clear that for aquifers having a slow response, a continuous lowering of the groundwater levels should not necessarily lead to the conclusion that abstractions exceed recharge, especially if observations are only over a few years [1, 2], although some of the undesirable effects are the same.

Also, a significant advance (exceeding hundreds of metres) of a salt-water/fresh-water interface or mixing zone within a few years must give rise to concern [1], and this may happen with gross abstraction being clearly less than gross natural recharge.

As a result overexploitation cannot be defined by simply comparing abstraction with recharge. The full set of terms of the groundwater-balance equation must be considered. A given aquifer can be hydrologically unbalanced, i.e., presenting continuous groundwater head drawdown, even if abstraction is less than recharge, in the case outflows are not conveniently reduced. This is the situation in Gran Canaria and Tenerife islands.

As far as abstractions increase, groundwater heads cannot stabilize. In this case it is possible to pass from a situation of extensive exploitation - less than mean recharge - to one of "excessive exploitation" - greater than mean recharge - without notice. In both cases groundwater head reduces continuously.

C. Overexploitation and safe yield

For some hydrogeologists the term overexploitation describes a level of groundwater development which exceeds what is called the "safe yield" of the aquifer system.

The safe yield of a groundwater system may be defined, according to Meinzer [39], as the maximum rate of artificial withdrawal that can be maintained over an indefinite period

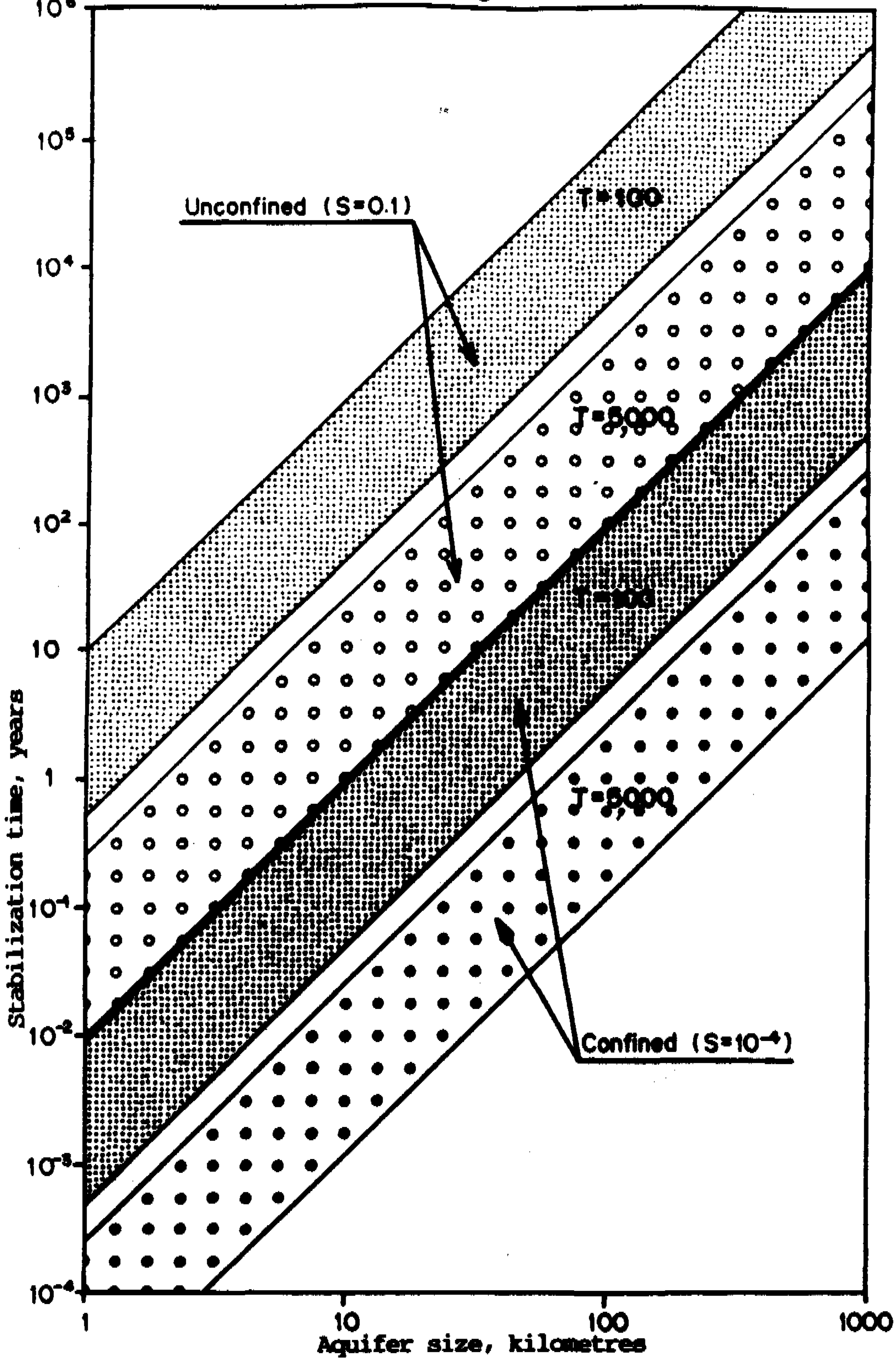

Figure 1. Time for stabilization of drawdowns (in years) in an aquifer after a sudden change in the water balance, according with size (L, in km) and as a function of transmissivity (T, in m^2/day) and the storage coefficient (S). The time is proportional to L^2S/T.

without adverse effects on the resource. In principle, the rate of natural replenishment constitutes the upper limit of the safe yield. Apart from that, there is no simple connexion between safe yield and replenishment. In order to understand the limitations of the safe yield concept, the following points must be considered:

1. The terms "safe" and "adverse effects" are difficult to define. They are perceived differently by the groundwater abstractor itself, other aquifer users, environmentalists and society. They can be defined only in relation to human intervention in the hydraulic system, and have no relevance to natural phenomena. Safe yield can be modified by intentional (e.g., artificial recharge) or non-intentional human intervention (eg. induced recharge, river diversion, change in irrigation pattern, urbanization). It is by no means a mathematical constant of a given aquifer.

2. If the water resource is already adversely affected (e.g., by sea-water intrusion, restriction of exploitation to the assumed safe yield may not suffice to remedy the situation. In critical situations, much more radical measures may have to be applied.

3. In many cases, the determination of safe yield depends strongly on the location and characteristics of production boreholes, their spacing and depth. If a water table coastal aquifer is developed by boreholes near the shore, the danger of sea-water intrusion will be greater and the safe yield of these boreholes will be less, than if the boreholes are drilled farther away from the shore line, or its depth and screening are correct.

4. If the term safe yield is to be related to average annual replenishment, the term "average" needs clarification. Averages are defined only in mathematical terms; they need not have any physical significance. However, safe yield is a quantity of water actually available each year without regard to climatic fluctuation. In fact, the storage of the aquifer is called upon to "iron out" seasonal and yearly fluctuations in replenishment, so that a dependable safe yield can be obtained. In this respect the function of groundwater storage (reserves) is identical to the function of storage reservoirs in surface water supply systems. It is depleted during given periods whilst it is refilled in others. Therefore, when the safe yield of an aquifer is determined, it is necessary to take into account its storage as well as the fluctuations of replenishment that can be expected.

D. Water management considerations

Differences of opinion, if not antagonistic views, exist on the subject of groundwater overexploitation. The concept of aquifer overexploitation is ambivalent and even ambiguous, because it is defined in some cases by the hydraulic concept of unbalanced exploitation and exhaustion of reserves, and in other cases by multiple criteria of excessive exploitation, considering multiple consequences and environmental issues. It is essential for groundwater developers to consider all aspects: hydrogeologic and environmental conditions, the economic objectives and their social implications [1, 2].

The term groundwater overexploitation, as far as water resources management is concerned, is understood, or misunderstood in many ways; it does not have an adequate or uniform definition. Other expressions describing specific situations such as "groundwater mining", "unsustainable groundwater development" and "extensive exploitation" may be more appropriate [1, 2, 6, 23].

Overexploitation - or excessive exploitation - of an aquifer is, in the broad sense of the word, a situation in which exploitation generates an unwanted physical, socio-economic, quantitative or qualitative effect. Many such situations are described in the scientific literature, under very diverse conditions [22]. When the socio-economic aspects are considered, the analysis becomes extremely complex, as the exploitation of the aquifer is considered both in terms of economic production of groundwater and social benefits [36, 40].

Therefore, in assessing a situation of overexploitation, the views of diverse professional collectives may differ. Also, economists may hold different points of view. Differences of opinion arise over the criteria to be used and how to use them. Situations considered as overexploitation may be the result of excessive exploitation or simply the consequence of unsatisfactory resource management [2]. Moreover, situations seen by many as undesirable, and consequently called overexploitation, are necessary effects of beneficial groundwater exploitation that can be corrected and may be the result of inadequate well design and distribution.

In many cases, groundwater development, even sustainable, can be termed irrational and a case of overexploitation [23], such as so many wells drilling as to interfere with existing wells, water galleries and springs. This is especially true near discharge areas. Any exploitation of groundwater necessarily and normally creates an imbalance, even if the extraction of groundwater causes an increased recharge flux to the aquifer, which is sometimes the case. That situation is not to be considered as overexploitation which is at times done by mistake [1, 2]. Controlled intensive exploitation of limited duration can have beneficial effects; the storage capacity of the groundwater reservoir can be utilized as a regulatory device providing that equilibrium is re-established over the mid-term or long-term and that exploitation is fully controlled [2].

The exploitation of vast "fossil aquifers" with little or no present recharge, but with enormous storage, is necessarily unbalanced but may be highly profitable under given circumstances. It is not to be condemned without further consideration. This is the case in the northern Sahara (Libyan Arab Jamahiriya, Egypt) and Saudi Arabia. This kind of exploitation is subject to the same constraints as mineral exploitation in that it is a non-renewable natural resource, which must be decided by an assessment of whether it is non-detrimental to overall national water resources and environmental policy and long-term socio-economic objectives. But water is not a common mineral for it is essential to life and no other substance can be substituted for it. This introduces a difference that must be taken into account when considering the needs and rights of both present and future generations.

E. Signals of groundwater overexploitation

Owing to the different ways people define and feel overexploitation or related circumstances, consideration of what to consider as overexploitation signals may differ greatly according to the different professional orientations and the several kinds of groundwater exploiters and users. But a combination of some of the following aspects almost always appear:

1. A lowering of groundwater levels in wells (several metres or more)
2. An increase in dissolved solids more than a gram per litre, including in some cases naturally contributed toxic elements (on the order of a milligram per litre)
3. Land subsidence (a few millimetres or more per year)
4. Along coastal areas, progression inland of the sea-water/fresh-water interface or mixing zone (on the order of metres or tens of metres per year)
5. An unusual increase in complaints and legal actions

Signs of what in some way can be called overexploitation have appeared recently (mostly since the early 1960s) in well fields serving large urban communities, in coastal areas and islands of modest dimensions, in agricultural areas, in arid, semi-arid or Mediterranean-type climates with extensive irrigation from groundwater sources, and in areas of hard rock.

Groundwater overexploitation, generally refers to a trend seen during several years of exploitation, to which seasonal fluctuations may be superimposed (recharge events, changes in abstraction, inter-annual variability). The situation of an aquifer subjected to large drawdowns or saline intrusion during the abstraction season, recovering afterwards, cannot really be termed overexploitation. This is normal functioning of an aquifer as a water source, although undesirable effects could be derived. The term "temporal overexploitation" is thus abusive.

F. Circumstances leading to overexploitation

The easy availability of fast drilling methods capable of attaining great depths, and the widespread use of powerful submersible turbine pumps, helped to establish the extensive and intensive, sometimes wild, exploitation of groundwater that leads to the feeling, true or not, that an aquifer is overexploited due to unusually fast rates of change.

What seems excessive groundwater exploitation - overexploitation in a broad sense - may be the result of several situations or a combination of them [11], and not necessarily imply unbearable negative impacts or that abstraction is greater than replenishment. These situations are:

1. A lack of awareness of the need of groundwater management
2. A lack of historical management
3. Poor hydrogeologic understanding of the aquifer system
4. Evaluation of exploitable aquifer resources by the yield of existing wells, a common major error
5. Calculation of total exploitable water resources by simply adding different kind of resources, regardless of interaction between them and of quality changes
6. Poor licensing policies and legislation
7. Disregard for legislation and poor enactment of it
8. Poor training of water resources personnel

Unplanned and unexpected aquifer overexploitation often brings negative impacts for many groundwater users [23]. Development may prove "unsustainable" in situations where groundwater abstraction exceeds recharge, leading to the consumption of groundwater reserves ("mining" or "storage overdraft" or "storage exhaustion"). But this is not always true since development may continue with less and less water if savings and new processes are progressively introduced. This requires some kind of plan, by means of legal and administrative regulation, by simply increasing the price of water, or by a more or less deliberate combination of them. All aquifers do not behave equally, some being more susceptible to dewatering than others, specially the small, low storage coefficient ones in arid or low recharge areas.

G. Examples of so-called overexploitation

During the Congress and the Workshop a series of examples were presented of situations designated as overexploitation. The label was put by describing the undesirable effects, often without evaluating the duration of these effects and the benefits derived from the situation.

Table 1, showing such examples, is based on data from various United Nations publications and papers presented at the Congress and Workshop. Some examples, in greater detail, follow.

Table 1. Examples of detrimental effects of extensive pumping of groundwater

Country	Area	Lowering of groundwater head: Number of years	Total (metres)	Per year (metres)	Effect
Argentina	La Plata	70	15 to 25	0.2 to 0.3	Sea-water intrusion progressing at 75 m/yr. Well-water salinity up to 20 g/l. Sea-water
	Mar del Plata	30?	20 to 50	0.7 to 2.5?	intrusion moved 5.5 km inland.
	North-west of Buenos Aires	20	7	0.35	Piezometric level 27 m below sea level. Increase in salt concentration, including nitrates.
Brazil	Nordeste (N.E.)	30	-	-	Salinity increase from 0.5 to 5 g/l in some wells in fractured aquifers.
	Urban areas	20	-	-	Sea-water intrusion. Nitrate from upper levels.
China	West of Beijing	25	10 to 15	0.4 to 0.6	
	Tianjan	-	-	-	Subsidence of 2.6 m in 30 years: 100 mm in 1986.
	Liadong and Shandong Provinces	-	-	-	Sea-water intrusion, far-reaching in karstic aquifers, with 0.5-6 m land collapse (143 occurrences in 1970-1985).
Egypt	Nile Delta	-	-	-	Mean salinity increase from 600 to 950 mg/l from 1980 to 1990.
India	Indo-gangetic plain	10	10	1	-
	Hard rock areas:				
	Karnataka	10	30	3	-
	Tamil Nadu	10	46	5	Well yield reduced from 2.3 to 1.4 l/s.
	Calcutta	25	6	0.25	Subsidence of 10 mm/yr.
Jordan	Basalts of Dhulleil Hallabat		-	-	Salinity has increased from 0.5 to 2,5 g/l and up to 6 g/l.
Lebanon	Coastal areas	-	-	-	For certain wells, salinity increased from 3.4 g/l in 1970 to 22 g/l in 1985.
Mexico	Guanajuato	30	58	2.5	Recent subsidence 150 mm/yr; total 1.5 m.
	Arid areas in Hermosillo	10 to 20	up to 60	1 to 3	Saline water encroachment up to 25 km inland.
Morocco	Souss Valley	20	40	2	-
Nigeria	Bornou State	10	8.5	1	-
	Niger delta	-	-	-	Settlement of terraces, increased erosion, landslides.

Table 1. (Continued)

Country	Area	Lowering of groundwater head Number of years	 Total (metres)	 Per year (metres)	Effect
Peru	Pampa de la Yarada Antigua, Tacna	-	-	0.6	Groundwater levels 12 m below sea level.
	Lima	-	-	2 to 5	-
Philippines	Metro Manila, Cebu	2	40	20	-
Senegal	Southeast of Dakar	-	-	-	Fluoride contamination of confined aquifers by intrusion (from upper layers) generated by pumping.
Spain	Daimiel National Park	20-25	20-30	1	Marshes and springs of Guadiana River dried up.
Thailand	Bangkok area	17	45	2 to 3	Subsidence 50 to 100 mm/yr.
United States	Coastal area: Gulf of Mexico (Texas, Oklahoma & Tenessee)	43	15 to 30	0.3 to 1 (Ogallala aquifer).	Subsidence 5 to 12 mm/yr
Venezuela	Coastal plain	30	20	0.6	Salinization up to 15 g/l.
Viet Nam	Hanoi	-	-	2 to 10	Subsidence increase 2-5 to 20 mm/yr.
	Ho Chi Minh City	-	-	-	Subsidence increase.
Yemen	Wadi Surdud	50	30	0.6	Projections for 1990-2040
	Wadi Hadramaut	20	10 to 40	0.5 to 2	-
Yugoslavia	Zagreb Plain	10	5	0.5	-

* Figures in metres are maximal, applicable to only a fraction of the territory. The observed rate (m/year) is often the result of short-term observations.

Note: Extensive pumping of groundwater is when total abstraction is close to or exceeds natural replenishment, for some years at least. This assertion may be controversial, but it is a guide to select examples. Groundwater exploitation is nearly always accompanied by drawdown and extensive exploitation is generally accompanied by large drawdowns before stabilization occurs. Some examples may refer to these last situations, and groundwater head lowering may reflect only transient stages.

1. Argentina

The Puelche aquifer, around Buenos Aires - La Plata, is composed of fine and medium sand, 15 to 30 metres thick, and is semi-confined under a clay layer 25 to 50 metres thick. It provides half the supply (50 million m^3 per year from 85 tubewells) to La Plata (a city of 700,000). It is also exploited for irrigation and industrial purposes. Well-field yields are in the range of 10 to 45 l/s per well. Water salinity increases up to 20 g/l towards the coast, situated 15 km to the north-east. It is estimated that recharge is about 45 hm^3 per year (185 mm per year). Since 1912, water levels have fallen 15 to 25 metres. The fresh-water/salt-water interface is moving inland at about 75 metres per year [25]. About 15 wells have been abandoned after salinization.

2. India

In India the volume of groundwater stored down to 300 metres depth is estimated to be at least 10 times that of the mean total annual rainfall. Most of it occurs in the Sindhu-Ganga-Brahmaputra plains and the sedimentary coastal plains of peninsular India. Although in India groundwater has been used for irrigation purposes for thousands of years, in the last 30 years or so, water resources have been developed in a "phenomenal" way, particularly groundwater. From 1950 to 1980 nearly 80 million dug wells, 2.25 million private tubewells and 40 million public tubewells were constructed. The number of motorized pumps increased 200-fold. Some 27 million hectares of land are now being irrigated by groundwater compared to 39 million hectares by surface water. This has introduced a food production revolution that has allowed passage from a situation of deficit to one of a certain surplus for export. It is estimated that 10 to 15 million hectares more can be irrigated in this fashion.

Such groundwater development has consequences of water table drawdown and reserve depletion. Close attention to groundwater exploitation will be required if serious and unwanted side-effects are to be minimized [33]. Signs of excessive drawdown have been observed, however, especially in relation to the increased abstractions to cope with droughts of recent years. The groundwater demand is continuously rising as a result of population increase (by the year 2000 the population of India will increase from its present 830 million to 940 million) and also industrial and agricultural development. At a national scale, there is still plenty of groundwater: recharge is estimated to largely exceed use (by four times), but continuous drawdowns have been observed in northern Gujarat and in northern Rajasthan, where abstraction is recknoned at more than 75 per cent of recharge. In coastal areas of Maharashtra, Andhra Pradesh and West Bengal sea-water intrusion is increasing [33].

In the Central Ganga Basin, extensive abstraction by a large number of wells drilled or excavated without allowing adequate space among them is producing a drawdown of about 0.6 m per year [49].

From 1956 to 1981, the water-table level fell by 6 metres under the city of Calcutta and subsidence has been occurring at the rate of about 10 mm per year over the past 25 years [33]. Subsidence in some old temples (Warangel, Andhra Pradesh) are attributed to extensive abstractions in dry years [33].

Excessive groundwater exploitation is of concern particularly in peninsular India where hard rock formations prevail, such as crystalline shield basement rocks and lava flows (figure 2). The availability of groundwater in crystalline rock is limited by the nature and extent of weathering and fracturing. In the granite or gneiss terranes of southern India, well yields of 1 to 2 l/s can be expected. It has been determined that fractures contribute as much as 68 per cent of the well yields, the weathered zone (generally 15 to 40 metres thick) accounting for the rest. The considerable increase in groundwater development, mainly for irrigation during the late 1970s and the 1980s, resulted in the drainage of the weathered zone [26]. In some villages well density is 25-30 units per square kilometre. The situation has been aggravated by the failure of the monsoon for three consecutive years (1985-1987). It has been studied in detail in two pilot areas of about 20 square kilometres each, in Karnataka State (Zone 1) and Tamil Nadu State (Zone 2). By 1990, a majority of the forty-one Zone 1 wells pumping during 1980 had been abandoned, due to drastic reduction in yield. In the same period, the average depth to the first water-bearing horizon ($ > $0.5 l/s) increased from 22 to 54 metres. Fifty-seven per cent of the wells drilled encountered water-bearing fractures yielding more than 0.5 l/s at depths of more than 75 metres. In Zone 2, the average depth to the first water-bearing horizon (> 0.5 l/s) increased from 38 to 84 metres during the same period, while the average yield reduced from 2.3 to 1.4 l/s. The rate of success in siting wells with more than 0.5 l/s yield below 150 m was only 30 per cent. Also, the yields of wells which did not reach such deep water-bearing zones were much lower than those which did. It appears that the rate of abstraction exceeds available recharge in the areas investigated, leading to a situation where groundwater reserves are being mined.

3. Sri Lanka

Crystalline basement rocks occupy most of Sri Lanka (figure 2). In 1987 some 25 pilot areas were studied for their groundwater resources within the framework of a rural water supply project with wells about 35 m deep, penetrating the bedrock under an overburden about 15 metres thick. Water table variations, evaporation and precipitation were measured. The water table variations were a direct response to rainfall and evaporation. For one well the safe yield was estimated to be equivalent to a recharge of 14,600 m^3 per year (occurring during a small number of days of heavy rains) - that is, in theory, a water resources availability of 40 m^3 per day (0.5 l/s) [30]. A short pumping test would have led

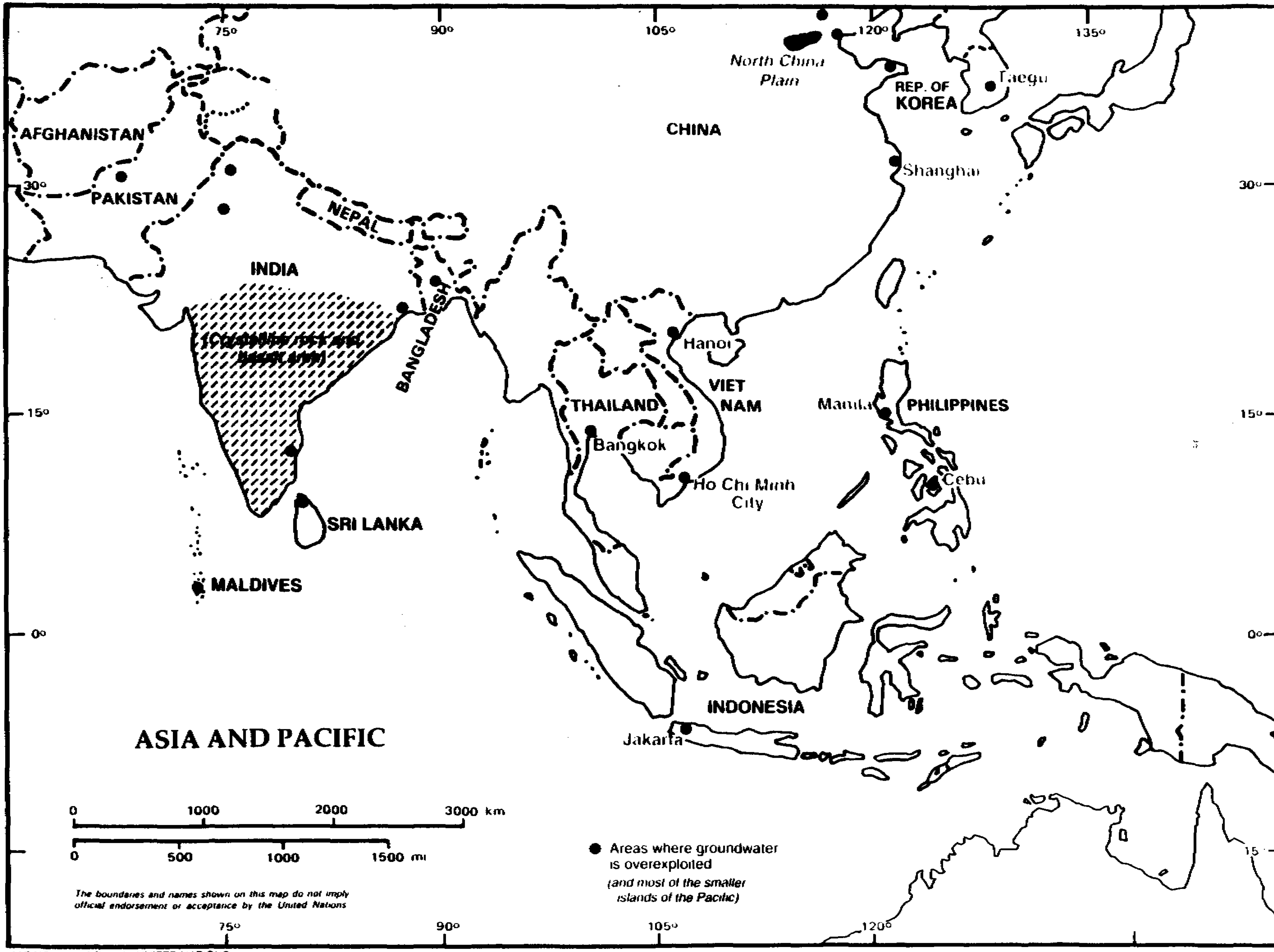

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Figure 2. Groundwater overexploitation in southern Asia and western Pacific

to assessing the specific capacity at 2.5 l/s/m drawdown while, in the long term, the sustainable yield of the well is much less.

4. United States of America

The unconfined Ogallala aquifer which underlies 135,000 km^2 in the south-western United States (Texas, Oklahoma and New Mexico) is a heterogeneous sequence of sand, clay, and gravel. It is 60-180 m thick and saturated through 30 to 120 m. Recharge occurs at a rate of 5-13 mm per year, from precipitation that averages 400-600 mm per year. The main sources are direct rainfall and infiltration in temporary playa lakes (90 per cent of the area is endorheic, with only internal drainage), although river and excess irrigation water infiltration, and upward flow from underlying formations also contribute [20]. Total dissolved solids average 200 to 400 mg/l. Following the droughts of the 1930s, irrigation from groundwater was developed rapidly, at a rate exceeding replenishment by a factor of 6 to 16 (to 8,000 hm^3 per year for the irrigation of 1.8 million ha in 1980). In nearly half of the region, water levels declined by 3 to 15 m by 1980 and by 15 to 30 m in 20 per cent of the area. Without reduction of water use, the drainable storage of the aquifer would probably have decreased by half. By the year 2020 the water levels will probably decline an additional 3-30 m and saturated thickness reduced to less than 30 metres. Dewatering slowed after 1980 because actual water use diminished as a result of increase in rainfall (nearly 100 mm greater than normal during most years of the decade). Also, less land was irrigated and pumping was reduced as a result of an increase in fuel and energy costs as well as in interest rates. The rise in water levels observed in 1986 and 1987 may have resulted from recovery of local cones of depression, something that has to be considered when evaluating groundwater level trends. Resumption of water-level decline in 1988 and 1989 shows that on a long-term basis the aquifer is still overexploited from the point of view of groundwater head lowering [20], but enormous benefits have been derived for the region.

5. Yemen

In the mountainous hard rock areas of Yemen (figure 3), rainstorm flow recharges the alluvial aquifers of the valleys, but alluvium has only limited storage capacity. The water balance of a major valley, that of Wadi Markhah, has been studied in some detail [31]. The alluvial aquifer, mostly sand, gravel and conglomerate, is 60 km long and 50 m thick. Groundwater storage is estimated to be about 100 hm^3, while groundwater abstraction is about 12 hm^3 per year. The frequency and magnitude of floods allow for a satisfactory recharge of the reservoir even though a considerable lowering of groundwater levels occurs in some areas after extended dry periods. This lowering could be interpreted as overexploitation if the study were limited to a small area.

6. Brazil

The north-eastern Nordeste region of Brazil (1,000,000 km^2 and 35 million inhabitants is the oldest settlement of the country, and also the most problematical in view of its concentration of wells in a semi-arid area. It comprises what is called the drought area (área das secas), of about 950,000 km^2 and 20 million inhabitants. Seventy per cent of the population is engaged in primary activities, predominantly agriculture and cattle-raising. The economic unity is traditional and its productivity extremely low. The droughts provoke the failure of subsistence farming causes an exodus of population to the urban centres of the country. Some deception exists in the fact that the many large hydraulic projects (thousands of dams and wells) brought no improvement in living standards. About a third of the drought territory comprises sedimentary rocks generally capable of yielding between 20 and 500 m^3 per hour per well, with a salinity less than 900 mg/l. Data supplied to the Workshop shows that more than 70 per cent of the wells already drilled (about 25,000) derive their water from crystalline rocks (figure 4), the remaining from sedimentary rocks. In spite of some claiming of overexploitation due to local lowering of the water table and an increase in salinity, the wells are underutilized. With those existing it should be possible to supply the rural population and sustain small irrigation schemes. The hydrologic consequences are not known. In urban areas, thousands of uncontrolled private wells provide significant groundwater supply for hotels, hospitals, residences and industries. Water quality suffers from poor well construction, waste dumping and inadequate sewage treatment.

H. Conclusions

Overexploitation is a relatively new concept in groundwater hydrology. It is best defined in terms of the unwanted effects of excessive groundwater development. Overexploitation is not necessarily the result of a recharge deficit against groundwater abstraction [1]. Factors other than hydrogeology must be taken into consideration, such as economy, life preservation and the rights of future generations.

A possible general definition, commonly accepted, may be: a type of exploitation that causes harmful results and therefore must be avoided [36]. The definition is so wide that from the management and legal point of view it is useless, and does not compare drawbacks with benefits. Probably it is impossible to reach agreement on what is a harmful result. Moreover, the term overexploitation is used sometimes with a derogatory meaning, and is more an emotional or sectarian term than a scientific term [6, 23] without - and perhaps incapable of - adequate definition. Consequently overexploitation is considered an ill-defined term that should probably be avoided and replaced with a more comprehensive description of groundwater exploitation and its consequences. When the term overexploitation is used, it is highly recommended that an explanation be given of its intended meaning, in order to avoid confusion.

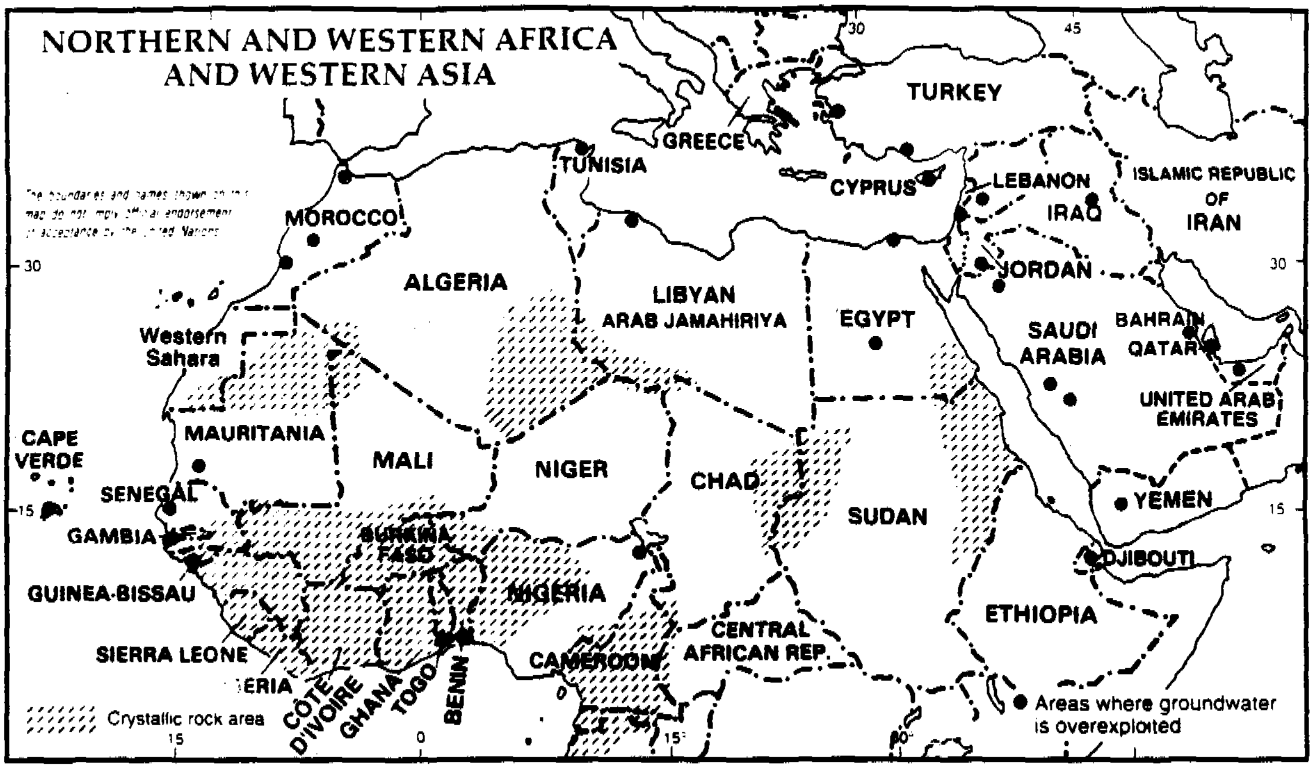

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Figure 3. Groundwater overexploitation in northern Africa and western Asia

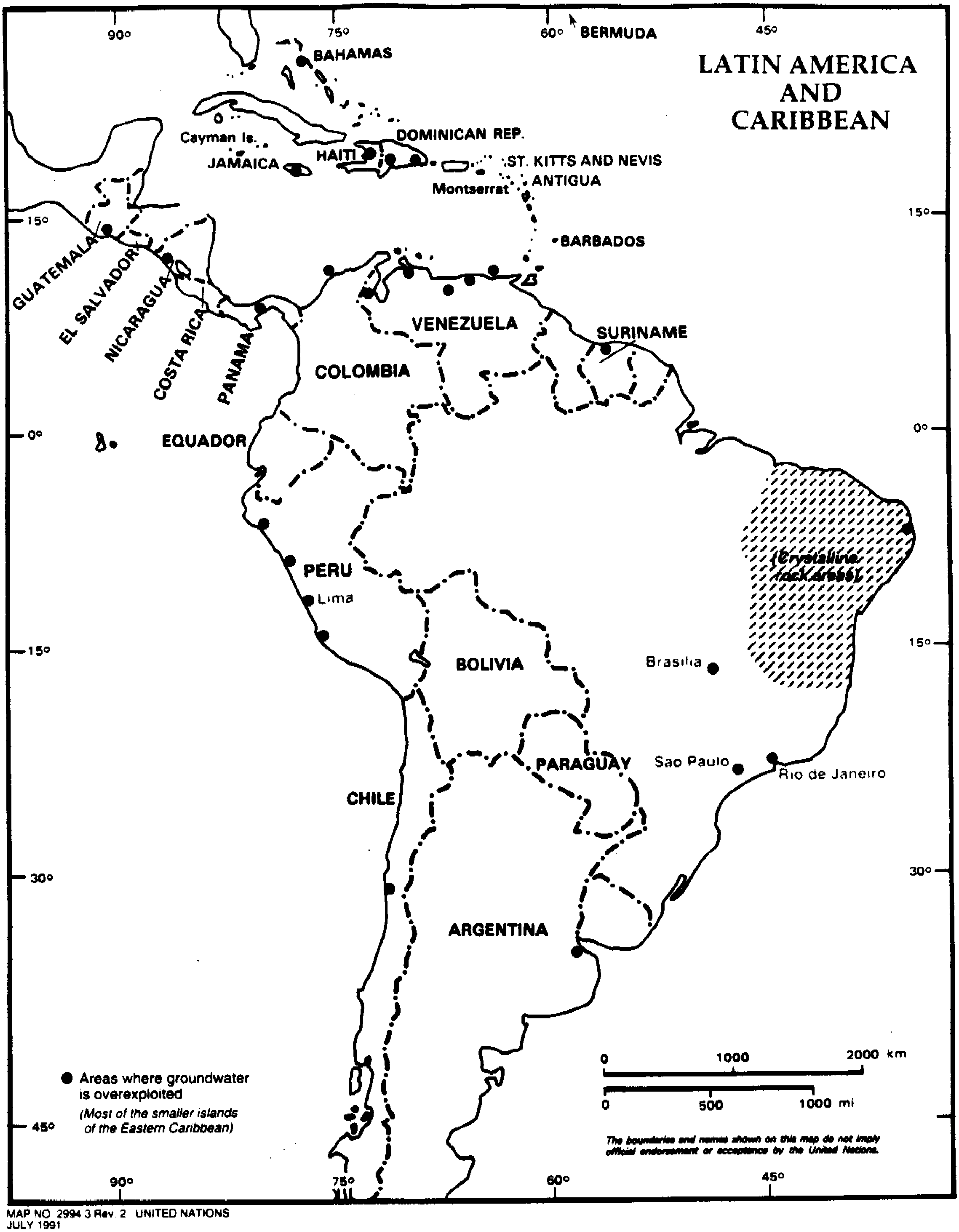

Figure 4. Groundwater overexploitation in Latin America and the Caribbean

A more clear-cut definition would link overexploitation to any abstraction that exceeds a given value. This transfers the problem to the definition of this value. It can be defined hydrogeologically, economically, socially, by means of political pacts or dictated by decree. Physically, surpassing the limit is not necessarily overexploitation and remaining below it does not necessarily mean that all undesirable effects are avoided and that beneficial aspects are optimized.

Two separate problems have been identified. The first is that of the detrimental effects of groundwater development and of "non-sustainability" of the resource exploitation, in quantity and quality. This includes exploitation of the (fresh)water reserves without conscious intention. The second is that of choice of a strategy for groundwater mining or exploitation as a non-renewable resource, with a time frame. This applies to exploitation that is much greater than recharge. In both cases it is the responsibility of hydrogeologist to anticipate the situation and to advise water resource managers in their policy decisions [2].

The collection of reliable physical and quality data is an essential prerequisite for the assessment of groundwater exploitation. However, it is important to note that the observation of groundwater level and quality (normally salinity) changes are not enough to decide if an aquifer is overexploited. Also, a good quantitative assessment of the potential of an aquifer and of its behaviour, and also close monitoring over a substantial period of time is necessary prior to deciding whether it is overexploited [1].

Before declaring an aquifer overexploited, circumstances other than those stemming from the review of physical - mainly hydrogeologic and hydrologic - data should be considered, namely, the common interest, the economic situation, a realistic appraisal of the availability of both surface water and groundwater and an optimal solution for their development, the benefits, both economic and social, derived from groundwater exploitation, and the foreseeable evolution of the area, including changes in water demand due to technology, economy and social habits evolution.

II. DETRIMENTAL EFFECTS OF EXTENSIVE GROUNDWATER EXPLOITATION

A. General considerations

Most detrimental effects of what can be termed groundwater "overexploitation" coincide with those produced by aquifer exploitation. What happens is described differently if they are considered: 1) by the groundwater exploiter himself, for his concern is mainly on the water he is abstracting and the negative interference from others; 2) by the aquifer exploiters as a collective interested in getting and sustaining a given level of water production that respects a given set of quality restrictions; 3) by society, which implies considerations related with issues such as ecology, environment, equity for present and for future generations, improved economy, sustainability and welfare. There are impacts on the groundwater exploiter himself, other exploiters or third persons not involved directly or even indirectly in groundwater use [1, 2, 22].

Detrimental effects can be grouped into:

1. Hydrogeologic

Hydrogeologic effects related to groundwater level drawdown are the results of any groundwater exploitation, and do not necessarily reflect abstraction exceeding recharge. As formerly said, transient stages may last many years in large unconfined aquifers, and when permeability is low it may produce drawdowns of ten of metres and decline rates up to several metres per year over long periods of time. In thick formations containing aquitards with thin interlayered aquifers, the exploitation with deep wells may produce a fast and large piezometric decline that reflects only the inability to draw water from the aquitards. From the point of view of the groundwater user this decreases well yield and may require the deepening of wells or their replacement, or new pumping machinery; flowing wells decrease discharge or cease to yield water. Shallow, thin aquifers may become practically dry in some areas, especially if they are highly heterogeneous. The same is true for carbonate aquifers [3, 44], when permeability concentrates around thin layers close to the water table, a common situation. From the point of view of other water users this translates into a decrease or stoppage of springs and river base flow. The deeper the water table the more delayed is the recharge effect of rainfall; the change in the effective replenishment period also affects water-table behaviour. Fissured rock aquifers in many cases are especially sensitive to water-table drawdown and well yield may decrease sharply after some time.

2. Hydrologic

Hydrologic effects, in this context, refer to the reduction of other water resources, such as spring and river base flow. Total water resources are increased only when groundwater storage is used (limited in time), there is a reduction of evaporation, flood water that otherwise should be lost is recharged or the groundwater basin is enlarged (to the loss of some others). Overexploitation is thus related to total water resources.

3. Water quality

Groundwater quality is related to the displacement of saline, brackish or poor-quality water towards the wells or water galleries due to new water gradients being created by exploitation. Other factors may be dominant over recharge effects, such as well construction, geographical distribution and pumping schedule. The most common situation is sea-water intrusion in coastal aquifers, a complex situation in which only a fraction of recharge can be abstracted - depending or local conditions - if saline water penetration in the aquifers or salt-water upconing is to be limited. The closer to the coast and the deeper the well (under certain circunstances) the more serious and faster may be the negative impact on the well itself or on other wells in the aquifer system. Carbonate coastal aquifers, especially of karstic nature, are highly vulnerable [3]. Many developing coastal and island areas suffer severely from these problems, especially where wells are too close to the coast, where population and productive activities are often concentrated. But also the displacement of poor-quality groundwater and surface-water bodies is of concern, in coastal and in continental aquifers. Some authors ascribe overexploitation to the consequences of poor quality water penetration into the aquifers, or to wells being affected by polluted water, or to recharge leaching undesirable substances from the surface or from the formations due to groundwater head changes produced by the exploitation itself. This is probably an overextension of the overexploitation concept and shows how different are the attitudes towards the term. In this regard an aquifer may become overexploited when abstraction is only a small fraction of recharge.

4. Economic

Economic effects upon groundwater abstractors include, mainly, the increasing cost of water pumping, the new investments needed for well or water gallery deepening or substitution, and the cost of early replacement of pumping machinery and energy supply facilities (electrical or by means of petrol motors). This increased cost can lead to abandonment of unamortized investments and an increase in water prices for the community or of the products in which water cost is a significant item. This is not necessarily bad and can be compensated by productivity increase or a change in economic activity. Overexploitation can be seen, from this point of view, as a situation in which costs are unbearable for the abstractor, the groundwater user or the society receiving the benefits of groundwater.

5. Ecologic and environmental

Ecologic and environmental effects have been known for a long time but only recently is society paying attention to them, as aquifer exploitation is more intensive and extensive. Seldom is the groundwater abstractor concerned about possible environmental impact, since most of is beneficial to him, at least in the short-term, by increasing the availability of groundwater and reducing drawdown. For years wetland desiccation has been a wanted objective and intensive groundwater abstraction has been considered beneficial since the dewatering was accompanied by evapotranspiration reduction, thus saving water from being lost to the atmosphere. In many areas in densely populated industrialized countries, and also in developing countries, the situation is reversed not only owing to the scenic and touristic value of these areas - lake districts, swamps, riparian vegetation belts, gallery forests - but also for the preservation of living species and biologic diversity. Under this point of view any groundwater abstraction that significantly reduces flow to groundwater-dependent wetlands is considered overexploitation, even when abstraction is still a small fraction of recharge. This is a question of land use and water resources planning, rather than of overexploitation [6]. Because in industrialized countries ignorant destruction has progressed dangerously far, developing countries constitute a reserve for mankind to be preserved for the benefit of all as well as themselves in the long-term, at the same time industrialized countries are attempting to preserve what is left and to restore wherever possible.

6. Other environmental

Other environmental detrimental effects include geotechnical problems of land subsidence and collapse due to groundwater abstraction. Subsidence is the result of non-elastic or irreversible compaction of unconsolidated sediments - mainly aquitards - by reduction of pore-water pressure. Collapse is the more or less sudden sinking of land above karstic formations (carbonates and gypsum) by the collapse of cavern roofs as groundwater pressure decreases or fluctuates too much and too often. This is referred to also as the consequence of overexploitation, and has little relationship to replenishment. Differential subsidence occurs when a sudden change in sediment thickness exists, generally due to a deep buried fault. This can disrupt water and energy transport lines and sewers and create problems for roads and buildings. Conversely, when for some reason, extensive or intensive groundwater exploitation ceases - due to salinization, displacement of irrigated lands or industrial areas by urban settlements, or a new water supply - groundwater level recovery may create problems of a high water table. This may happen in building basements, buried structures, civil works, underground parking lots and transportation systems, constructed when the water table was low. These areas were formerly wetlands or shallow water table lands [1, 2]. This is sometimes called an after-effect of overexploitation.

7. Legal

Negative legal impacts are the consequence of complaints of groundwater abstractors against other abstractors or authorities; or of groundwater authorities, environmentalists and citizen associations against groundwater exploiters, generally related with some or a combination of the above-mentioned negative effects. Often they refer to the restoration of well or gallery flow, recognition of rights or economic compensation. This occurs in industrialized countries more often than in developing countries, but the frequency is increasing as freedom, culture, legal means and legislation improve. Perhaps a greater negative legal impact consists of inadequate, sectarian, poorly produced or non-applicable legislation, and the resulting excessive power in untrained, negligent, biased and sometimes corrupt administrators and authorities. The term overexploitation may promote such situations when its negative connotations are overstated. Sometimes they can be used as a political weapon to achieve goals unrelated to groundwater or as a means to justify other water projects, generally much more expensive, needing higher external financing, technology and expertise, that burdens unnecessarily the economy of developing countries, and that are more prone to bribes to local, national and foreign receivers.

Circumstances related to what can be termed overexploitation can be induced by other actions not directly related to aquifer exploitation. Most are related to such land-use changes as urbanization, changes in vegetation, river-channel and coastal erosion or excavation of inland harbours or navigation lines. Forests are effective in evaporating soil water, thus reducing aquifer recharge, other circumstances being the same. Forest destruction or burning (increased recharge) and reforestation of large areas (decreased recharge) may affect not only aquifer resources but also total water resources. The final effect is not easy to predict owing to many other complicating effects, sometimes dominant, such as increased runoff and erosion, which reduce recharge. Evaluation must consider also hydrologic, ecologic, scenic and economic issues. The increase in recharge by the cutting of forests cannot be naively taken as a positive effect, as shown by studies in the Murray basin (Australia), where slowly downward moving brackish water in the unsaturated zone (the result of low recharge) is now moving faster, thus polluting rivers and aquifers. The problem will last until the large store of brackish water is leached down from the unsaturated zone and discharged.

Side-effects of extensive exploitation can be temporary, and in many cases reversible, or long-term. Temporary effects include increase in pumping costs or reduction in yield of neighbouring wells, and reduction in springflow and other groundwater discharge to surface watercourses. Large drawdowns in unconfined aquifers in dry areas, however, produce effects that are almost irreversible. The long-term, and in many cases practically and economically irreversible, include sea-water intrusion, infiltration of poor-quality water, and land subsidence resulting in problems with building stability, land drainage and sewer flows. The reversibility is more difficult the longer the time for the undesirable effects to appear. Some generally long-term effects are reversible only painfully. These include inadequate legislation with poor licensing or permit procedures for groundwater abstraction, the construction of unsuitable groundwater abstraction works, the impairment or destruction of agricultural land by degradation of applied poor quality groundwater, and the destruction of valuable ecosystems by overpumping.

The drying up of pre-existing shallow wells and water galleries by deep wells is sometimes presented as another case of overexploitation. This is a controversial situation because shallow wells limit the rational use of aquifer storage reserves for groundwater production regulation. In many cases this has nothing to do with overexploitation, but can be rectified with suitable management and with compensation of water rights and for excess water elevation costs, if appropriate. The same is true for flowing wells that cease to flow due to aquifer exploitation. An example is the Cochabamba aquifer in Bolivia [23].

B. Examples of temporary effects

Most cases of excessive exploitation of groundwater are related either to irrigation schemes, in relatively arid regions or to large urban water demand centres. They refer to excess relative to safe yield or to detrimental effects, or to both of them. This excessive exploitation - overexploitation for some - is not necessarily bad and in some cases its disadvantages are less than that of other supply alternatives, and surely is better than to leave people without water or with decreasing economical production. This is to be kept in mind when considering detrimental effects. Undesirable and harmful effects are mentioned in absolute terms, but they may be only a minor evil, necessary and correctable, if there is the willingness to do it. (The location of most examples cited in this section can be seen in figures 2-5.)

An important part of the water supply of the city of Lima, Peru [23], in an extremely arid climate, is secured by 320 tubewells which produce 650,000 m^3 per day (figure 4). The aquifer is also tapped by other users. As a result of the low recharge, mainly the deteriorating river channel infiltration, water levels have been dropping at a rate of 2 to 5 m per year. Well yields have diminished, and production costs have increased.

In the Punjab, in the north-western part of the vast alluvial Indo-Gangetic plain (India) [15], extensive groundwater development to irrigate needed crops, has resulted in a significant lowering (4 to 9 m) of groundwater levels in the last 10 years (figure 2). As a result, a number of boreholes dried-up or reduced yield, or groundwater quality deteriorated. This development may cause serious harm in the long term. Groundwater is exploited without legal restriction.

C. Examples of long-lasting effects

During the civil war in Lebanon, thousands of wells were drilled indiscriminately in the coastal areas [7] for the purpose of securing emergency supplies, in response to the destruction of water-supply systems (figure 3). In some wells near Beirut, water salinity increased from fresh in 1970 to sea water in 1985 as a result of overpumping, which was aggravated by a series of dry years (1983-1985).

In the intramontane Valencia Lake basin of Venezuela [24] groundwater abstraction reached 14 m^3/s, or 2 to 10 times the recharge rate, depending on the year (figure 4). Water levels fell by at least 10 m, and as much as 25 m below the level of the lake in some locations, thus creating up-coning of saline water from depths and a flow of contaminated water from the lake into the aquifer.

In the arid Hermosillo Coast of (Mexico) [17, 23] highly profitable irrigation of cereals has been developed since the 1960s (figure 5). Groundwater abstraction from 500 boreholes, yielding an average of 85 l/s each, has depleted the alluvial aquifer and generated sea-water intrusion that can be noticed 25 km inland from the coast - with related loss of wells and soils to salinization. However, some hydrogeologic facts are unclear and saline return irrigation flows has to be considered a source of salinization beside sea water. But irrigation is still an important source of income and new practices are helping to solve the problem. Forecasts for imminent social disasters, forecase for the last 15 years as imminent, have not occurred. In Guaymas, south of Hermosillo, sea-water intrusion has necessitated abandoning about three wells and about a square kilometre of arable land per year [50], displacing activities towards the north. Drawdowns of more than 90 m have required relocating shallow wells. But the area is changing to high technology irrigated crops, and aquaculture with brackish groundwater being introduced. In Chihuahua [23] overexploitation of the aquifer underlying this important Mexican town has resulted in deep infiltration of urban effluents directly and wastewater from the river and irrigation areas downstream.

Landslides and subsidence have been observed in Nigeria [13] as a result of groundwater withdrawal (figure 3). In the middle zone aquifer of the Chad Region, Bornou State, groundwater levels have been lowered 8.5 m in the past 10 years. Consequently, well yields have reduced and many wells have run dry. Drilled wells last less than 15-20 years, and many less than 5 years. Land settlement has occurred in the Niger delta area, as well as erosion and landslides, causing loss in towns, villages, and parts of mangrove forests. Oil and groundwater extraction are held jointly responsible for the situation.

The city of Mar del Plata, Argentina [28], has a permanent population of 500,000 and a tourist population of 2 million in January-February. Its water supply was obtained by tubewells tapping a Quaternary semi-confined aquifer 70 m thick. Sea-water intrusion has been observed in the town since 1943. The main impacts have been increased pumping costs, sea-water intrusion up to 5 km inland, subsidence, and also flooding as a result of water-table recovery, which affected such structures as basement parking lots which were constructed under maximum drawdown conditions. This is due in part to overconcentration of wells in a poorly protected area, and to poor management. A new well field was developed north of the town under better conditions and management.

Sudden formation of sinkholes and "catastrophic subsidence" has occurred in the karstic terranes of the south-eastern United States, mainly Alabama and Florida [5]. Several thousands of cases have occurred since 1950. Subsidence is caused or accelerated by various processes following a decline of the water table. Induced sinkholes can be expected in areas affected by activities, such as dewatering, which lower the groundwater head and bring it down from the unconsolidated overburden deposits into the rock mass.

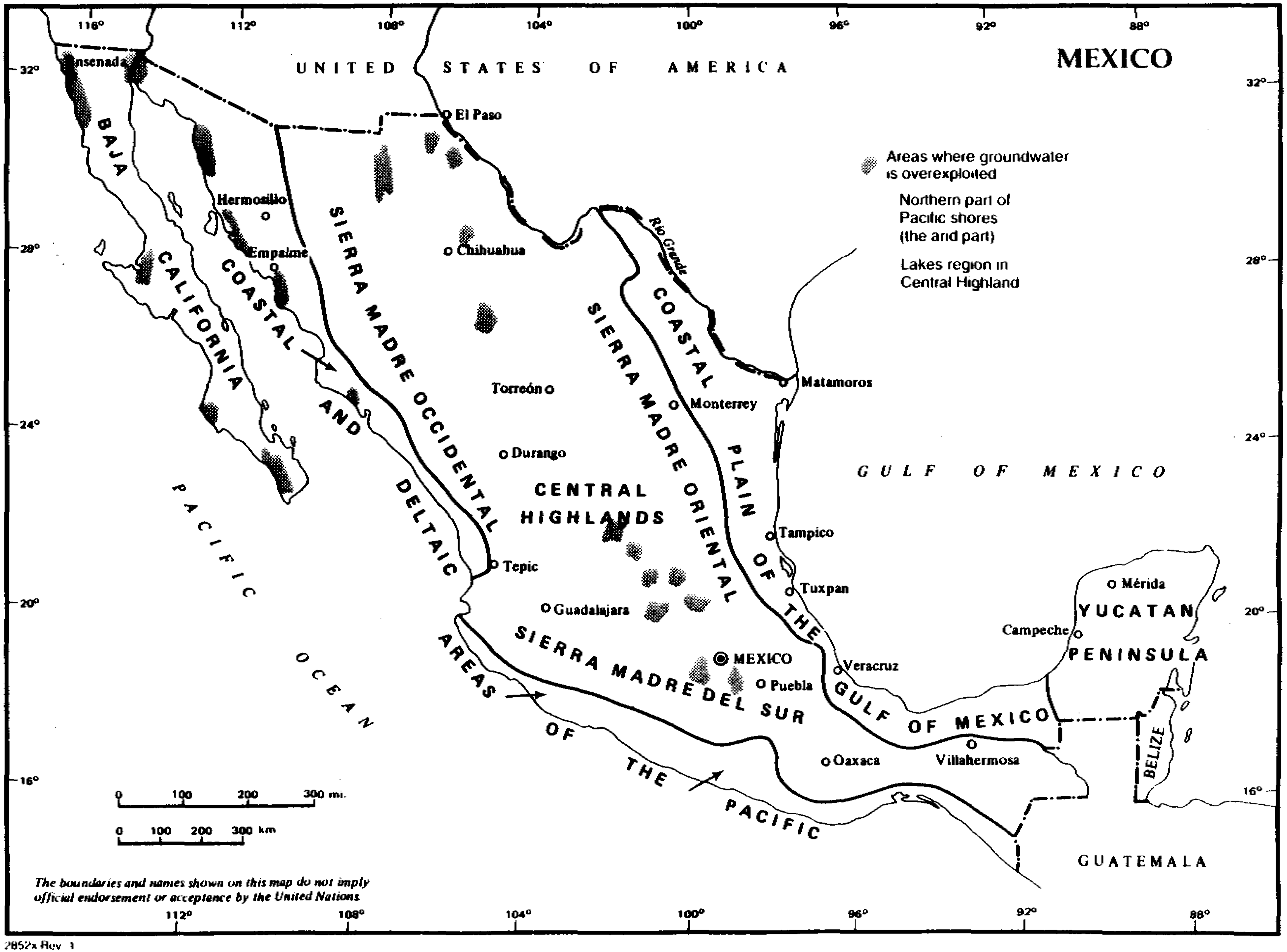

Figure 5. Groundwater overexploitation in Mexico

A study by UNESCO quoted in [2] shows that of a total of the 42 cases of land subsidence considered, only 7 refer to developing countries, but this is due more to differences in availability of documented studies than actual circumstances. During the Congress and Workshop numerous cases were mentioned jointly to well known cases in industrialized countries. These include Berlin, Milan, Venice, London, Denver, Houston, Las Vegas, San Joaquin Valley, San Francisco, surroundings of Tucson and Tokyo; other well-known cases occur in developing countries, such as Mexico City, Bangkok and Jakarta [23].

In Celaya, Mexico [10] a differential subsidence of 150 mm per year is observed with a total vertical displacement of 1.5 m in 5 km as a consequence of groundwater table drawdowns of as much as 70 m.

Collapses are less frequently reported but well known cases exist in Alabama and Florida in the south-eastern United States [5], and in northern Catalonia and near Zaragoza in Spain.

The subsidence situation affecting important parts of Bangkok, Thailand, is probably one of the most serious in the world owing to its being at about sea level (figure 2). The effects of heavy rains and high sea tides are augmented, thus producing increasing concern. The situation is similar to that in Venice and some areas of Japan. Subsidence in Mexico City (figure 5) is still greater but problems are different owing to its high elevation; subsidence is the combined effect of load compaction of recent, unconsolidated sediments, and extensive groundwater abstraction.

On the western border of the Senegalese sedimentary basin, southeast of Dakar, Senegal [9], a Paleocene aquifer, slightly karstified and in part confined under Miocene formations, is affected by high fluoride concentrations, up to 13 mg/l (figure 3). Fluoride is taken by water percolation from the upper-level aquifer, through the phosphatic roof zone. In this context, extensive exploitation by rural boreholes from well fields supplying the Dakar metropolitan area could easily aggravate the fluoride contamination. There is an increase in fluoride concentration in waters previously free of it.

In the London Basin, United Kingdom [43] a large area has been dewatered by intensive pumping. As a consequence, air has penetrated what was formerly saturated ground under non-oxidizing conditions. This allows pyrite in the sediments being oxidized and dissolved by atmospheric oxygen, mainly in the more diffusive sand formations. Thus pore water becomes acidic with a very high sulphate content. The salts are incorporated into groundwater when saturation levels recover.

The exploitable groundwater resources in the North China Plains [35] are estimated to be 3×10^{11} m^3 per year (figure 2). Owing to extensive exploitation, adverse effects in addition to groundwater table decline have been observed.

Through attenuation and drying-up of springs the yield of a large karst spring near Taiyuan city has decreased from 2,000 l/s in 1950 to about 300 l/s in 1989. Stream flow has decreased by about half in the last 30 years in the Shiyang River. In Shanxi province, springs flow at but a sixth of their former rate. There has been widespread sea-water intrusion in Liadong and Shandong peninsulas as a result of pumping in karst aquifers. Ecologic conditions have changed in the Shiyang River due to flow reduction by half in 30 years; water shortage and saline irrigation water has caused farmland to be abandoned, trees have died as a result of the lowering of the water-table and desert encroached. In Tianjan land has subsided 2.6 metres since 1959, 100 mm in 1986 alone. In karst areas 143 occurrences of collapse were observed between 1970 and 1985, ranging 0.5 to 6 m in depth, occupying 12 km^2 in central and southern Shandong peninsula.

In low-lying coastal areas of the Gulf of Mexico (United States) [8], extensive pumping of il and groundwater have accelerated the rate of natural consolidation in Cenozoic clastic units (figure 5). Coastal flooding and erosion in response to subsidence is now particularly acute during major storms. Groundwater pumping has activated faults and caused differential subsidence with ensuing engineering problems. The subsidence rate is not well correlated with withdrawal rate and oil exploitation, owing to other complicating factors. Salt-water intrusion created by aquifer exploitation is a major problem on the Gulf of Mexico barrier islands and along the coasts of the Florida and Yucatan peninsulas, which possess extremely permeable carbonate aquifer systems and where surface water-supplies are non-existent.

In the Po Basin Plain of northern Italy [45] the mean rate of subsidence in Milan and Modena between 1950 and the 1970s was 10 and 28 mm per year respectively, but a decrease in groundwater abstraction has reduced these figures to 4 and 3 mm per year in the 1980s. Generalized drawdown has allowed for the penetration of about 51 t/km^2 of chlorinated organic solvents in Milan and about 11 t/km^2 in its surroundings.

D. Impact on wetlands

In Spain, two cases of wetlands in national parks, affected differently by groundwater development, have been studied in detail. They are of special relevance for Europe because Spain is a bridge between Africa and Western Continental Europe for migratory birds. Owing to political and administrative constraints, social and economic development were slowed in some regions for almost two centuries. They played a protective role in the conservation of some wetlands until recent times.

The Doñana National Park (Huelva and Sevilla) [6] includes three ecosystems: marshlands, stable eolian sands (cotos) and moving sand dunes. In the 1970s an ambitious groundwater irrigation project, jointly sponsored by development-oriented Spanish Government Institutions and FAO, was designed for the Almonte-Marismas plain. About

25,000 hectares are to be irrigated by 150 hm^3 per year of groundwater. Unofficial estimates show that in 1991 up to 10,000 hectares were potentially under irrigation - receiving up to 50 to 70 hm^3 per year. The publicly founded project does not seem to have generated the expected economic returns and in some cases have operated at a loss, in contrast with other privately promoted development schemes in the region. Since 1984, scientists have warned of ecologic deterioration, but have not been taken seriously. Recent studies confirm earlier predictions of dessication of a main groundwater discharge zone that supports vegetation needed for food and nesting, reduction of the fresh water supply to the swamps and contamination of groundwater, among other serious land management problems. But the situation is complicated by the planting in the 1950s of 20,000 ha of eucalyptus-trees for paper pulp, that also draw enormous quantities of groundwater and would-be recharge. This extension is now shrinking, but irrigation has notably expanded. They do not compensate since water is drawn from different places. The case is receiving considerable attention from the international press, UNESCO and the European Community. The size of the irrigation project has been reduced to 10,000 ha (that is, 40 per cent of the initial objective) and it may be reduced further. An ad hoc Commission is considering regional development alternatives that would preserve the obvious values of the National Park and also the surrounding natural park lands.

Damiel National Park [6, 42] is in La Mancha region, in south-western Spain at the confluence of the Guadiana and Cigüela rivers. The Tablas (marshes) were formerly covered by a metre of water most of the year, constituting the discharge area of a vast limestone aquifer. The recharge is estimated at 200 to 300 hm^3 per year. The Tablas are also fed by the two rivers. The limestone aquifer has been extensively developed for irrigation purposes from 180 hm^3 per year in 1974 to irrigate 31,000 ha, to 600 hm^3 per year in 1990 to irrigate 135,000 ha [58]. Renewable resources are estimated to be about 300 hm^3/year. Water levels in some wells fell 20 to 30 m after more than 2,000 hm^3 of groundwater had been taken from storage. The Tablas disappeared in 1983 and became a recharge area for Cigüela River water. During the dry years from 1981 to 1983 the Tablas were without water. In summer, peat layers burn spontaneously, a rare phenomenon before. Measures had been taken to make water resources available. Emergency wells were drilled in the Park and a dam is planned on a tributary of the Guadiana River to bring water to the Tablas, both for environmental preservation and artificial recharge. But timing and quality of water is not the same and consequently vegetation and animal diversity has not been fully restored. Thus some environmentalists call the restoration measures an ecologic make-up. Also, some irrigation groundwater is now substituted provisionally with imported water from the Tajo River basin. There are plans to reduce irrigated land to 60,000 ha, but this is still insufficient to restore the aquifer owing to the large volume of reserves already abstracted. Groundwater levels will need many decades or even centuries to recover, depending on the management scheme applied. In 1987, the Mancha aquifer was officially declared "provisionally overexploited" according to the Spanish Water Act, which requires that a groundwater management plan be drafted and user communities to be created in each of the

30 municipalities of the area. The exploitation led to the disappearance of the Guadiana River in the central part of its basin and to serious, and in some aspects, irreversible ecological deterioration of the National Park. But it effectively led to developing one of the poorest areas in Spain. This is a classic conflict that needs careful evaluation and land use planning, which involves international issues, since Spain has signed transnational wetland conservation agreements.

E. Conclusions

The possible negative consequences of groundwater extensive exploitation can be listed as follows:

1. Diminution or exhaustion of aquifer reserves accompanied by lowering of water levels and a rise in pumping costs

2. Degradation of water quality, including salinization of coastal aquifers
3. Interference with other water users due to diminution of spring and stream flows
4. Negative impact on the environment, including destruction of valuable wetlands
5. Land subsidence or collapse

This is sometimes called excessive exploitation, or overexploitation. But excessive must be interpreted in the right context, since there are situations with adverse effects to a collective or individual but still beneficial to the area, region or country. Among these consequences, one should include those experienced by the groundwater developers themselves, such as excessive costs; operational problems; degradation of water quality; and those experienced by other parties in terms of direct degradation. It is also important to identify both short- and long-term detrimental effects. The balance between the benefits of intensive exploitation and its disadvantages can change over time. Predictions may then prove incorrect [2].

Finally, consequences for the environment should receive full attention. The need to protect certain ecosystems may offset any considerations related to economic development in the areas based on groundwater development.

III. BENEFITS OF EXTENSIVE GROUNDWATER EXPLOITATION

A. General

The advantages of groundwater exploitation are qualitatively the same as for an aquifer being normally exploited, or conducive to situations that may be termed as overexploitation, with the detrimental effects discussed in section II. Some of the advantages, mainly from the economic point view, follow [21].

Development is in simple stages, with new wells drilled only as the need for additional water arises. This is especially advantageous for developing countries, allowing for better fit between demand and supply, progressive rather than costly intensive financing and the payment of works from revenues of the part of the project already finished. This advantage partly disappears when large groundwater projects, mainly internationally sponsored, are executed without adapting water production to progressively expanding water needs, and when future water demand has been forecast with poor data or under changing conditions.

Little surface area is needed for wells and related water-obtaining facilities, new surface area is more easily acquired, there is no displacement of towns, agricultural lands or transportation ways, and rivers are much less affected. Construction by locals is possible; maintenance costs are low and can be solved locally if actual circumstances are taken into account in the project. In remote rural areas, pump maintenance and energy supply may be a major problem; this shifts preference to gravity-fed water of a surface water scheme. But when considering investment costs and risks of failure in a wide framework, wells - or water galleries - are most suited if the savings and benefits are used to create maintenance and energy services. They contribute to development of the area.

Water resources are increased by evaporation reduction. Some surface-water reservoirs lose so much water to the atmosphere as to leave a brackish residuum. Besides, the lowering water table allows for valuable use of shallow groundwater which, under natural conditions, would be lost through evaporation. In arid areas most water occurring at a depth of less than 3 or 4 meters below the surface directly evaporates to the atmosphere. Also in arid lands, pumping in an alluvial aquifer creates a storage capacity for flood water to infiltrate. If the alluvium reservoir is of significant dimensions, especially its thickness, it may have the capacity to absorb and regulate vast amounts of water associated with rare and violent flashflooding which in many cases is the only significant source of recharge. These may recur for periods of 3 to 5 years, in some cases 7 to 10 years. The infiltration rate may be increased if the velocity of surface-water flow is decreased by small dams, dikes and other works. Groundwater, in most instances, is suitable and safe for human consumption with no, or only simple, treatment, if wells are properly contructed and maintained. Wells may produce water close to where it is needed, thus obviating the need for water lines that are costly to install and to maintain. The aquifer plays this role, at least to some extent. Groundwater is generally more efficiently used in the rural world since it is close to the user. And finally, complex and sometimes unfair subsidizing can be avoided or reduced and administration made easier.

These advantages are not absolute and must be weighed against other factors, case by case, taking into account physical, human, economic, legal and local circumstances. They are, in many aspects, common to developing and industrialized countries, but some are more significant for developing countries, even if they lead to overexploitation. What is needed is to be aware of the consequences and extract a part of the benefits - or of the subsidies that would come - to compensate for them, now or in the future, when investments produce the expected economic return.

In most instances, groundwater allows the temporary solution of acute problems of urban population explosion or of abandonment of rural areas. It is beneficial to allocate some water to the suburbs - as the pueblos jóvenes (young towns) around rapidly expanding Lima, Peru, or to start irrigation or animal raising activities in rural areas. The alternative is to leave them to starve or to be deserted, awaiting difficult, slow, expensive and uncertain schemes based on often overstated assumed overexploitation problems. This does not mean a simple laissez faire attitude since the aquifers have to be studied and monitored, with undesirable effects corrected to the maximum, and provisions made to cope with water reserve depletion and serious ecologic impact.

The possibility of avoiding megaprojects for water supply that cripple the economy of developing countries by unnecessarily increasing external debt - generally because they need financing from other countries or international institutions - that have an uncertain output, with frequent failures, and requiring years, even decades to be completed, is something of utmost importance. The negative consequences are more easily, clearly and readily corrected when groundwater is used, if there is the will to do it. Around megaprojects in some cases there are selfish interests from other countries, local megalomania, ill conceived schemes of large works, concrete, and corruption politics. The evils of aquifer overexploitation are frequently less.

B. Groundwater mining

Sound groundwater management may involve a decision to abstract significantly more water than the annual recharge of the aquifer. This is the situation by which groundwater in storage is developed as a one-time, little or non-renewable resource, like oil or minerals. Such a mining operation should normally be planned in some detail considering, among others, the duration of the operation in years, the amounts of water to be abstracted each year, and changes anticipated in the groundwater heads.

For such situations the term overexploitation does not really apply, although from the hydrologic point of view, abstraction exceeds replenishment and some undesirable effects are the same. It should apply only if development does not proceed according to plan, as for example excessive drawdown rates or water quality deteriorating faster than expected.

Such intensive exploitation should only be the result of a deliberately planned groundwater development with full awareness of long-term consequences. To make sure that such a policy is not against the general interest, an economic study must be carried out to evaluate several aspects. The interest rate during the period should suffice to amortize the capital investment. There must be clear local benefits and the general interests satisfied by the proposed development. The consequences deriving from progressive reduction in the availability of water, including ecologic impact, and the needs of future generations should be anticipated. The preservation of existing installations (wells and pumps) may prove to defend general interests, but the Administration may decide to exploit the aquifer above levels of private interests, for the common good [36].

A frequent decision is to overpump coastal aquifers until sea-water encroaches. This is a reasonable kind of groundwater mining if carefully planned. Near large urban areas, however, aquifers play an important back-up role in the event of failure or major contamination of other water-supply sources. This strategic value of an aquifer must be considered and evaluated before deciding to mine it. Conservation may be a wiser alternative.

C. Examples of benefits through extensive exploitation

The main aquifer in Wadi Hadramaut, Yemen [29], of 500 m thickness, is composed of interbedded Cretaceous sandstone, claystone and limestone (figure 3). It is overlain by Neogene and Quaternary, mostly unconsolidated, alluvial and eolian deposits. Rainfall does not exceed 60 mm per year. Traditionally, groundwater was exploited by the nomads from shallow (2 to 6 m) wells in the alluvial deposits. The development of irrigated agriculture since the 1970s through intensive groundwater abstraction, at a rate of 140 hm^3 per year, caused water levels to fall 10-40 metres. They should not, however, fall more than 10 metres in the next 20 years at current pumping rates. The occurrence of floods in Wadi Hadramaut provides good recharge to the aquifer. Extensive groundwater development has dramatically increased water-table fluctuations. Significant drawdowns are observed during the irrigation season (March-June), and allow for an increase in infiltration potential and a decrease of evaporation. It has been determined that 3.5 to 4 m is the optimum depth for the water table. Exploitation mainly affects deep artesian aquifers which supply urban communities, especially in coastal areas.

The city of San Luis de Potosí, Mexico [34] gets 90 per cent of its water supply from a valley aquifer, 300 m thick, made of sand and gravel interbedded with clay (figure 5). Natural groundwater discharge was mainly by evaporation but owing to lowering of water levels at a rate of about a metre per year, evaporation losses have been reduced, and the groundwater basin has enlarged. Currently 27 per cent of recharge is by unintentional recharge of waste water and leakage from piping.

Four urban centres in north-west Buenos Aires Province, Argentina [32], obtain their water supply from shallow sandy-silt deposits at the rate of 30,000 m^3 per day (figure 4). In the course of the last 20 years, water levels fell about 7 metres. As a result, well efficiency decreased, but as the unsaturated zone became thicker, it also allowed for increased storage capacity during wet periods, thereby eliminating local flooding caused by rejected recharge in past years. But some water quality problems related to increase in fluorides, nitrates and arsenic are appearing.

In the North China Plains [35], particularly in the Huang Huai Hai Plain, groundwater is intensively developed for irrigation by means of hundreds of thousands of wells (figure 2), a development that has dramatically increased water-table fluctuations. Significant drawdowns are observed during the irrigation season (March-June). This allows for an increase of infiltration potential and a decrease of evaporation. It has been determined that 3.5-4 m represents an optimum water-table depth.

D. Examples of aquifer mining

Aquifer mining was not dealt with comprehensively in the Congress, and many of the main world examples were not cited. The following, however, were discussed.

The major aquifer in northeast Africa (Egypt and the Libyan Arab Jamahiriya), Mesozoic in age and known in Egypt as the Nubian Sandstone, constitutes a huge reserve of fresh groundwater (figure 3). Geometrical calculations give exploitable reserves of 60×10^{10} m^3 with a total drawdown of 100 m, or 3×10^9 m^3 per year (95 m^3/s) during 200 years in the hypothetical and probably infeasible assumption of uniform exploitation over the area [51]. The aquifer has been tapped in Egypt for about 25 years by means of several hundred artesian tubewells in southern oases of the Western Desert. Over the years, the artesian head has fallen locally and shallow aquifers and oases have suffered from the effects of the deep wells [11]. But the enormous potential of the aquifer remains virtually intact in Egypt. In the Libyan Arab Jamahiriya, the desert aquifers are intensively developed by means of large well fields located in the south-east part of the country. Water is conveyed to the Mediterranean shores by means of large-diameter pipelines which constitute what has been called "the great man-made river". Discharge was in the range of 720 hm^3 per year in the first phase, started in 1991. The Government believes that the project is economically acceptable and sustainable for some decades. The only, and much more costly, alternative to supply the coastal areas would be desalination of sea water. Libyan circumstances are quite different from those in Egypt which benefits from the Nile waters, but which has a much smaller per capita income.

Calculations considering technical and economic feasibility in time-limited scenarios give groundwater reserves between 15 and 23 billion (10^9) m^3 usable for 30 years in the northern Sahara (Algeria and Tunisia), in what are called Intercalar Continental and Terminal complex aquifers [51].

In the Souss Valley, Morocco, extensive development of modern irrigated agriculture, mostly for exported cash crops, has consumed large quantities of groundwater in excess of recharge in that area. In 1990, 425 hm^3 of groundwater were abstracted; the depletion of groundwater reserves was about 250 hm^3 per year in 1985-1986 (i.e., four times that in 1971). The construction of works to slow flood waters should increase recharge in the upper and middle sections of the valley. A water management plan has been prepared to optimize the availability and use of water. It is expected that by the year 2020 or 2030 groundwater resources will have been depleted beyond the depth of economic exploitation, unless present technological and economic conditions, including energy costs, change dramatically. The profits generated in the interim by the exploitation of those groundwater reserves will, none the less, be considerable. The period of exploitation may be extended somewhat by conservation measures, but probably not beyond the middle of the twenty-first century.

E. Conclusions

The exploitation of groundwater resources in excess of recharge potential or producing effects that can be called the result of overexploitation, can be a source of benefits, in several ways, at least to start development. Benefits can be improved if carried out within the carefully designed framework of a realistic water resources management plan. Groundwater management must confront problems of political justification and hydrogeological uncertainty.

Evaluation of aquifers that have been overexploited around the world indicates, with few exceptions, the causes to have been less the lack of available water or excessive demand than the lack of adequate knowledge, evaluation and planning to balance availability with need.

An adequate groundwater development policy normally aims at a compromise between the competing goals to be met, of which the major ones are:

1. Economic efficiency, that is, getting the maximum long-term output from a minimum of resources,
2. Equity among water users: water availability should not be a privilege,
3. Preservation of individual rights, as long as they do not interfere with the rights of others,
4. Intergenerational equity, and
5. Respect for the environment.

Secondary criteria include local control, popular participation, and ease of monitoring and enforcement.

It appears justified to distinguish two separate problems:

1. That of detrimental effects of groundwater development, of which the most serious is the threat to long-term resource availability. Stated simply, this case represents overexploitation without understanding or conscious intention.
2. That of the choice of a strategy directed at deliberate exploitation of the non-renewable reserves or groundwater mining.

In both cases, it is the duty, competence and responsibility of hydrogeologists to anticipate potential problems and to advise water-resources managers in their policy decisions.

IV. ECONOMIC, SOCIAL AND LEGAL ASPECTS OF OVEREXPLOITATION

A. General

The hydrologic aspects of so-called overexploitation are easily seen - although not necessarily correctly interpreted - but water is more than a fluid; it is an economic good with the special characteristic for which there is no substitute. Furthermore groundwater flows so that actions in one place may affect other places, owned or administrated by others, even at the level of municipalities, regions or countries.

Access to potable water is essential for all human beings and should be a social and polical priority. When it becomes, apparently or really, scarce or needy of expensive treatments to correct the quality, it becomes goods subject to market forces. But its social value must be preserved to some extent by means of rules that guarantee the access to water, with the adequate quantity and quality, to all citizens. Thus, laws are needed; they are especially needed under conditions that could be called overexploitation, although there are legal excesses as bad as they are inadequate.

B. Economic and social considerations

Because water is an economic good that produces benefits or gives satisfaction, besides sustaining life, and because in some areas it may become scarce or polluted, thus requiring concurrence for getting it, control is to a large extent by economic forces, whether free market, centrally planned, or some kind of mix. Regulations, habits or religious feelings tend to guarantee free or cheap access to vital water to those who lack resources to buy it. Also, it is necessary to maintain flows for landscape, wildlife or ecological conservation.

Legally, groundwater can be termed a "common-property" resource which may generate economic benefit to the individual user and to society, but it also is subject to external factors notoriously difficult to control. Unrestricted groundwater development can lead to serious problems of social inequity if scarce resources are diverted by some at the expense of others [23]. In such cases the exploiters receive all the benefits but pay only a part of the costs.

Because the resource is open to all and owned by none (even if it is declared a public - "domanial" - property), no user will have the incentive to conserve it simply because refraining by one individual enhances the neighbour's opportunities. Then, when available resources become scarce, and regulations are lacking, some aquifers would be subjected to excessive depletion from society's point of view [40]. Who sets these regulations and how they are enforced is an open question, and in the real world there are many different systems, adapted to local, regional or national circumstances. Regulations are enacted and modified by some kind of public authority or governmental institution, and the same or other institution controls the application. A common sense rule indicates that development institutions should be separated from control- and law-implementation institutions.

The problem of exploitation exceeding recharge is essentially economic. In the long run, a balance is somehow reached, or the exploitation is finally abandoned (a rare situation), but meanwhile a major investment in money, effort and hope is lost [23].

Pure economic treatment of aquifer exploitation is not easy and entails consideration of not only the quantity of water being abstracted but also the groundwater level and quality when it is variable or may change in response to exploitation intensity and duration. To the physico-chemical parameters must be added an economic one represented by the discount rate. Its value may greatly influence the results. The discount rate to be used does not necessarily coincide with the rate being applied to other economic goods, since the social value of water must be taken into account. Assigning a value is not only an economic issue but a political one, and may change a frugal policy into a spending one.

The lower the discount rate, the higher is the initial allowable groundwater reserve use [40]. The same effect results from a higher storage coefficient or a smaller recharge rate. This leads to the conclusion that under high discount rates, the best exploitation policy for an unconfined, poorly recharged aquifer, under the economic point of view, is to promote heavy pumping during the initial stages of development and then progressively reduce it. Economic theory does not consider social problems when water supply diminishes, and this has to be solved by politically-oriented decisions. But reality is often different because as aquifer development progresses, other water sources can be found or imported, water savings can be introduced or economic activities changed to new ones that need less water or that produce goods in which water is but a small fraction of total cost. These considerations imply that oversimplified economic analyses of aquifer exploitation may be too naive and the results may be wrong.

As far as the deliberate abstraction of reserves is concerned, the preferred policy would be to specify the rate of pumping - by geographic area, if appropriate - which maximizes the net present economic value of the groundwater asset, subject to avoidance of damage to third parties. The optimum economic rate of abstraction, in most cases, can exceed the rate of recharge. The optimum can be expressed by a decision rule, which specifies the desired pumping rate. Within this framework, aquifer overexploitation is defined as extraction in excess of that specified by the decision rule, not simply as pumping in excess of recharge [16].

Economic analysis points to a workable region with an upper limit [40]. If a combination of mean water depth and installed pumping capacity yield points above the upper limit of the workable region, there is aquifer overexploitation from an economic point of view; then the suggested policy is to discard some groundwater exploitation even when the values are not fully amortized, and this may happen where the total rate of abstraction is less than recharge. Conversely, when points plot below the limit, the aquifer is economically underexploited and the recommended policy is to increase the pumping rate, even in cases when it already exceeds natural replenishment, that is to say, introducing a certain degree of groundwater mining. It is important, however, not to pump beyond the "irreversibility margin" with related deterioration of groundwater. But an optimal development scheme which would combine maximum production of water through a minimum number of wells with lowest level of recurrent costs - taking all factors into account - is utopian and unachievable [23].

A given economic analysis, however, is not permanent since parameters may change in time, thus modifying the conclusions. Owing to the social value of water, some conservative policies seem logical, such as those favoring policies for aquifer storage rehabilitation, if feasible. For irrigation-based economies it must be realized that there are public and private investments not directly linked to water production and that labour cannot be easily and quickly transferred to other productive sectors or other areas. This a complicating factor that favors the tilting of political decisions toward aquifer rehabilitation.

Some policies also include the tendency to provide only for the interests of future generations (there would be no future generations if the present ones lack water) or to block imaginative developments that afterwards might produce dramatic social improvements. Care, therefore, must be taken to avoid the excesses of "big brother" policies or to adopt catastrophistic or Malthusian views of the future, which might create more problems than they solve, and unduly scar the present generation.

Aside from local situations, there is no known instance of an important aquifer in a more or less developed country whose overexploitation has given rise to economic or social catastrophe [6]. Instead the opposite seems to have happened: some kind of groundwater overexploitation has been the drive behind agricultural development in many regions, in both industrialized and developing countries.

C. Groundwater management and legal aspects

Groundwater management includes two main aspects [16]: First, the management of water should include decisions on appropiate annual rate of pumping, its geographic distribution, whether to increase water supply or whether to introduce such management techniques as conjunctive use of surface and groundwater or artificial recharge, provided they are feasible. Second, the management of people, should include definition of the institutions and policies that divide the extraction rate among potential individual users and user classes, the monitoring and enforcing of rules for limiting pumping, the nature of education and research programmes and the conflict resolution mechanisms.

There are many possible management policies. Choosing one involves a selection among complex strategies so as to balance achievement of competing goals [16], including economic efficiency, equity and the respect of individual liberty. Generally an optimum is sought. It should be expressed as a rule that specifies a variable such as flow according to existing water reserves, anticipated pumping costs, interest (discount) rate, expected economic benefit and a sound evaluation of external costs, such as the ecologic ones. The rules may include a slowdown of groundwater abstraction as aquifer reserves are depleted or restrictions on abstraction as greater external costs are anticipated. Reductions can be levied on all wells or some, depending on location, use and other factors. As stated before, an abstraction rate higher than the rule is overexploitation, whether it be more or less than replenishment.

In a perfectly planned economy, from the economic and administrative point of view there is no aquifer overexploitation since abstraction conforms to rules. But this is unaattainable as practice has clearly shown. Moreover, from the hydrologic point of view, detrimental effects are not necessarily avoided. In a pure market economy decisions are taken by individuals according to their best interests, e.g., to maximize immediate benefits. In that case, to redress negative effects, besides institutional mechanisms some economic intervention can be introduced in the form of incentives or taxes, or better a mix of them, to change individual or corporative behaviour in order to get better agreement with wider interests. But there is no guarantee that conflicts between individual and social interests in the aquifer exploitation would not appear, and then fiscal mechanisms (taxes) would be needed as well [46]. A logical approach is to submit all groundwater development to a compensation criterion. One possibility is that development would be permitted only if those who would benefit can afford to compensate those they damage, and still be better off. In practice, however, the evaluations of appropriate compensation is problematical and thus the criterion cannot be widely adopted [23].

Neither utopian government control nor a perfect groundwater market is likely ever to be found in practice [23]. Governments often prefer some kind of subsidy on public water supply and especially on irrigation water, even if efficiency is proven low. Besides, there is often a lack of political will or power to enforce controls upon economically and politically powerful lobbies.

Even under the most free-market-oriented policy, legislation is needed to set basic lines of behavior. But too detailed, inflexible rules or excess of regulation and intervention is as bad as no legislation. When legislation is missing, regional or local (municipal) decrees can be a temporary substitute, but favoritism should be carefully avoided. Being public or private groundwater makes no difference with respect to overexploitation situations and problems. The important issue is public acceptance of the law, efficacity in the application, democracy in the writing, and the will and controlled power to enforce it.

The lack of control may ruin efforts to manage an unsustainable situation. For example, if the public sector tries to reduce abstraction to redress an undesirable situation, but other sectors are beyond control and continue to drill wells, the effort is lost and the situation unsolved. Such are the cases in Bangkok, Manila, and many other large urban areas.

Also, whether or not groundwater is considered public domain or private seems irrelevant for good management if there is good law and the common interest is protected and balanced with reasonable private ownership. In the Ogallala aquifer example presented in section I.G, the three States over it have different legislation. In Texas, water is private; there is a State Water Development Board for information but it does not control water abstraction; this is the responsibility of users, who can form water management districts to forbid misuse of water. In Oklahoma groundwater is private, and a Water Resources Board controls well location and makes measurements; it is possible to constitute water districts but none exist now [20]. In New Mexico, however, groundwater is public, but State Agencies regulate groundwater only in a series of basins, about one third of the total; in them drilling is restricted and groundwater use is limited to a maximum of 9,000 m^3 per hectare per year.

Overexploitation is an acceptable policy if planned with specific aims, and as long as the negative consequences have been technically evaluated by those who make the decision and are economically and socially acceptable. Even so, the issue of intergenerational equity can arise [23]. Some considerations valid for surface water reservoirs also apply to some extent to aquifers, and thus an aquifer that is always full is almost as badly utilized as one which is almost always empty, but some economic (cost of water abstractions) and ecologic (maintaining water in such natural outlets as rivers, springs or water-table-dependent vegetation) considerations may modulate the assertion.

D. Overexploitation as understood in Spain

As a whole, Spain is the most arid country of the European Community, although large variations can be found in the about 500,000 km^2 territory, from areas with more than 1,000 mm per year of rainfall to areas as low as 100 mm per year in the south-eastern Iberian peninsula and in the eastern Canary Islands. Good climate and long agricultural traditions have helped develop a prosperous irrigated agriculture over large surfaces, many in formerly semi-desert areas. Many large urban areas, some with industrial belts, and tourist resorts are close to the coast, generally in low-rainfall regions.

Present groundwater development accounts for 20 per cent of water consumption, or about 5,000 hm^3 per year, of which 85 per cent is used for agriculture; also, 70 per cent of the townships are supplied by groundwater. Abstraction sites have been selected mostly on a local basis, in the absence of a national planning process.

The traditional view has been to prefer the development of surface water resources by means of dams, canals and interbasin water transfers. In parallel, private interests have intensively and extensively developed groundwater, more efficiently and to the point of converting economically depressed regions into properous ones. About 1 million hectares are irrigated with groundwater, and 2,2 millon hectares with surface water, part of which depend on springs.

The intensive exploitation of groundwater, partly poorly controlled, is not without problems of excessive drawdown - more than 300 m in some aquifers in the south-eastern peninsula and in Gran Canaria and Tenerife islands - loss of well yield, sea-water intrusion and deterioration of valuable wetlands.

Recent studies [42] divide the peninsular territory and the Balearic Islands into 369 aquifer units. Of them, 78 present exploitation problems and in 42 there is an excess of abstraction over estimated recharge. The total deficit in a surface of 23,000 km^2 is 650 hm^3 per year, or about 13 per cent of total groundwater abstraction. It is recognized that overexploitation has been the drive for development in many areas of south-eastern Spain [52]. Reserves are expected to last only a few decades in some areas [55, 56], but solutions are sought since the existing worth warrants the development of other water sources - even interbasin transportation - that was before unthinkable.

Water was regulated by the 1879 Water Act (drafted in 1866). In simple terms, surface water was public domain but groundwater was the property of the abstractor. In spite of its being a nice piece of legal work, through the years a series of problems appeared as water abstraction methods developed, water use expanded and quality aspects became more acute. Problems which people and administrators interpreted as alarming overexploitation insistently attracted Government attention. Finally a new Water Act was enacted in 1985. All water was considered public domain and the term overexploitation given legal status. In some aspects it was a reaction - perhaps an overreaction - to local situations considered critical.

Neither the Water Act nor its Regulations provide a clear definition of overexploitation; it happens when abstraction rate is greater than recharge rate, but also when detrimental impacts appear, that endanger the sustainability of groundwater exploitation. The concept is also linked to that of risk of aquifer salinization [1].

Overexploitation is provisionally declared by the Basin Water Authority, after its data and studies. The definitive declaration is done by the National Water Council - or the corresponding body of the Regional Governments when they have competence to do it - with the advice of official Institutions and a time for public hearing. The declaration of overexploitation requires the constitution of groundwater users associations, implies changes in groundwater abstraction (quantity and pattern) and modifies the Basin Water Plan (if one exists).

Up to 1991, there has been little experience but much controversy. Such a declaration obligates the Water Administration to undertake studies, institute controls and initiate management. In reality, however, the Administration is understaffed and lacks the resources to carry out the task effectively.

As of 1991, there have been 13 provisional declarations of overexploitation [37], affecting some 9,000 km^2 of territory and 460 hm^3 per year of the 650 hm^3 per year of excess abstraction over recharge. Only 7 of the 13 areas declared provisionally overexploited have a clear deficit. Actually only 3 still have a clear excess, the declaration being produced because of other circumstances or political pressure. In fact, in the only aquifer presently declared definitively overexploited, abstraction is less than 40 per cent of assumed recharge, there is no clear trend in groundwater levels and overexploitation has been called "temporal". The objective has been environmental, i.e., to maintain water flow to some lakes. This provoked much argument [53, 54], during the Congress discussions. It was implied that the provisions of overexploitation in the Water Act have been used to achieve other goals, probably reasonable and necessary, but with the wrong tool.

Special hydrogeological conditions exist in the Canary Islands which consist, mainly, of low permeability volcanics. The islands are small, but have strong orographic effect on rainfall (from 100 mm per year in the southern coastal areas as much as to 1,000 mm per year on the northern slopes of the high islands) and recharge, and high abstraction rate. In some areas a continuous groundwater level decline - up to 10 m per year - is observed, with total drawdown of several hundred metres, even when recharge is close to or less than abstraction. There is a long-lasting transient situation, and with existing water gallery and well patterns, the final result is high abstraction costs, non-recoverable loss of yield in some areas, and water quality degradation. The old Water Act was adapted to cope with local problems, concentrating water management in only one institution. The new Spanish Water Act made provisions for a separate Law for the Canaries, respecting the general directives. The regional Law was enacted with provisions for tight control and intervention of the well-established and popular private water rights - something deeply rooted in the social context - and poor public hearing. When it was enacted public reaction was so strong that the Regional Government fell and another elected that promises to change the Law. It was finally done after overcoming difficult legal actions. Some old rights have been preserved, such as the existence of companies created to explore, drill and sell groundwater, and more power is given to island governments to organize their own water plans.

The islands with excessive groundwater exploitation are suffering a series of problems and there is serious litigation, but they have developed their economy to provide a reasonable standard of living for their inhabitants, and there are no signs of serious deterioration due to groundwater overexploitation. High-water-demanding crops are being replaced with others less demanding or with such high value that water cost is unimportant. Desalination plants have been introduced, some using brackish groundwater to supply agricultural farms. Urban sewage water re-use for irrigation, gardening and some urban services is being introduced. Actually, in Gran Canaria groundwater abstraction has been reduced without hindering economic development.

The Spanish experience is quite interesting, in spite of the short time of existence of the new Water Act, and the fact that the Basin or Island Water Plans - the key for applying the Water Act - have still (1991) not been approved. But it may be too early to assess the real impact of the overexploitation component of the Spanish Water Act in terms of benefits by its enforcement. Efficient application of the Water Act must overcome a series of economic, administrative and social problems and perhaps some provisions should be changed in accordance to experience to get a better balance between Administration power and water-users rights and needs. In fact, when an aquifer is declared overexploited, under the new Water Act the powers of Administration officials may practically override the rights of groundwater users and even legally constituted user associations, as defined in the Water Act. Such power, although a help in solving acute situations, is prone to deviation and abuse.

The fact that recent water legislation of such an industrialized, relatively dry country deals with overexploitation of groundwater is of interest to developing countries where massive and concentrated groundwater development is a relatively new situation. It would apply to large urban concentrations, coastal areas, irrigated areas in semi-arid or arid lands, especially in Central America, the Mediterranean region, the Arabian peninsula and vast areas of Asia including peninsular India and the North China Plains, where this development has generated a number of undesirable effects. But if the situation or the risk of overexploitation is overestimated by authorities, it may result in what some have named "hydraulic Malthusianism", with considerable economic loss and social problems, especially in irrigated areas with many small farmers.

It has been argued that the way overexploitation has been handled in the Spanish legislation, drafted by lawmakers and administrators not fully informed in the groundwater field, is not entirely satisfactory, and that its lack of clarity may generate difficulties. For example, a lowering of water levels and an increase in salinity is not necessarily a sign of the overexploitation the law is trying to avoid. In fact, some of the measures proposed by legislators could lead to a worsening of the situation. For example, the closing of salinized wells or a reduction of abstraction may be detrimental if wells reducing saltwater head are suppressed [1].

It is interesting to note that, at the country level, overexploitation in Spain is not extraordinarily high, although it may be of concern under the special conditions of the Balearic and Canary islands. The Ogallala aquifer, in the southern United States (see section I.G) is more overexploited but has produced less official nervousness. Spain can be compared in some aspects to California: 500,000 km^2 as compared to 400,000 km^2; 40 million inhabitants compared to 25 million; climate ranging from wet to desert, although California as a whole is slightly more humid than Spain. California uses as much as twice the surface water and three or four times the groundwater that does Spain. Aquifer water reserves use attained 5,000 hm^3 per year, although presently it is reduced to 2,500 hm^3 per year, still much higher than in Spain. Of 392 groundwater basins (369 in Spain) 42 are considered overexploited, 11 of them critically. This situation is considered bearable and controllable, and the benefits are evident.

E. Conclusions

Groundwater overexploitation in most instances is related to economic factors, so is groundwater mining, as commented in section III.B. Economic analysis of overexploitation may help to understand many practical situations. However, there are so many factors affecting a given case that water planning based on pure economic approaches needs simplifying assumptions that may prove naive or produce erroneous results.

Groundwater management options include considering aquifer water exploitation as capital producing a rent (when there is good water renovation), or as a loan to be repaid or not (the case of a large unconfined aquifer) or as the consumption of a capital (when there is no renovation) or a mix of them.

The fact that water is essential for life and has no substitute introduces a social dimension and ethical questions; the problems must be solved with some dosage of politics.

Management should be carried out on a technical and economic framework, but also some kind of legal rules are needed when overexploitation is serious. That the groundwater is public or private does not seem a key issue for overexploitation management. Good regulations, enforceable, widely accepted, democratic and applied by an effective administration and judicial system are the key factors.

A close look at the legislation of other countries and the success or failure in their application is recommended. But local circumstances must be taken carefully into consideration since simple transpositions might be too risky and probably unfitted.

V. PROTECTIVE AND CORRECTIVE MEASURES

A. General

As explained in the preceding sections, besides beneficial effects, in most cases "overexploitation" refers to the undesired and unforeseen detrimental consequences of groundwater exploitation, except in the case of aquifers containing non-renewable or minimally renewable water resources which are "mined" according to a planning process that takes into consideration both the estimated duration and economic benefits of the exploitation. In that particular case, overexploitation is considered to occur only if depletion proceeds at a rate faster than planned. But the existence of negative consequences does not imply necessarily that extensive and intensive exploitation leading to what may be termed overexploitation is undesirable, since benefits - especially social benefits - may overcome inconveniences, at least during a period that allows for corrective measures to be introduced or to happen. The economic, social and political issues have already been discussed.

More detrimental is the lack of understanding and data on aquifer behaviour that impedes effective management and the introduction of corrective measures. This lack of knowledge happens sometimes in industrialized countries and, unfortunately, is the rule in developing countries, where they are more needed to help solve problems with affordable means and before the damage is too serious. Studies and monitoring, jointly with appropriate management rules can save much effort and money, preserve productive sources of much-needed water and avoid investments in other more expensive ones. As a general rule, it is better to prevent than to cure.

There are no universal cures for the detrimental consequences of overexploitation. In each case they must to be tailored to local physical, economic, legal, administrative and social circumstances. What is good and feasible in one place may be unsuitable and detrimental in another. Special attention must be paid not to transfer solutions from industrialized and well developed areas to developing regions without a deep knowledge of the whole set of circumstances. Costly errors may be made.

B. Technical management measures and options

Some management measures and options of a technical nature are briefly presented below. They are only ideas whose applicability should be carefully checked in each case.

Groundwater conservation is a first objective. But since existing human and economic activities already exist, it should be accompanied by improvement in water use efficiency (leakage reduction, in-house water metering, improved irrigation practice, industrial water recirculation) or by developing new water supplies (if they exist). There is a cost increase. Agricultural use should be reduced mainly by eliminating non-beneficial evaporation loss (local irrigation, mulching, shadowing) since the simple reduction of applied water may produce a more saline return flow that in the medium or long term might jeopardize aquifer water quality or even aquifer recharge in the case irrigation uses imported water.

Imposing an abstraction reduction, if not done carefully and by steps may produce new detrimental effects in the social and economic context of the area. Certain detrimental effects such as saline water intrusion, wetland and riparian belt desiccation or excessive decrease in spring flow can be solved to some extent by rearrangement of the pattern of abstraction. This is best suited when some aquifer water resources are still untapped. In other cases rearrangement does not solve the problem but delays undesirable consequences.

Better use of all existing water resources is a form of reducing non-beneficial water loss, such as flood water, excess winter (low-demand period) water in the aquifer or through-flowing untapped seasonal river water. This is the objective of what is called conjunctive water use [22] and includes management of river storage, in-channel and off-channel river water infiltration and artificial recharge. Conjunctive use is easy to plan but much more difficult to implement technically and legally [27]. Also, some components may fail owing to poor implementation, lack of expertise or unforeseen behaviour.

Artificial aquifer recharge includes a wide set of methods and techniques to enhance aquifer resources, ranging from simple dispositives to sophisticated ones [47], according to site condition, origin and characteristics of recharge water, acceptable cost of water, aquifer characteristics and land properties. Artificial recharge is a management tool, sometimes inexpensive, sometimes costly, but always requires a good understanding, maintenance and operation skills and some administrative and legal support. In some cases it may be as simple as restoration of river bed infiltration capacity. Artificial recharge is feasible both in industrialized and in developing countries, but is more prone to failure in the developing countries owing to operational difficulties.

Artificial recharge is considered by many as the ultimate remedy for the exhaustion of groundwater reserves. Although induced recharge may be an easy cure in some cases (for example for depleted alluvial aquifers under arid climate, or to increase infiltration) and is relatively easy to generate, artificial recharge is much more difficult, taking into account the number of favourable conditions necessary to make it successful - and also the amount of investment needed. It appears that no major developments have occurred since 1975 [48]. In fact, while artificial recharge was mentioned in several publications presented at the Congress as a possibility, no example was cited of a successful artificial recharge operation aimed at correcting the negative impact of groundwater overexploitation. In many cases artificial recharge is recommended as a cure or as a management technique to redress water balance figures, but rarely is there a study of its real feasibility. Propositions remain hypothetical, with no clear indications on how to implement them.

New water resources can be found in treated urban sewage water. The feasibility of sewage water re-use depends on its quality (mainly salinity), the absence of detrimental pollutants (mainly of industrial origin) and the ability for collection and cheap treatment, transportation to demand points and temporal storage without being degraded by sunlight. Agricultural uses and garden and street irrigation are the main possible demanders. Treated sewage water can be also used for aquifer recharge, to protect against saline water intrusion or to increase storage, but it is not an easy task and existing drinking water in the aquifers must be protected against possible degradation. Still there is little experience in artificially recharging reclaimed water. Serious clogging, aquifer chemical changes and variable water quality add to normal artificial recharge problems. When re-used water may have contact with persons, directly (bath, swimming) or indirectly (raw edible vegetables, fish) other possible health effects related to disease producing microorganisms are to be considered; viruses may be specially resistant to treatment.

Desalination of brackish or salty water is another possible, though expensive source of fresh water in cases of aquifer overexploitation, if water to be desalinated is available. Brackish water can be transformed into fresh water at relatively moderate cost by electrodialysis and reverse osmosis, but a uniformly saline raw water is needed, free of substances harmful to the membranes (and also to water consumers), and with the possibility of safely disposing residual brines. Salty and sea-water can be economically treated only by means of more expensive, high-heat-recovery distillation or high-salt-rejection reverse osmosis methods. Desalination should be considered an alternative or complement only after sound economic analysis. In Las Palmas Province, Canary Islands (Gran Canaria, Fuerteventura, Lanzarote and La Graciosa) desalination of sea and brackish groundwater is extensively used for supplying urban and tourist centres and, in some cases, for greenhouse agriculture as well.

Some cases of groundwater quality deterioration (mainly salinization) that has been called overexploitation are the result of improper well construction (too deep, screened in poor water quality layers) or inadequate exploitation. In some cases cementing part of the well or grouting well screens or isolating the annulus is enough to correct or redress undesirable effects. In coastal aquifers, in areas above the saltwater wedge, numerous shallow scavenging wells can be a solution to overexploitation problems. In thick formations with only thin pervious layers, the rest being aquitards, exploitation with deep, high discharge wells, as stated before, produce a fast drawdown that might be termed overexploitation since there is not enough time for groundwater in the aquitards to move to the transmissive layers. In that case a much more distributed abstraction might help solve the problem.

Undertakings such as cloud seeding and dew collection are feasible only under special conditions and contribute little water. Rarely do they help in alleviating overexploitation problems. Rainwater collection into individual or collective cisterns may be a better-suited solution for house needs, at least for in-house water that does not need to be potable. In the Maltese islands such cisterns are required by law.

C. Studies and data

From the technical point of view and to efficiently apply solutions, as above said, the aquifer should be adequately known, the more exploited it is, the better it should be known. This means to be able to sustain a continued effort to improve the knowledge and to incorporate new information. An essential item is to have the capability to obtain newly generated information and to have the effective power to ask for this information.

Periodic reappraisal of the resources on the basis of data collected by means of an adequate monitoring process are essential - in relation to management criteria - if protracted situations *indicateing overexploitation* are to be avoided [11].

Existing hydrogeological criteria for declaring that overexploitation is taking place are neither exclusive nor fully reliable, because of the uncertainties in quantifying hydrologic parameters. The evolution of drawdowns cannot be conclusive if the data are collected over too short a time.

Thus, sufficient and reliable monitoring is an essential part of protective and corrective measures for so-called overexploited aquifers. The possibility of vertical changes in groundwater head and quality need careful consideration. Existing exploitation and abandoned wells may yield mixed information, difficult to interpret or misleading. The abstraction rate is a key value that should be carefully monitored. Experience shows that it is not as easy to monitor as it first seems.

D. Examples of technical measures

In Mexico, a country with major groundwater exploitation problems [17], situations that some may call overexploitation are observed in areas where groundwater is the only source, and demand is high, especially in semi-arid and arid areas, of about 70 per cent of the country. About 70 per cent of the groundwater extracted in Mexico (28,000 hm^3 per year) is used for irrigation (2 million hectares), 20 per cent for community water supply (for 55 million people), 7 per cent for industry and 3 per cent for rural water supply. It is estimated that 10,000 hm^3 per year of non-renewable groundwater resources are abstracted, with water levels declining steadily at rates of 1 to 3 m per year, and pumps set at depths of 70 to 130 metres. The agricultural sector has suffered more than others from the related increase in water costs. In some areas, urban growth required the incorporation of agricultural wells to municipal water systems. It has been recognized that whenever possible, joint development of surface water and groundwater, including artifical recharge, should be considered in order to remedy or avoid groundwater overexploitation. The following policies have been implemented to various degrees during the last 15 years:

1. Collection of data on water resources in the course of development,
2. Coordination of the agencies collecting water resources data for storage in a single data bank, with common standards for data presentation,
3. Control of aquifer overexploitation,
4. Development of aquifer reserves only if proven beneficial,
5. Promotion of more efficient water use through adequate pricing,
6. Promotion of participation in and cooperation among water users in the preparation and implementation of groundwater development programmes, and
7. Prevention of the discharge of pollutants threatening groundwater quality through more adequate regulation.

Probably a third of the aquifer units of Mexico are already in various stages of overexploitation: actions undertaken in the course of the last 15 years have enabled definition of policy in half the cases [17]. In Mexico, groundwater has been public since early revolutionary times.

Northwest of Buenos Aires, Argentina [32], four townships obtain water supplies from wells abstracting some 30,000 m^3 per day from sandy formations. Overexploitation of the wellfields of one town (9 de Julio) caused an increase in salinity: specifically chlorides, sulphates and also nitrates. An increase in the area of well fields and in well spacing was proposed, as was reduction of exploitation as a last resort prior to developing new sources of water.

In Pampa la Yaranda Antigua, Peru [19], near the border with Chile, water resources are scarce. Mean rainfall is less than 10 mm per year. Groundwater is abstracted in significant quantities (30 hm^3 per year), only 500 metres from the coast. Water levels during pumping may fall to 12 metres below sea level and sea-water intrusion occurs. The water-table is falling at a rate of 0.6 metres per year. The following measures have been considered:

1. Changing the areal distribution of irrigation wells, that is, closing existing wells and replacing them with new ones, and
2. Improving irrigation practices so as to save water.

Wadi Surdud, Yemen [14] crosses the Tihama Plain from Sana'a (the capital) in the east to the Red Sea in the west. An alluvial aquifer, 250 m thick, is underlain by poorly permeable Tertiary strata containing saline water. It is recharged by infiltration of up to 60 to 100 hm^3 per year of flood water. Groundwater extraction amounted to 91 hm^3 per year in 1984 and is increasing. Natural discharge of about 50 hm^3 per year occurs by evaporation from a zone near the Red Sea coast and by seepage of groundwater into the Red Sea. Through a mathematical modelling exercise, it has been predicted that, at current pumping rates, water levels may seriously decline in the eastern part of the wadi and lead to abandoning many shallow wells or when pumping costs rise too high. This could be delayed by special allocation measures; i.e., reducing abstraction in the east and pumping more to the west. Nevertheless, sustainable groundwater exploitation is possible only if pumping is significantly reduced. In that case sea-water intrusion would not be a major problem in the medium term.

Celaya city, Gunanajato, Central Mexico [10], has a population of 500,000. It is crossed by three parallel active geologic faults. The vertical movements along these faults may be as much as 150 mm per year. In the most seriously affected buildings, differences of level of 1.5 metres have been observed. It has been determined that the main cause is the extensive exploitation of some 2,000 wells which has resulted in a lowering of the piezometric surface by 2.5 m per year. Under Celaya, the water-table decline since 1956 has now reached 60 metres. For the Celaya area a set of technical and other measures are being considered, including:

1. Closing of unauthorized wells,
2. Limiting extraction (after installing water meters on wells),
3. Developing artificial recharge schemes,
4. Delivering treated used water to the farmers near the city,
5. Improving water use efficiency,
6. Rehabilitating water-supply and sewerage systems, modifying the layout if necessary (so as to avoid crossing faults), and
7. Studying in detail land movements along the faults.

In the mountainous valleys of Yemen [31], the construction of spate breakers in the upper reaches of rivers should reduce flooding, increase irrigation and recharge of the intensively developed alluvial aquifers.

In the Punjab, India, to try to restore well yield or groundwater quality, several artificial recharge schemes have been studied using various methodologies such as spreading and injection.

Excessive groundwater abstraction in western Catalonia, north-eastern Spain [12], have dramatically reduced well yield in fissured rock. Exploitation should be reduced to allow rural water-supply to continue and off-season surface irrigation water can be used for artificial aquifer recharge along the canal, for example, by over-irrigation in winter.

E. Economic and legal measures

From the practical point of view it should be recognized that neither the common pool nor the unwanted external costs problems are likely to be effectively met by purely technical solutions; a mix of technical and institutional actions are needed, jointly with research and education. Education is powerful and cheap but slow and is not sufficient alone. It is sometimes held that economic constraints are the only effective way to control aquifer exploitation. For example, pumping from greater depths may become uneconomical and preclude groundwater development [23].

Sanctions on those not complying with established rules are necessary and must be applied when there is an abuse or deviation. Monetary sanctions (fines) are in common use but frequently they are not effective, sometimes difficult to apply and are unpopular. Other types of sanctions may be more effective and more easily accepted by society, such as prohibition or limitation of the use of a water right, or permit-cancellation or withholding of concessions.

In many cases, overexploitation problems are experienced in areas where groundwater resources are tapped in the absence of prior comprehensive planning. The question then arises of whether to pursue the same pattern of groundwater abstraction [36]. After hydrologic assessment, conservation measures should be taken within a legal framework of action.

As stated in section IV, control can be exerted only if adequate legislation has been enacted [23]. Local regulations to limit or stop pumping may not be enforceable if they are not backed with a Water Law. Groundwater users themselves, through legally established associations are capable of carrying out effective control on aquifer exploitation and positively participarting in water plans and administration, provided that all interests are adequately represented and democratic rules respected. Private water rights are partly transferred to the association or institution (district).

The larger public interest, however, would not be met by solutions designed by the user groups themselves since they would probably not adequately account for external costs, would entail high interest rates, and tend towards free-riding and imperfect information. Thus, a public institution is needed to redress excesses, co-ordinate efforts and link local interests to regional and national interests, respecting liberty and working jointly with the user groups. User groups and municipal teams can easily provide means of control, gather reliable data, monitor, and enforce rules in ways that local or central governmental agencies cannot achieve without considerable, costly and complex technical and organizational means.

F. Proposed legal and administrative measures

In India, excessive groundwater exploitation occurs when farmers recognize the benefits from well irrigation. The situation usually goes without control since managers and politicians do not intervene until deterioration is clearly noticed [57]. Remedies include legislation, abstraction control, recharge increase if feasible, and sometimes reforestation to reduce overland flow. Late decisions sometimes are unpopular. Although in remediation, politics and culture play a dominant role, it is the task of the Government, since individuals lack the motivation. Non govermental organizations (NGOs) may play a decisive role in fostering solutions. At the local level, Village Councils are proposed [57] to redress inefficient and sometimes corrupt governmental licensing practices.

G. Conclusions

A certain measure of control is in many cases exerted when groundwater development reaches a certain level, by restricting construction of new boreholes and limiting the output of existing ones.

Possible undertakings and economic and legal actions can be grouped in [22]:

1. Those of a technical nature:
   a. Better water use
   b. Redistribution of wells and well improvement
   c. Increase in total water resources
   d. Monitoring
2. Those of a legal, administrative or political nature:
   a. legal tools to implement decisions and set priorities
   b. incentives and education for water saving
   c. control of water rights
   d. punishment of abuses
   e. education

All require careful assessment, monitoring and operation flexibility [11].

In developing countries there is pressing need to expand food production and to provide water for urban growth; groundwater resources are under strong development pressure, especially in arid regions. This situation is aggravated if water costs are subsidized, and if government authorities are reluctant to enforce control for lack of manpower or for political reasons.

Also, in certain areas in developing countries, the number of shallow wells may be extremely high. Such wells are highly vulnerable to interference or "excessive" exploitation effects. On the other hand, the institutional capacity of regulating government agencies is insufficient to cope with the implementation of controls. Also, as adequate information on water resources is not always available, it may be difficult to diagnose incipient signs of overexploitation [23].

Priorities for implementing regulations should be allocated by considering the importance of the aquifers and the level of their exploitation, as well as the risks and level of adverse side-effects. Control measures work better if there is a regional or catchment agency that has good relations with the well drillers and owners. To be effective, licensing of groundwater abstraction should be directed mainly to major water users. Penalties should be instituted on unauthorized groundwater abstraction. They should be equitable and enforceable [23].

A water policy cannot be effective if water users do not understand the issues, especially as regards the sustainability of resource exploitation and accept their share of the necessary sacrifice for the common good. In developing a groundwater management scheme, it is essential to educate the users - who may number in the thousands - in the basic principles of hydrogeology - that is the occurrence and the behaviour of groundwater. This will facilitate reaching a general agreement between the public and government officials and officers on the conservation measures to be taken in order to guarantee sustainable development of groundwater resources [6].

A good understanding of the aquifer system behaviour is always needed. Mathematical models are good tools of much help but they are not mandatory in reaching a good understanding. Other techniques such as groundwater level analysis, hydrogeochemistry and environmental isotopes have a high potential in the beginning and as study progresses. Mathematical models constructed with poor aquifer system understanding, with poor data or insufficient data may be misleading. The same is true for the determination of aquifer hydraulic parameters with ill-designed tests, too short or with inadequate observations [18].

Monitoring is an essential tool for evaluation and to design effective corrective measures. Monitoring should include groundwater level, chemical and isotopic environmental composition and abstraction, in a dense enough network that considers existing aquifers and also aquitards. Periodic reports on aquifer system behaviour should be planned and carried out. A board of advisers should discuss them and make them public.

Education, from elementary to university level, is a necessary and powerful tool to correct undesirable aquifer exploitation, although it alone is not enough. Educated people can communicate more easily with managers and administrators and especially influence political decisions through their conscious vote.

VI. FINDINGS AND RECOMMENDATIONS

A. Contributions of participants

Several participants presented papers at the Workshop and all presented notes in manuscript (annex IV). The material is of considerable interest and deals with such topics as overexploitation classification and evaluation, integrated water resources development in areas with serious aquifer extensive exploitation problems, subsidence problems, widespread water quality deterioration as a result of excessive groundwater abstraction and problems with aquifer knowledge in order to efficiently manage it. Under the concept of overexploitation undesirable effects and groundwater reserve depletion were pointed out. But also, that clear benefits, if only temporary, obtained from extensive groundwater abstraction were pointed out as well. In any case good knowledge and control are needed to avoid deterioration and to make benefits sustainable.

B. Clarification of issues

Groundwater exploitation has contributed significantly to the solution of crucial problems in developing countries, such as providing potable water to large urban areas faster and cheaper than conventional surface water schemes and megaprojects. In many countries like China and India, groundwater has contributed to dramatic increases in food production. In spite of some real or assumed overexploitation problems, groundwater use should be promoted in developing countries as a means of improving their economic and social situation, avoiding the loss of opportunities because of overstated adverse situations. Nevertheless, groundwater exploitation should avoid unsustainable development as a permanent goal, although aquifer reserves can be used for limited periods under controlled and planned form to attain objectives of better use of total water resources. But the detrimental effects are real in many circumstances and they need control and correction if development is to be sustainable, and this has to be achieved through improved the knowledge, monitoring, adequate management, legislation and realistic water planning. The ugliest adjunct of overexploitation is to ignore it and fail to apply any regulating mechanism.

Socio-economic development based on groundwater mining is unsustainable if there is no water source to substitute after the reserves are exhausted or no new trends in the local economy can be foreseen. The problem has some similarities to mineral exploitation, especially oil, but the unique and vital character of water defines the difference.

The basic information, ideas and concepts contained in the abundant material presented at the Congress and which are of particular relevance to developing countries were identified and discussed in the report. They include:

1. The concept of overexploitation may be confusing as it can be understood in various ways, namely:

   a. As a level of exploitation that goes beyond the some safe yield value.
   b. As a form of exploitation of groundwater that produces unexpected detrimental effects in terms of water resources availability, quantity, quality and costs, in terms of damage to the environment (wetlands), and structural damage (subsidence).
   c. As the "mining" of a non-renewable resource that does not proceed according to plan and results in lowering of the piezometric surface, specific capacity of wells and water quality.
   d. As more generally a form of groundwater development that causes harmful results and which therefore must be avoided.

Overexploitation is seen as a form or level of groundwater development which is not sustainable. It should not include a level of exploitation which intentionally and through carefully planned management, including economic and social issues, draws upon aquifer reserves so as to increase water resource availability by eliminating such losses such as continuously flowing spring water to waste, shallow groundwater evaporation and flood water recharge that is rejected and eventually lost to the sea.

Yet other meanings may be attributed to the word overexploitation, but two important observations hold throughout. First, although Meinzer's safe-yield concept constituted a landmark in groundwater hydrogeology, overexploitation cannot be considered and defined only from a hydrogeologic point of view, but economic, social and political components dominate. Second, the word overexploitation which, at the outset, has a connotation of illegality if not immorality, should not be used without referring to the broader context of socio-economic factors and beneficial aspects. The term should be avoided and replaced by more accurate expressions defining a particular situation, under the umbrella of extensive or intensive groundwater exploitation.

2. Overexploitation can be recognized as such only on the basis of:

   a. A reliable assessment of the hydrogeologic situation based upon several years of adequate monitoring and data collection,
   b. A full assessment of economic and social benefits of the exploitation of groundwater, and
   c. An assessment of the impact of groundwater development on the environment.

3. In examining the consequences of what is assumed to be overexploitation, the time factor must be considered, as the situation in the short-term may appear quite different from that in the long-term. Also, the negative effects should be considered as affecting several parties in different ways, namely water developers; such other parties as owners or users of springs which have dried-up as a result of the developers' action, and the environment, or general interest, for an indefinite period of time.

4. The beneficial aspects of groundwater development beyond the limits of safe yield must be taken into consideration in water resources management, especially in arid countries. Some kind of overexploitation that uses groundwater reserves has been and is the drive behind development of many areas.

5. Overexploitation is not necessarily a lasting situation that needs drastic intervention since circumstances change and in the future the same or greater economic output and social welfare can be attained with less water or new sources of water can be developed. Overexploitation that uses and depletes reserves is physically limited in time and this compels to groundwater abstraction reduction. If overexploitation is the result of considering detrimental effects, these effects may be permanent if an equilibrium is attained, and then the correction requires the will to redress under ethical, or economic or political push.

6. Although in most cases overexploitation cannot be prevented, adequate groundwater resource monitoring would allow detection of signs of its occurrence in the early stages. In many instances these signs are simply due to groundwater exploitation.

7. Many negative effects of overexploitation can be corrected if adequate steps are taken. But some measures may aggravate the situation. Water legislation will remain ineffective if it is not accepted by the majority of users. This is mainly the result of the users lack of understanding of the real situation. In fact, in most cases exploitation will come to an end when water quality becomes unacceptable or when yields and water levels have fallen to a level that renders production of water uneconomical. Such a regulatory effect may well occur long after the environment has been heavily, if not irreversibly damaged. The environment factor should thus be carefully considered in assessing the sustainability of a groundwater development scheme.

C. Conclusions of participants

By the end of the discussion, the participants agreed on a list of conclusions and control strategies including protective and corrective measures, as follows:

1. There was general agreement that governments should make more efforts to control groundwater exploitation in areas subject to irreversible deterioration in groundwater

quality and other external effects. There is also need to avoid major unexpected and unplanned depletion of groundwater reserves. But this control should not cripple development by creating unnecessary obstacles.

2. The situation in urban areas is distinct from that in rural areas, with agriculture dependent upon intensive groundwater exploitation. The problems in establishing effective groundwater management are also different in each case, and require different approaches.

3. In many but not all cases, the nature and scale of negative effects generated by extensive groundwater exploitation had not been anticipated. Many aquifers have reached high or excessive levels of exploitation without the corresponding investigation and monitoring needed to understand the groundwater flow and quality regime. Such understanding is essential to appraise the likely effectiveness of possible control and corrective measures.

4. There are many instances in which groundwater exploitation has continued up to high levels with no control being exercised, but there is now valuable experience in some nations of more positive management of groundwater resources. This has generally occurred earlier in countries with greater public awareness and political acceptance of the need to conserve water resources and the existence of a single strong agency responsible for water resources management with both local and regional offices, and working together with water users.

5. In relation to urban water supplies, it was generally agreed that the price paid by consumers - at least the larger consumers - did not reflect the true production cost and scarcity value of water, and this is counterproductive in terms of managing urban water-supply aquifers. It is also essential to manage public and private use of these aquifers in an integrated fashion, and to avoid non-efficient investment and expense.

6. As regards agricultural irrigation from groundwater, experience is more varied, but even where the full capital and operational costs of groundwater production are met by the individual farmer, there are few instances of the water-user being asked to contribute to the cost of water resources management and to share the responsibility of management.

7. While adequate legal provisions to manage groundwater resources exploitation are highly desirable, they must not be considered as prerequisite. There are many instances of effective control on aquifer exploitation (prohibition of further well drilling or deepening in certain areas, restrictions on pumping periods, etc.) being made through the action of local commissions or committees acting under local decree through the creation of groundwater conservation or protection areas.

8. There was universal agreement that public awareness of the need to improve management and protection of groundwater should be increased as a matter of urgency. Of particular importance in this context is that administrators and politicians also be made fully aware of the consequences of inadequate groundwater resources management.

9. Much more emphasis should be put on artificially increasing the recharge of aquifers under extensive exploitation using such simple technology as small flood-retention dams in surface watercourses, recharge pits and contour channels. There is useful experience of these techniques in some countries which needs to be transferred to others. Artificial recharge is not, however, always possible, as a result of the unavailability of surface water, or of suitable land for recharge works or inadequate hydrogeological conditions.

10. Other opportunities for conjunctive or coordinate use of groundwater and surface water resources should be more actively pursued, conserving groundwater for drought relief and emergency situations.

D. Potential involvement of United Nations system

Several participants enquired about the possibilities offered by the United Nations system of organizations to assist developing countries in dealing with the problems generated by overexploitation of groundwater. The following information, which was provided to them, may be of interest to decision-makers in developing countries.

DTCD may lack the resources to deal with groundwater overexploitation issues in the near future, with the exception of short-term visits by Interregional Advisers, whom countries must request through their local UNDP office.

On a country basis, UNDP may finance projects within the budgetary limits of its programme (1992-1996) for that country. The process should start with a preliminary identification of the project and its purpose.

On an intercountry basis (in one region), especially in cases of aquifers shared by several countries, a request should be made by at least two countries to UNDP and also to the United Nations Economic and Social Commission of the region.

On a global basis, one may consider an overall approach in which several United Nations agencies and programmes may be involved, including the International Hydrological Programme, for a project which among others would utilize the potential represented by the Technical Cooperation Among Developing Countries (TCDC) programme.

The International Conference on Water and the Environment, held in Dublin, Ireland, in January 1992, was cited as an appropriate opportunity for exchange of information and expertise on the subject. It was hoped the conference might organize a World Groundwater Watch aimed at safeguarding the environment against potentially harmful modes of groundwater development, wherever justified and feasible.

Annex I

LIST OF PARTICIPANTS

A. Host Country Organizing Committee

Mr. José Jiménez-Suárez
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Prof. Lucila Candela
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Prof. Emilio Custodio
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Prof. Manuel Ramón Llamas
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Ms. Marisol Manzano
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Mr. Carlos Soler
Director de los Planes Hidrológicos de las Islas Menores, Santa Cruz de Tenerife

B. International Organizations

United Nations Dr. Robert Dijon
Interregional Adviser
DTCD, NRED, Water Resources Branch, New York

Ms. Fabiola Knight
Technical Cooperation Assistant
DTCD, NRED, Water Resources Branch, New York

UNESCO Dr. Habib Zebidi
Programme Specialist
Division of Water Sciences, Paris

C. Developing Countries

Argentina	Mr. Miguel Auge Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires
Brazil	Prof. Aldo Rebouças Universidade de São Paulo, São Paulo
China	Mrs. Wang Zhaoxin Senior Hydrogeologist China Institute of Hydrogeological and Engineering Geological Exploration Ministry of Geology and Mineral Resources, Beijing
Egypt	Mr. Abdel Fattah Metawie Senior Researcher - Chief Engineer Water Distribution and Irrigation System Research Institute, Delta Banage, Cairo
Guinea-Bissau	Mr. Francisco Fernández Hydraulic Engineer Ministry of Natural Resources, Bissau
Jordan	Mr. Raja Gedeon Water Authority of Jordan (Laboratories and Quality) Ministry of Water and Irrigation, Amman
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Papua New-Guinea	Mr. Jyrki Laitinen Hydrogeologist/Associate Expert, project RAS-87-009, Port Moresby
Peru	Mr. Jaime Uchuya Cornejo Chief, Groundwater Department, Water Supply and Sewerage Authority, Lima
Philippines	Mr. Ricardo T. Quebral Administrator, Local Water Utilities Administration, Quezon City
Thailand	Mr. Bannan Charukalas Senior Hydrogeologist, Chief of Groundwater Development, Royal Irrigation Department, Pakred
Venezuela	Mr. Jorge Alvarado Engineer-Geologist, Ministry of the Environment, Caracas
Viet Nam	Mr. Cat Ngoc Researcher-Hydrogeologist Head of Division of Groundwater Resources Geography and Natural Resources Institute, Hanoi
Yemen	Mr. Awad Omar Bamatraf Hydrogeologist, High Council for Water, Sana'a
	Prof. Mohamed Fara Mohamed Al-Dubai Faculty of Sciences, Sana'a University, Sana'a

Yugoslavia	Mr. Bozidar Biondic Head of Hydrogeology and Engineering Geology Division, Institute of Geology, Zagreb

D. Industrialized Countries

France	Mr. J. Margat, Adviser, Water Department Bureau de Recherches Géologiques et Minières, Orléans-La Source
United Kingdom	Dr. S. Foster, Chief Hydrogeologist British Geological Survey, Wallingford
United States	Dr. William Back, U.S. Geological Survey, Reston, Virginia

Annex II

PROGRAMME OF THE CONGRESS

Monday, 15 April Registration, Opening Session

Topic I. Characterization of Aquifer Exploitation: Hydrogeological and Hydrochemical Aspects

Keynote papers:

Prof. E. Custodio (Spain). Development of topic I and the situation in Spain

Mr. J. Margat (France) Development of topic I

Proceedings include 15 papers, 3 from a developing country (Mexico), 10 presented

Tuesday, 16 April Topic II. Environmental Effects Related to Overexploitation

Keynote papers:

Prof. R. Llamas (Spain) Groundwater and conservation of aquatic ecosystems

Mr. E. Lamoreaux (United States) Environmental effects of overexploitation in karstic terrains

Proceedings include 12 papers, 5 from developing countries (Mexico, Colombia, Lebanon, Senegal), 11 presented

Topic III. Protective and Corrective Measures in Cases of Overexploitation

Keynote paper:

Prof. J. Lloyd (United Kingdom) Protective and corrective measures with respect to the overexploitation of groundwater

Proceedings include 10 papers, 5 from developing countries (Nigeria, Yemen, India, China), 7 presented

Roundtable on "New contributions to the Canary Islands Hydrogeology"
Poster session

Wednesday, 17 April Field trip through six of the eight hydrogeologic zones into which Tenerife island is subdivided.

Stop 1. Visit to a 'Canarian well' sunk in the coastal platform, one of many drilled to compensate for the loss of yield from the galleries located on the northern slope, which have already reached a thick impermeable layer called mortalon (highly weathered breccia from major landslides) that covers a core.

Stop 2. Visit to the entrance of a drainage gallery, 'Buen Viaje', dug in the early 1960s. Total length is 2,360 m. Initially the the saturated zone was at 1,000 m, but with time and extensive drainage, about 25 per cent of present length is now dry. The yield is about 90 l/s. The basaltic aquifers involved are an upper system with high-permeability young rocks which absorb rainfall, and a lower aquifer, not as permeable, containing dykes which modify groundwater flow. Both are drained by many galleries 3 to 4 km long, most of which have reached the island low-permeability core. As a result, there is a progressive diminution of specific yield. In the coastal zone, wells have been dug 2 to 3 km inland to avoid sea-water intrusion.

Stop 3. The "tanquillas of Aripe" (town of Guía de Isora). Within the boundaries of the municipality, 48 drainage galleries exist, whose total yield in 1985 was 306 l/s. Canals or bajantes start from 15 of these galleries, ending in a narrow ridge northeast of Guía de Isora, at levels of 650 to 700 m. The canals conduct water into measuring receptacles called tanquillas in which it is divided in portions. Because many owners obtain water from the tanquillas in a narrow space, the ensuing clusters of pipes can be identified only by their owners or the foreman in charge of the installation.

The field trip ended with the crossing of the vast depression of Las Cañadas which contains young lavas and pyroclasts with high hydraulic conductivity. This combination of a water-tight basin with permeable deposits constitutes a hydrogeologic trap. At present, this reservoir is drained by five galleries with a total yield of 400 l/s. Groundwater abstractions cause a moderate lowering of 'Las Cañadas' water table, since they are compensated for by high direct recharge. Although this sector is probably the most promising in terms of quantitative water resources availability, in such an active volcanic area, gas emissions negatively affect water quality, in terms of bicarbonate and sodium concentration in some areas.

On the way back to Puerto de la Cruz, were seen several small artificial lakes which have been covered by a waterproof coating.

Thursday, 18 April

Topic IV. Legal and Socio-economic Problems Related to Aquifer Overexploitation

Keynote papers:

A. Sánchez González (Spain) Economic criteria for the characterization of overexploited aquifers

R.A. Young (United States) Managing aquifer overexploitation - an economic and policy analysis

Proceedings include 10 papers included in proceedings, 4 from developing countries (Mexico, India, Nigeria, Peru), 9 presented

Topic V. Overexploited Aquifers in Water Resources Management

Keynote papers:

J. Lehr (United States) Perceived aquifer overexploitation is in reality mismanagement commonly correctable by artificial recharge and well-field design. Groundwater recharge with reclaimed water in California

K.S. Johnson (United States) Exploitation of the Tertiary-Quaternary Ogallala aquifer in the High Plains of Texas, Oklahoma, and New Mexico (south-western USA)

Proceedings include 9 papers, none from developing countries, 9 presented

General Assembly of the International Association of Hydrogeologists

Friday, 19 April

Topic VI. Case Histories

a) Developing countries

Keynote paper:

S. S. D. Foster (United Kingdom) Unsustainable development and irrational overexploitation of groundwater resources in developing nations: an overview

Proceedings include 21 papers included (India, Venezuela, Argentina, Nigeria, Uganda, Algeria, Yemen, Sri Lanka, Mexico, Egypt, Puerto Rico, China), 13 presented, of which 2 (Peru and Morocco) not in Proceedings

b) Europe

Proceedings include 18 papers, 10 presented

Closure of Congress

Annex III

PROGRAMME OF THE WORKSHOP

Saturday, 20 April, Conference room of Feria del Atlántico, Gran Canaria

Morning: Opening Session

Welcoming Address by J. Jiménez Suárez (Host country organizing committee)
Introduction of partipants
Chairmen: R. Dijon and H. Zebidi

Afternoon: Discussion of Topic I. Factual Evidence of Overexploitation
Chairman: A. Rebouças

The Participants were invited to answer the following questions:

As a result of extensive groundwater development

1. Are significant overexploitation problems experienced in your country?
2. On what territorial scale? Regional? Local?
3. How are these problems showing?
   a. declining piezometric levels (metres per year)?
   b. deterioration of water quality?
   c. decreasing well (or gallery) yields?
4. What have been or are the benefits of extensive (or excessive) groundwater development?

Sunday, 21 April

Morning: Discussion of Topic II. Impact of "overexploitation"
Chairman: B. Biondic
Speaker: E. Custodio

The participants were asked to answer the following questions about the consequences of exploitation of groundwater in their respective countries. The substance of their answers was incorporated into the body of the report.

1. Groundwater mining (non-renewable resource abstraction) assuming that in your country this situation exists.

    a. Do you think that up to now it has contributed significantly to the socio-economic development of the region?

    b. Are there socio-economic difficulties now, or do you think there will be such difficulties in the near future?

2. Normal groundwater exploitation (as a renewable resource):

    a. Do you think that in this case groundwater exploitation has had a positive effect on socio-economic development, in a more efficient way than surface water projects?

    b. Do you consider that problems (ecologic, subsidence, sea-water intrusion, groundwater pollution, etc.) are caused by excessive exploitation or simply by mismanagement?

3. Do you think that in your country there is some kind of 'Malthusian' underexploitation of groundwater resources? In those areas where extensive groundwater development is undesirable:

    a. What is the problem?

    b. Is it desirable to invest to solve the problem? in other words:

        i. What could be the consequences if the problem is not solved?

        ii. What are the benefits to be expected if the problem is solved, in the short-, mid- and long-term?

    c. In the search for the optimal solution:

        i. What are the actions to be taken?

        ii. What are the data to be obtained? Type of data: hydrogeologic?, economic?, other?

4. How can the activities be implemented? What should the participant do back home in this respect after the workshop?

Afternoon: Field trip in the vicinity of Las Palmas de Gran Canaria. The Isthmus, the Old Town, caldera of Bandama, Tafira and Atalaya de Santa Brigada. Hints about groundwater use in the northern part of the island were provided

Monday, 22 April

Morning: Discussion of Topic III. Control Strategies, Prevention, Remediation
Chairman: R. Quebral
Speaker: S. Foster

In areas of extensive groundwater development as described above

1. Prevention

a. Were the effects of exploitation anticipated, considering hydraulic, water quality and external effects?
b. Was there any attempt to control groundwater exploitation?
c. Could the groundwater supply obtained been produced with less capital investment in pumps, pipes and wells?
d. Was a realistic price paid (directly or indirectly) for the water-supply?

2. Remediation

a. Can groundwater exploitation be controlled (reduced/redistributed)?
   i. by which practical methods?
   ii. are administrative or legal powers adequate?
b. Does public or water user awareness need to be increased?
c. What are the possibilities for the introduction of artificial recharge?

Afternoon: General Discussion. Comments on draft outline of the final report

Concluding session
Addresses by: J. Jiménez Suárez, R. Dijon, R. Quebral and L. Candela.

Tuesday, 23 April Field Trip

1. Visit to a well (Pozo Piletas) yielding brackish water and supplying a desalination electrodialyis plant for farming uses
2. Visit to a storage dam (Presa de Tirajana) for flood water retention
3. Visit to Fataga Valley and Canyon. Explanation of water resources problems in the area.
4. Visit to the Playa del Inglés-Maspalomas tourist complex, and surrounding agricultural areas, to see:

   a. Electrodialysis desalination plant of brackish water from the Amurga phonolite massif, for town supply
   b. A waste water treatment plant with water reuse for irrigation and gardering
   c. A reverse osmosis sea-water desalination plant for town supply

Closing of seminar, conference room of Centro Insular de Turismo, in Maspalomas. Final addresses.

Annex IV

CONTRIBUTIONS OF PARTICIPANTS
(Summaries)

The participants from developing countries were asked to provide summary reports of what they considered as overexploitation in their countries or in the areas they were more familiar with. Most reports were prepared during the meeting and in some way adapted to the questions asked at the beginning of the workshop, as shown in annex III. The summaries below were based on these drafts.

A. Argentina

The area most subjected to overexploitation is that of "Conurbano Bonaerense" or metropolitan Buenos Aires, excluding the Federal Capital, whose 3 million inhabitants are supplied by water from the Rio de la Plata. The area includes some 10 million inhabitants, that is, about 30 per cent of the total population of the country. It covers some 2,500 km^2, and extends from Buenos Aires to La Plata in a strip parallel to the Rio de la Plata, with an average width of 30 km. About half of the population of the Conurbano is supplied through distribution systems with 550 hm^3 of water a year of which 220 hm^3 are groundwater. The other half obtain supplies from small-diameter private tubewells delivering an estimated 150 hm^3 per year. The industries have their own well fields and surface water sources which deliver 500 hm^3 per year. The irrigated area covers some 20,000 ha and receives some 190 hm^3 per year from 4,000 tubewells. Groundwater accounts for 70 per cent of the water consumed in the area, as summarized in Table 2.

Table 2. Sources of water by user, Buenos Aires, Argentina

user	surface water (in mm^3 per year)	groundwater (in mm^3 per year)
Served by reticulated system (5 million)	330	220
Served by private wells (5 million)	-	150
Industries	100	400
Irrigation (20,000 ha)	-	-
Total	430	960

Groundwater originates in two granular aquifers with different hydrogeological characteristics.

1. Upper aquifer

The Pampeano or Epipuelche aquifer, formed by interbedded Holocene eolian sand; clay and limestone, with a thickness of 20 to 50 m. Permeability ranges from 0.5 to 50 m per day and well yields are commonly less than 4 l/s. The aquifer is exploited by the communities which do not benefit from regular reticulated central water distribution systems. It is vulnerable to contamination. Tubewells are small in diameter (about 7.5 cm) and are in many cases bacteriologically contaminated due to a lack or inefficiency of the sewerage system. Only some areas with important concentrations of population show signs of overexploitation. Abstraction is moderate as compared with the lower aquifer (150 compared 620 hm^3 per year) and the small yield of the tubewells (0.8 compared to 14 l/s).

2. Lower aquifer

The Puelche semi-confined aquifer is formed by Pliocene-Pleistocene, deltaic fine to medium quartzitic sand. It is encountered at depths of 25 to 50 m and is 15 to 30 m thick over an area of 85,000 km^2 north-east of the province of Buenos Aires. It overlies an aquifer saturated with saline water. Well yields are from 15 to 45 l/s. The waters are of the sodium bicarbonate type, with a salinity of 1000 mg/l. Average permeability is 25 m per day and transmissivity 500 m^2 per day. It is the most developed aquifer in Argentina, especially by the Central Water Distribution systems: National "OSN", Provincial "OSBA", municipal and cooperatives, and industrial. It is also used for irrigation of orchards, flowers and other agricultural uses. Owing to the increase in demand, groundwater development increased considerably. As a result, the piezometric level decreased by about 40 metres, and well yield also diminished. By now (1991), few wells yield more than 15 l/s in the overexploited areas, and salinity has increased. Contaminants have also been identified in groundwater samples: nitrates up to 200 mg/l and heavy metals (Cu, Pb, Hg, Zn), phenols and detergents. As a result, entire batteries of wells were abandoned and surface water was brought in from Rio de la Plata.

No corrective measures have yet (1991) been taken. In fact a water law has recently been enacted by the Province of Buenos Aires, which aims to regulate the extraction and use of waters, both surface- and groundwater, so as to protect their quality.

Similar problems are experienced in the city of Mar del Plata, located 400 km south of Buenos Aires, on the Atlantic Coast. Its permanent population is 500,000, whereas the tourist population during summer (December to March) is about 2 million, thus creating a strong change in water demand between summer and winter. All water supplies originate from a Quaternary, limey sand aquifer overlying Paleozoic quartzitic formations. The Quaternary aquifer is up to 70 metres thick. Its permeability is in the range of 10 to 15 m per day and transmissivity 500 to 700 m^2 per day. The water distribution network has been in operation since 1913. The first sign of sea-water intrusion materialized in 1943 as the result of a dramatic lowering of water levels. Wells were abandoned and a new battery of wells was created 6 km to the north, farther from the shore.

B. Brazil

In the course of the last two decades, groundwater development intensified as a result of the higher costs of storing and treating surface water and also because of a better understanding of the advantages of groundwater. During that time, some 200,000 tubewells were drilled by municipalities and industrial companies, and more recently by farmers, for irrigation. Most of the tubewells are 6 inches (11 cm) in diameter and less than 100 metres deep, but about 30 per cent exceed 200 m. However, in the large sedimentary basins with extensions from 10,000 to 1,300,000 km^2, mostly of Paleozoic and Cenozoic formations, several thousand wells 500 to 2000 m deep have been drilled and are tapping vast confined sandstone aquifers.

About 30 per cent of the population of rural areas, 90 per cent of the industries and 50 per cent of urban dwellers use groundwater, in sum about half the population of 140 million.

Overdraft has been observed in two areas of the semi-arid zone (Simplicio-Mendes-Gurgeia projects, Piauí State; and Maiza project, Rio Grande do Norte State) where groundwater is developed for irrigation. The main problem is deterioration of groundwater quality with increasing concentrations of sulphates and chlorides. Nevertheless, the projects generated economic benefits with a positive impact on social development. Problems are also generated by poor use and mismanagement of the resource in the sense that much of the water extracted from aquifers is wasted needlessly.

In several coastal areas, where extensive groundwater development is taking place, problems have been identified and investigated. That situation is due to mismanagement, defective well construction and operation, and groundwater pollution by sewerage and industrial effluents. In spite of these problems, groundwater exploitation has significantly contributed to the socio-economic development of the regions concerned. But it has induced a large increase in drilling activities and no enough skilled professionals were available.

In fact, in Brazil overexploitation is insignificant except for some particular locations, where a moderate decline in water levels has been observed. Inadequate design of wells had propitiated contamination of good quality aquifers by mineralized waters originating from overlying strata.

In Brazil, groundwater is a privately owned resource, free of charge and control-free, especially when used for industry and agriculture. To offset the effects of mismanagement, professional and scientific organizations are exerting considerable effort to implement water legislation, enacted in 1934. Since 1982, efforts have been made to institute a water tax for all users, finance water research programmes, organize data bases and set up training programmes in the field of water resources.

C. China

Semi-arid conditions prevail in northern China where most groundwater development takes place. Conversely, in the humid climate of southern China, groundwater resources are underexploited.

In northern China, overexploitation is a problem of both regional and local magnitude. Such exploitation, however, has also had positive results by increasing the potential for direct infiltration, rainwater and runoff infiltration. In the plains of Henan and Hebei provinces, in areas where groundwater levels were only 1 to 2 metres below the salinized ground surface, groundwater development has induced positive results by lowering water levels (mining the reserves). The salt has been washed out of the soils and agricultural production has increased. Evapotranspiration loss has been greatly reduced. The need to develop better irrigation systems in areas short of water has appeared, in order to save as much water as possible. The main problem is attaining better water efficiency in irrigation.

In recent years, measures have been taken to reduce pumping rates, for example from deep aquifers in the Taingjin city area, which put a stop to land subsidence (it could similarly be stopped in Shanghai). Although groundwater management has improved, especially with regard to the water supplies of major cities, consumers do not pay a realistic price for water and it is heavily subsidized. Water management thus needs to be strengthened from the administrative and legal points of view. Drilling of new production wells should be properly planned.

Some wells which were located, constructed and operated irrationally should be closed and replacement wells drilled. In areas where overpumping is a threat to the environment, pumping rates should be reduced. Public awareness should be increased and joint development and use of various sources of water organized, especially in river valleys, maximizing bank storage.

D. Egypt

A debate has been going on in Egypt for some time on the subject of renewable and non-renewable groundwater resources, especially with respect to the recharge of the vast Nubian Sandstone aquifer. As the effects of recharge in the upper parts of the aquifer - if recharge occurs - are not to be felt in northern Egypt for centuries, if not millenia, the debate is mostly of scientific interest.

Meanwhile, artesian well fields in many oases in the south-west, tapping the Nubian sandstone aquifer have experienced reduction of their hydraulic head and no longer flow; they have been used for years and water levels are falling. Of more immediate concern is the salinization of soil and of groundwater on the edge of the Nile Delta (Wadi El Natroon, from 600 mg/l in 1979 to 950 mg/l in 1990) due to extensive pumpings and recent drought years which have considerably reduced the Nile flows and, therefore, recharge of the Delta aquifer. Crops have been lost. New types of crops - more salt-resistant but also less profitable - have been developed, such as olives. Salt-water intrusion has increased along the Mediterranean coast and also the coasts of the Sinai peninsula.

Extensive groundwater development is relatively new in Egypt, having started in the 1960s. There is little knowledge and control on the drilling of wells, installation of pumps and patterns of pumping. While such controls may be necessary in some areas with extensive development, one may consider that groundwater resources are largely underexploited in Egypt, taking into account the huge and largely untapped groundwater reservoirs of the Nubian Sandstone aquifer. In addition, in areas irrigated by Nile water, excess irrigation water and leakage from canals have resulted in waterlogging. This undesirable groundwater must be removed by means of drainage or pumping. Drainage water is evaporated in artificial lakes.

E. Guinea-Bissau

Thus far, no significant problems of groundwater overexploitation have been experienced. However, the ongoing large-scale groundwater development (3 hm^3 per year) of the Maestrichtian aquifer in the coastal area for the water supply of Bissau, the capital, may generate sea-water intrusion. In the southern part of the country (Costeira) well water has been salinized as a result of extensive development. It would be worthwhile to carry out geophysical surveys to site wells for tapping deep freshwater aquifers. It would be advisable in the Bissau area to monitor the water quality of highly productive tubewells so as to detect signs of sea-water intrusion in its early stages.

In Guinea-Bissau, a national network for the periodical observation of water levels has been organized. Also a mathematical model has been devised for the Maestrichtian aquifer in the Bissau area. In the southern part of the country, recharge experiments by means of dams are being carried out.

Water costs do not reflect reality, as water production is subsidized.

A water law will be implemented in the near future. The government has a policy of decentralization of services. In rural areas, maintenance and operation of wells are the responsibility of the local population.

F. Jordan

Good quality groundwater was discovered in a sequence of basalt flows overlying limestone in the Wadi Dhuleil area in northern Jordan in 1965. Water quality in the basalts and limestones was found to have a similar chemical character indicating hydraulic contact between the two units. Recharge occurs to the basalts from the Jebel Dinze in Syria. Groundwater flows south to the Zeiga River.

In the basalts, well yields vary from a few to 400 m^3/hr. In 1970 a safe yield of 20 hm^3 per year was calculated for the aquifer. This threshhold has been exceeded, since withdrawal was about 35 hm^3 per year in 1981.

The most serious consequence of overexploitation, in addition to aquifer dewatering, has been the excessive increase in water salinity, from approximately 400 mg/l to 6,000 mg/l in some wells. It is due mainly to return irrigation flows. Since 1981, groundwater development has diminished as a result of deterioration of water quality. A study recommends a redirection of irrigated areas, a replacement of vegetable crops by fruit trees and drip irrigation to reduce water consumption. Artificial recharge was not recommended owing to high silt loads in flood runoff waters.

G. Lebanon

1. General

Groundwater exploitation problems exist in the Beirut metropolitan area where extensive unplanned groundwater development has taken place during the civil war. Thousands of wells have been built. In some wells salinity has increased to 22,000 mg/l as a result of sea-water intrusion, but exploitation has continued.

To a lesser extent, such problems are also experienced in southern Lebanon and in the Bekaa plain. Water levels have been declining from several to tens of metres, but groundwater quality deterioration affected only a few wells. Some wells dried out and the discharge of some springs declined severely. Wells had to be deepened or replacement wells to be drilled, looking for deeper aquifers.

Groundwater extraction largely exceeded the yield of the springs, which disappeared, and river flows decreased due to well pumping during the dry season, making surface water less reliable for supply and electric power generation. Groundwater reserves have been tapped. In 1984 and 1985 the quality of groundwater deteriorated as a result of saline intrusion. In the Beirut area the effects of intensive pumpings had been anticipated but owing to the country's political problem no attempts were made to control groundwater development (especially since 1975), and the private sector has tried to solve supply problems by means of wells.

The present (1991) situation is not without serious risk for the environment. A review of the condition of the water supply is necessary as well as restoration and expansion of the reticulated water systems and connection to secure sources of water, while closing wells that are a threat to the environment. Surface water discharging into the sea could be used for groundwater artificial recharge.

2. Schematic classification by excessive aquifer exploitation

The effects of mismanaged overexploitation and water table drawdown are different in terms of magnitude and type, so any systematic description or evaluation should encompass these two aspects:

a. The types of problems that mainly arise upon excessive exploitation could be: 1) land subsidence (S), 2) reduction in the available hydraulic head (H), and 3) deterioration of water quality, including sea-water intrusion, contamination by other compounds (D).

b. The magnitude or extent that each of these types has attained can be largely different, starting from (I) slight changes; through (II) significant changes to (III) great changes. This way any aquifer or basin affected by mismanaged overexploitation can be described by a systematic scale, and remedial measures be proposed accordingly.

Table 3 elucidates the limits of different magnitudes and indicates the proper preventive measures towards improving the quality of water or dealing with the imposed situation.

H. Mexico

Arid or semi-arid climatic conditions prevail over 75 per cent of Mexico. During 1990, some 30,000 hm^3 of groundwater were abstracted, about 25 per cent of which (7,000 hm^3) were drawn from reserves. As a result the following unwanted effects were observed: In coastal areas there was sea-water intrusion, abandonment of wells (and related economic losses), salinization of soils and loss of agricultural land.
Inland there was lowering of the piezometric surface, higher water costs, contamination of water by toxic elements such as arsenic (La Laguna), radon and fluorine (San Luis Potosí), subsidence, damage to structures and the obligation to bring water in from distant places.

In 1990 it was estimated that about 80 aquifer units were overexploited, including:

1. Valle de Mexico: with regional and differential subsidence values in the range of 80 to 300 mm per year. Some buildings have sunk to 6 metres below original ground level.
2. Comarca Lagunera (Coahuila) where about 50 metres of the saturated zone had been drained, with a 1.7 m lowering of the piezometric level per year and contamination by arsenic.
3. Costa de Hermosillo (Sonora) where in some areas the piezometric level is below sea level and where sea water intrusion has developed extensively.
4. Valle de León (Guanajuato) where groundwater levels went down 1.4 metres per year.
5. Celaya (Guanajuato), with differential subsidence, and values of about 1.6 metres per year. Other areas with similar problems are: Valle de Toluca (Estado de México), Valle de Mexicali (Baja California) and Valle de San José de Guaimas (Sonora).

Table 3. Classification of the effects of aquifer overexploitation

Type of problem	Magnitude of change	Symbol	Limits of magnitude	General preventive measures	Specific preventive measures
Land subsidence	Slight	S-I	Small cracks (non remarkable magnitude)	If the resource is indispensable, delineate zones of high differential subsidence, and take precautionary measures of any change in surface flow direction.	If available, pump water into aquifer.
	Significant	S-II	Up to 10 cm (vert.)/ meter (horizontally)		Exclude high land subsidence zones from planning.
	Great	S-III	> 10 cm/m great cracks		Evacuate houses subjected to subsidence.
Relative reduction in available hydraulic head	Slight	H-I	< 20% of origial level	Find other water resources from more distant areas, stop future projects requiring greater quantities of water.	Economize in water consumption.
	Significant	H-II	20-60% of original		Freeze project execution.
	Great	H-III	> 60% of original		Pass stronger legislation, close non-effective production sectors.
Water quality deterioration	Slight	D-I	< 1,000 mg/l TDS	Find water resources from other areas, reduce pumping in order to improve water quality.	Economize in water consumption.
	Significant	D-II	1,000-5,000 mg/l TDS		Stop pumping from critical wells.
	Great	D-III	> 5,000 mg/l TDS		Pass stronger legislation, pump only from least-affected wells.

Source: Lebanon country paper

Other valleys, mostly in coastal areas, are experiencing similar problems with generalized sea-water intrusion (water levels under pumping are below sea level) and lowering of the piezometric level at a rate of 0.2 to 1 m per year (average 0.5 to 0.6 m per year).

I. Morocco

The Souss Valley is triangular, about 170 km long, with an east-west orientation between t Atlas mountains, to the north, and the Anti-Atlas plateaux to the south. It opens widely on the Atlantic west of the city of Agadir, with a shoreline of about 40 km. Its area is about 4,150 km^2. The watershed of the Souss River is about 16,000 km^2. The Souss Valley ranks among the most important agricultural regions of Morocco, with 86,000 hectares of irrigated a 39,000 ha of rainfed crops.

Annual rainfall averages 240 mm in the valley, 350 to 800 mm in the Atlas mountains and 250 to 350 in the Anti-Atlas plateaux. The Souss River collects water in the plains, mostly seasonal flood water from tributaries originating in the Atlas mountains.

Most of the groundwater resources of the plains come from a phreatic aquifer occurring in heterogeneous Quaternary lake deposits which include sand, limestone, marly limestone and conglomerate, and unconsolidated coarse alluvium. The thickness of these formations increase from about 200 m in the east to 1,000 m near Agadir.

The hydrogeological characteristics of the aquifer differ widely according to lithologic type the storage coefficient is in the range of 3 to 4 per cent in most formations (up to 10 per cent i alluvium) and the transmissivity coefficient ranges from 100 m^2 per day in limestone to 1,000 m^2 per day in most formations and 10,000 m^2/day in unconsolidated Quaternary deposits

Recharge occurs through direct infiltration of rainfall (6-8%), infiltration of river water in alluvium and underground seepage of the mountainous formations along the boundaries of the valley, return flow of irrigation water and possibly leakage from deep artesian aquifers.

Discharge occurs along the shores into the Atlantic through drainage of the alluvium as riv flow to the Atlantic Ocean, and through such man-made outlets as wells and drains.

The depth to the water table increases from the river bed area (10 to 20 m) to the edges of the valley (100 to 130 m). Water levels have decreased considerably since 1968, from drawdowns of 10-20 m and in some cases 30 m in the fossil bed sectors and to the east, the areas exposed to recharge by surface runoff wells) to drawdowns of 40 m in the middle valley (Guerdanc), at a rate of 2 m per year.

The mean yearly recharge is estimated to be about 220 hm^3 per yr (240 hm^3 per year including return flow from irrigation). In 1985, a dry year, it barely reached 160 hm^3, while i 1979, a humid year, it reached 335 hm^3. The groundwater flow to the ocean is about 20 hm^3 per year. In 1985, more than 400 hm^3 of groundwater were abstracted, mostly by pumping. Over the period 1971-1986, the average depletion was 150 hm^3 per year (from 60 hm^3 in 1971 to 250 hm^3 in 1985-1986), as a result of extensive development of groundwater an also a succession of dry years. The amount of groundwater in storage is considerable, howeve if the steadily increasing lowering of the piezometric surface persists (75 cm/year in recent years), groundwater development for agriculture may prove uneconomical for the mid-term.

Groundwater development which did not exceed 0.25 m^3/s in 1940 has been increased 50 fold, up to 12 m^3/s currently (1991). The area irrigated has steadily been increased at a rate averaging 1,000 ha per year. As a result of extensive development, traditional underground drainage galleries - similar to the khanats of Iran - and springs occurring in the river bed or close to it have practically dried out.

In 1990, 425 hm^3 of groundwater were abstracted - about 400 for irrigation and 25 for community water supplies (including 15 for the urban area of Agadir and its surroundings).

The recently devised water plan aims at comprehensive, integrated development manageme of water resources in order to minimize water loss, to optimize recharge, to prevent sea-water intrusion in the coastal area, and the valorization of water resources especially for irrigation purposes. To achieve those objectives the following actions have been considered, some of which have been achieved, and others are in progress. A dam was to be built in Aoulouz, where the river leaves its mountainous watershed and enters the plain. The dam, which was to be completed in 1991, will retain flood water, which will later be released according to a scheme intended to maximize its infiltration in the dry alluvium. Small dams are being built o the High Atlas tributaries, mostly for flood control and irrigation of piedmont areas, and sever dykes cross the river channel to slow river flow and increase bank storage.

A mathematical simulation model has been devised to optimize the availability of water resources (surface water and groundwater) through the processing of data on water resources and water utilization. A special allocation of 45 hm^3 of surface water has been made for the irrigation of the Sebt El Guerdanc area in the middle valley, where the drawdowns have been particularly severe. The balance of surface water resources available will be directed at aquife recharge, up to 105 hm^3 per year.

The comparison of water demand and water availability projected for the period 2020-2030 shows that by then groundwater resources may have been depleted, especially in the Sebt El Guerdanc area, southeast of Agadir, where the piezometric level is already at 130 m below ground surface.

The model has also demonstrated that by 2020 or 2030 the fresh groundwater levels along the coast will have been depleted from 10 to 30 metres, thus triggering sea-water intrusion. Additional work is performed on the model to determine the feasibility of remedial measures. "Scenarios" are being considered which deal with:

1. A reduction of water demand - especially for irrigation,
2. Desalination of sea water to serve the needs of the urban areas of Agadir including those related to the tourist industry,
3. Enforced regulation for limiting groundwater withdrawals, and a cost policy for water - wi special measures in favour of small farmers,
4. Increased efficiency of the water distribution networks so as to minimize losses,
5. Developing in the public an awareness of the scarcity of water to avoid unnecessary waste, and
6. Introduction of water-savings technologies such as drip irrigation and sprinkler irrigation.

Many traditional farmers have experienced total loss of irrigation water as shallow wells, traditional drainage galleries and springs dried out. As a result, they have been looking in increasing numbers for low-paid jobs as labourers in the modern agricultural sector.

Efforts are now being made to rehabilitate the traditional sector through the irrigation of some 20,000 hectares by means of groundwater developed by 120 boreholes, 80 to 140 m deep Total yield to be delivered per borehole will average 1 hm^3 per year. As of 1991, there have been completed 61 boreholes and 3 large-diameter wells, which will produce 62 hm^3 per year for the irrigation of 9,700 ha. The project was expected to be operational in 1992. A source o environmental concern is the increased utilization of fertilizers and pesticides, coupled with the reduction of irrigation water.

In conclusion, the survival of the Souss Valley as a major agricultural region of Morocco, especially for cash crops, will require tight controls of groundwater extraction, maximization o the value of water and, above all, close monitoring in the execution of the water plan, includin the day to day maintenance of data bank systems and adjustment of the water management model.

The Berrechid aquifer example was presented informally at the Workshop. The Berrechid Plain, south of Casablanca, is irrigated from groundwater sources. In its lowest part, the soils are relatively impermeable and flooding occurs, as drainage potential is very low. Over most its area, however, infiltration potential is high.

The storage capacity of the reserve has been assessed at 600 hm^3, which, considering the dimension of the plains and the occurrence of dry years, would normally be considered insufficient to secure sustainable development. However, through a rational pattern of groundwater development, the specific conditions mentioned above would allow for the utilization of the regulatory capacity of the aquifer over periods of 2 or 3 years. The possibilit of artificial recharge seems to exist. Also, intensified pumping of the slightly brackish water in the centre of the plain would permit its replacement by better quality water, thus enhancing agricultural development.

J. Papua New Guinea

In Papua New Guinea rainfall is high, from 1,300 to 6,000 mm per year. Hence there are no actual shortages of water. However, in the coastal areas and on small islands, surface wate may be either contaminated or inadequate, and groundwater exploitation causes saline intrusion in the dry season. The problems of aquifer overexploitation in Papua New Guinea are local, limited to certain areas, owing to weather conditions (long dry season), geology (impermeable rocks with slow infiltration rate) and, in many cases, mismanagement.

Hydrogeologic monitoring is inadequate, with little data on piezometric levels. Aquifer overexploitation is usually evidenced by poor water quality and saline intrusion. There is a shortage of trained people in water resources management and of funds for studies dealing with groundwater resources assessment and planning.

Groundwater problems are limited to coastal towns and small islands. Most of the problem of aquifer overexploitation are the result of lack of knowledge and mismanagement. Planning of the wellfields and control of pumping are poor. Wellfields have been constructed as near to a town as possible to lower costs, and not always in the most favourable areas from the point of view of water resources availability. In small islands, sea-water intrusion is possibly caused by excessive pumping from wells. Infiltration galleries may constitute a better solution.

Groundwater resources may be underexploited in Papua New Guinea. Proper hydrologic and hydrogeologic surveys are required to obtain data for planning optimal groundwater exploitation. The most severe problems caused by groundwater overexploitation are in the tow of Rabaul, a coastal town of 30,000 inhabitants, the capital of East New Britain Province, whic is completely dependent on groundwater. It is located in a volcanic area, with very permeable volcanic sands. The supply boreholes are in the town area, only a few metres above sea level. By the end of the dry season the water is brackish throughout the well field. The population o the area has substantially increased during the last 20 years. Adverse effects of overexploitatio of the aquifer in the town area had already been foreseen by the early 1980s. Water quality suffers from saline intrusion more than expected. It has been proposed to find a new source o water for the town, but lacking funds the proposal never materialized.

At present it has become impossible to supply the whole town from the existing source. In 1991 investigations on another aquifer 6 km from town were to be undertaken. This aquifer is also situated near the coast and its exploitation must be planned and controlled properly so as t avoid a recurrence of past problems. This may prove difficult because of shortage of personne and funds. Water users are not used to reticulated water supply schemes. There are many leakages through illegal connections which are not properly installed.

K. Peru

In addition to the serious situation which has developed in the area of Lima (the capital), where groundwater levels are falling at a rate of 2 m per year, and in some cases 5 m per year (about 30 m in the last 20 years) as a result of intensive exploitation (650,000 m3 per day for the community water supply only), there are other areas in the country, especially along the Pacific Coast, such as Trujillo, Chiclayo, Ica and Piura, where the threat of overexploitation a its consequences are serious.

Also in the agricultural area of La Yarada, water levels are declining at a rate of a metre p year and sea-water intrusion is advancing. While mining aquifers for irrigation purposes may be an economically viable solution and may be a source of social benefits (farmer cannot pay for surface water developments), the sustainability of the water supply in urban areas, where groundwater is the only water source, must receive full attention.

L. Philippines

As of 1991, two places in the Philippines have experienced progressive and substantial groundwater quality deterioration by saline intrusion due to overpumping, namely: the Greater Manila Area (Metro Manila) in the major island of Luzon, and Cebu City in the Visayan island of Gebu. On-going studies as well as future surveys may reveal the existence of similar problems in other places of the Philippines.

Metro Manila covers a total area of 1,075 km^2. Piezometer changes show an average dewatering of about 40 m in two years with some local minima reaching 120 m below sea leve Change in the chloride content of groundwater in Metro Manila from 1981 to 1983 indicated a average increase of greater than 400 mg/l. From 1974 to 1982, the volume of mined groundwater was estimated at 530 hm^3, based on a freshwater recharge rate of about 140 hm^3 per year.

Cebu City experienced a period of rapid growth during the early 1970s, resulting in a situation where the water supply system of the city was outstripped by demand. Unplanned we drilling proliferated, resulting in sea-water intrusion into the aquifer. Various salinity surveys have resulted in significant shifting of the 50 and 250 mg/l isochlors during the same period. Since then, exploitation of the groundwater resource and well-drilling operations in Cebu City have been placed under control.

In Metro Manila and Cebu City the water utility companies that own and operate the two systems were constrained to search for, and found new sources of water. Without the pressure of the situation, the alternate surface water sources would not have been developed in so short a time.

Groundwater exploitation has had a positive effect on socio-economic development now tha the Philippines is experiencing (1991) a serious drought. Fortunately, groundwater sources for water supply, which comprise about 90 per cent of all sources of the country outside the Metro Manila area, are only slightly reduced by the drought. Meanwhile, water supply, hydropower and irrigation systems that are dependent on surface water sources are being severely affected b the drought.

M. Thailand

The Bangkok metropolitan area is situated on the delta and flood plain of the Chao Phraya River. The city covers an area of about 1565 km^2 with a population of 5.5 million. More than a third of the water needs of the metropolitan area are met through groundwater pumping from aquifers under the city. These strata are part of the large aquifer system of the Lower Central Plain, which extends about 200 km from north to south and about 175 km from east to west.

The Lower Central Plain of Thailand is a graben containing clastic sediments. The surface strata overlying the basement were described as fluvial and deltaic sediments aged from Recent to Oligocene. The topmost stratum is called the Bangkok Clay. It is about 20 m thick in the Bangkok area and consists of 12 m of soft marine clay overlying 8 m of dry clay. Geologic, hydrologic and geophysical studies have determined that the Bangkok area is superposed on eig aquifers extending to a depth of about 660 m; these include the Bangkok aquifer (50 m zone), Phra Pradaeng aquifer (100 m zone), Nakhon Luang aquifer (150 m zone), Phaya Thai aquifer (350 m zone), Thonburi aquifer (450 m zone) and Pak Nam aquifer (550 m zone). Groundwat is mainly developed from the Phra Pradaeng, Nakhon Luang and Nonthaburi artesian aquifers. At present (and since 1981), withdrawals are estimated to be in the range of 1.3 hm^3 per day.

Withdrawals of groundwater from aquifers underlying the city of Bangkok, mainly for municipal supply and industrial use, which have increased over the years, have exceeded the natural recharge to the aquifers, as shown by the rapid decline in piezometric levels from a few metres below the surface in 1955 to more than 50 m in 1982. The decline in artesian head has resulted in the compaction of clays and land subsidence as well as contamination of fresh water supply by salt water encroachment. Several wells had to be abandoned or rehabilitated.

More than 4,550 km^2 of Bangkok has been affected by land subsidence between 1960 and 1988. Maximum subsidence is due to the soil layer compression at 10-200 metres depth in response to reduction of the piezometric levels in the aquifers. As a result, seasonal flooding o populated areas during the rainy season is common and has often caused property damage, inconvenience and loss of human lives, especially in the period between 1983 and 1986. The damage in these years amounted to hundreds of millions of US dollars. In 1983 alone, the damage was about US$ 240 million.

Many problems are generated by subsidence, such as damage to structures and drainage systems, disruption of topographic benchmarks and impacts on urban activities. A recent investigation by the Japanese International Cooperation Agency predicted that Bangkok would sink below the mean sea level by the year 2000 if pumpage continues at the present rate. Overdraft of groundwater without compensation recharge causes piezometric levels and pore pressures to decline. In any area where an aquifer is connected to the sea, salt water will gradually replace fresh water. The deterioration of groundwater quality is also caused by the migration of the mineralized water from the higher pore pressure areas in the clay layers into t sand layers. Groundwater in the Bangkok aquifer (50 m zone) is now so heavily polluted that it is not suitable for consumption. Several wells which tap the lower aquifers are experiencing li problems.

From 1978 to 1982, the National Environmental Board of Thailand conducted a comprehensive investigation of land subsidence caused by deep well pumping in the Bangkok area, in cooperation with the Royal Thai Survey Department, the Department of Mineral Resources and the Asian Institute of Technology. Based on the results of the study, land subsidence has been strongly linked to extensive deep well pumping. For the purpose of formulating a strategy to solve these problems, the entire area of the Bangkok Metropolis, Nonthaburi, Pathum Thani and Samut Prakarn is now subdivided into three zones as follows:

Zone 1 covers the area in which land subsidence exceeds 100 mm per year and the groundwate head is decreasing rapidly.

Zone 2 refers to the area in which land subsidence is in the range of 50 to 100 mm per year, and where groundwater level declines are somewhat lower than those of Zone 1.

In Zone 3, land subsidence is less than 50 mm per year and groundwater level does not decrea significantly.

For controlling and mitigating groundwater depletion and land subsidence, it has been decided to establish remedial measures and methods to prevent ground surface from lowering more than 500 mm under the level measured in 1982; and also to arrange for preventing furthe lowering of groundwater levels in the critical area of zones 1 and 2 from year 1987 and for raising it from the year 1988 onwards.

The main measures which were approved by the Cabinet on 15 March 1983 are as follows

1. The National Economic and Social Development Board and government agencies concern are to provide raw surface water for the Metropolitan Waterworks Authority (MWWA) and the private sector in critical zones 1 and 2 from 1986.

2. The implementation of the MWWA Master Plan on Water Supply Improvement Project a the project to improve water supply services in the outer part of Bangkok is to be supported an accelerated so that the projects proceed on schedule.

3. MWWA must stop using groundwater in critical zones 1 and 2 from 1987 onwards. However, owing to problems in conveying surface water to those zones, MWWA continued to use the groundwater until the middle of 1989.

4. The Groundwater Act of 1977 is to be enforced so as to control groundwater exploration and pumping.

5. Fees on the use of groundwater should be levied at a rate comparable to the public water supply rate.

6. The Department of Town and Country Planning is to revise the land use plan within the Comprehensive Plan in such a way that the critical zones facing groundwater depletion and lan subsidence in Bangkok are taken into account.

The supporting measures include, among others, an experimental study or research to be conducted by the Department of Mineral Resources, MWWA, Public Work Department and th office of the National Environment Board to assess the feasibility of recharging the aquifers in order to raise the groundwater level up to the original level. Mathematical models have been developed to predict subsidence and recharge response. Monitoring and evaluation of the resu of the remedial measures are carried out periodically so that plan modifications to meet the objectives can be undertaken.

Before remedial measures were implemented, that is in 1983, groundwater levels in central Bangkok were 50 m below ground level. After wells were registered and pumping allowances reduced, water levels measured at the Nakhon Laung aquifer rose more than 16 m in 1990. However, on the outskirts of Bangkok, where development has crept in and the existing supply could not meet rising demand, groundwater levels continued to decline.

On the basis of data collected from 41 monitoring stations using automatic subsidence recorders, it was assessed that in the Bangkok Metropolitan Region, the total subsidence in the 1-100-m layer which, before implementation of remedial measures averaged 30-50 mm per yea has decreased to about 20-40 mm per year. For the 1-200-m layer, the present rate is about 40 mm per year as against 60 mm per year before the implementation of remedial measures.

Groundwater extraction in the Bangkok area will undoubtedly continue as the city grows and, as a result, land subsidence and contamination of groundwater resources are bound to reoccur. Remedial measures should be conducted with proper planning and sound managemen of groundwater and surface water. It is necessary to monitor and evaluate the results of remedial measures so as to modify them, if appropriate. Among others, international cooperation will be sought for further research on methods and feasibility of recharging the aquifers.

In the alluvial aquifer in the lower Central Plain Samut Prakarn, south-east of Bangkok, la subsidence has occurred in that industrial area as a result of extensive pumpings. Wells were abandoned and new wells were drilled down to depths of about 600 metres, to reach good-quality water. Also, in Samut Sakorn, an industrial area southwest of Bangkok, water levels which are declining rapidly are under close monitoring.

In the Northern Plateau the limestone aquifers overlie rock salt and as a result, groundwate may be brackish or salty. As groundwater development intensifies, the risks of widespread damage to water quality are becoming of concern.

N. Venezuela

In Venezuela, some 30,000 to 40,000 wells provide about half of the water consumed for community water supply, industrial use and irrigation. In some areas, owing to unplanned development by means of uncontrolled water drilling which renders necessary the enactment of legal and regulatory measures to serve as a legal basis for the activities of organizations responsible for water resources management, such as the Ministry of Agriculture and Natural Resources.

The damages experienced by aquifers are reflected in the steady decrease of water levels in wells, which has eventually resulted in vast cones of depression and salinization of groundwate Additional damage to water quality has occurred through infiltration of sewage water and wate from oxidation lagoons. In some areas aquifers have been completely destroyed as a result of mining activities, such as the extraction of sand and gravel from the infiltration or the saturated zone of preexisting aquifers. That situation developed in particular in the following areas:

1. Valencia Lake watershed

The watershed area (3,200 km^2), in the north-central part of the country, is covered over more than a third of its surface (1,200 km^2) by alluvium and lake sediments. It is a closed bas without runoff to the sea, with Valencia Lake in its central part (elevation, 406 m). The main cities of the area are Maracay and Valencia, with most industrial and agricultural activities of the region in their vicinity. Groundwater accounts for 85 per cent of the water supplies developed in the basin. In the eastern part of the basin (Maracay aquifer), water levels in well have been falling continuously over the period 1969-1983, with the highest value (24 m) east o Maracay city. In the industrial zone of La Hamaca, near Maracay, water levels fell below the level of the lake. For the period 1970-1982, water levels decreased by 7 to 14 metres between Flor Amarilla and El Recreo, that is, about 10 m below the lake. In the northern part of the basin (San Joaquin aquifer) water levels decreased by 3 to 17 m. South of the expressway from Maracay to Valencia, there is a risk of lake water intrusion. To the south (Güigüí aquifer), water levels have been falling since 1958. From 1961 to 1978 water levels decreased 8 m in Asentamiento Campesino la Linda; then they increased, probably as the result of a series of we years (1978-1982). Extensive groundwater development in the Valencia Lake basin resulted in both deterioration of water quality and infiltration of contaminated water from streams and ponds. Total dissolved solids in groundwater gradually increased from the rocky edges of the river to lacustrine deposits towards the lake along two intrusion fronts. One is the flat area ending with the western shores of the lake, where the mouth of Rio Las Guayas is located: the other in the south-western coastal area. In 1983 the intrusion expanded widely. In the coastal area the TDS of groundwater exceeds 1,000 mg/l and up to 3,800 mg/l north-east of La Culab peninsula (San Joaquin aquifer). The intrusion of lake water penetrated 1 to 2 km from the south-western shore. A new intrusion front developed from the north-east at the mouth of the Guey river.

2. Maracaibo aquifer

South-west and west of Maracaibo city, a vast granular aquifer occurs, corresponding to E Milagro formation for the most part over an area of 2250 km^2$. Recharge takes place in th west (up to 20 hm^3 per year) from rainfall and runoff infiltration. Groundwater extraction is in the range of 60 hm^3, of which about 50 are directed at the water supply of Maracaibo city. As a result of this overdraft, a saline intrusion front developed from the lake into the aquifer. North of the city of Maracaibo the salinity of groundwater exceeds 8,000 mg/l.

3. Barlovento

Barlovento is one of the main tourist regions of the country, with great agricultural potenti thanks to its good soils. Water quality 7 km away from the coast is still good with salinity less than 1,000 mg/l, but it increases dramatically (about 2,400 mg/l at 6 km from the coast) as a result of extensive development.

4. Isla de Margarita

Isla de Margarita (960 km^2) is the most important centre for tourism in Venezuela. In addition, agriculture is fairly well developed, especially in the eastern part. Five aquifers have been recognized in the island, of which two are overexploited: "Puerto Fermin" which has experienced significant intrusion of saline water with concentrations exceeding 1,000 mg/l and reaching 2,000 mg/l near the coast, and the aquifer Pedro González, where groundwater is stil of good quality.

5. Valle de Tibor

The aquifer is composed of Quaternary alluvial and lacustrine deposits, up to 230 m thick. The valley is a major agricultural area. Owing to the extensive exploitation of groundwater, water levels have dropped more than 50 metres in the north and nearly 100 m in the south. Detailed studies have been made which have shown that the groundwater resources will have been depleted within 20 years if no conservation measures are taken.

O. Viet Nam

The waters of the Red River are extremely polluted by industrial effluents and pesticides. Other rivers are also polluted. As a result, urban water supplies are in many cases developed from groundwater sources, which in turn tend to be overexploited. That is the case in Ho Chi Minh City where in 1960 groundwater was extracted at the rate of 80,000 m^3 per day and wate quality was good. Currently (1991), water production exceeds 160,000 m^3 per day, salinizatio from sea water has occurred in many wells, up to 10,000 mg/l in some cases.

In Hanoi, monitoring of water resources was initiated in 1988, especially as regards water quality, well yield and water levels. Water table drawdown is from 2 to 10 m per year. It wa concluded that exploitation should be discontinued for half of the wells. Groundwater levels have been dropping, and subsidence increased from 2 to 5 mm per year up to 20 mm per year. This situation is having a serious negative impact on the environment and socio-economic conditions. Close monitoring is needed.

P. Yemen

Dry, arid to semi-arid climatic conditions prevail throughout most of Yemen. Potential evapotranspiration exceeds rainfall during most of the year, with the exception of areas along t western escarpment. Regional climate ranges from the hot, tropical conditions of the coastal lowlands, to the temperate character of the mountainous highland.

Annual rainfall typically varies from less than 50 to more than 900 mm. Reported values for free water surface evaporation rates along the coastal Tihama Plain on the Red Sea range from 1,900 to 3,400 mm per year. Estimates of 1,650 mm per year are reported for zones at about 2,500 m metres, such as the central highlands.

The outstanding characteristic of the country's water resources is the limited occurrence an availability of surface water. Storage of surface water in lakes, ponds and streams is almost non-existent. Nearly all streams are ephemeral and the few that are permanent carry only low base flows.

In most zones where groundwater development is not too difficult, abstraction has increase enormously in recent years. As a consequence, water balances are being modified and in some areas the effects of overexploitation can already be observed. Therefore, a thorough groundwater level monitoring programme in such areas have high priority.

In general, both the design of waterworks and the rational management of water resources in the country are still handicapped by a lack of hydrologic and hydrogeologic data. For that reason, high priority should be given to:

1. Hydrologic networks for runoff, rainfall and groundwater levels: establishing new stations and new networks, improving existing stations and the quality of these records and guaranteein continuity of the records.

2. Accessibility of databases, proper organization of the archive, by timely processing of data and by providing access and retrieval services.

3. Field studies, especially in areas where lack of hydrologic information hampers economically optimal development or prevents appropriate management of water resources.

The overexploitation of aquifers is not only the result of excessive pumping from the aquifers, or of bad management. It is also the result of inadequate studies. The rational management, correct assessment and sound planning of groundwater use are possible only if th hydrological conditions are known.

Calculation methods used by firms working in Yemen may not apply to groundwater conditions in the country, which are characterized by water table, layered, anisotropic, commonly leaky aquifers, often partially penetrated by large-diameter wells with inflow from t bottom, influenced by high capillary rises.

Much emphasis should be given, therefore, to the quality of data on the basis of which mathematical models of aquifers and calculations for allocating groundwater use are constructe More information is needed on aquifer storage estimation, deduced either from pumping tests o monitoring of water table fluctuations.

The typical geologic profile of wadi alluvial sediments comprises layers of sand, loess, gravel, conglomerates, clay, sandstone, debris and weathered bedrock. Interpretation of pumping tests in such aquifers using conventional methods derived from schematization of homogeneous aquifers may lead to erroneous estimation of transmissivity and storage coefficients. Whereas transmissivity is characteristic of the whole aquifer profile, the storage parameters are characteristics of but a small part of the aquifer where the groundwater level fluctuates during the test. The rate of water-level decrease depends on the water table storage coefficient distribution in a vertical direction, for example when using groundwater for irrigation. In Yemen all aquifers are water table or leaky layered, anisotropic aquifers; wells ar partially penetrating, many are of large diameter and recharge is seasonal.

In many arid countries, and especially in Yemen, aquifers serve to store water infiltrated from floods and accordingly, may be the only source of water during the dry period. Therefor development of water resources in such areas entails development of spate recharge and groundwater use, and the maintenance of a mutual balance between spate recharge and groundwater abstraction.

Q. Yugoslavia

In the Zagreb area (Croatia-western Yugoslavia), groundwater levels have declined about 5 metres over the past 10 years. Groundwater extraction there is now in the range of 4.5 m^3/s. Artificial recharge might be a solution to that problem, but a decision has been made to construct a dam.

In karstic areas and especially along the Adriatic Coast, where industries and tourism are developing, the natural outflow of karstic springs is now insufficient to cover demand, by 30 p cent. New intake structures are constructed and the existing ones are rebuilt so as to expand them. As a result, an overexploitation of karstic reservoirs takes place which may cause sea-water intrusion of as much as a kilometre inland, and reaching fairly deeply (more than 10 metres).

All problems can be corrected with a better knowledge of hydrogeological conditions, bette monitoring of groundwater quality and better water resources management, including the development of artificial recharge schemes.

In karstic-coastal areas, overexploitation problems arise only during the summer season, bu several at a time. Conversely, in large mountainous karstic areas inland, groundwater reserves are enormous and practically undeveloped. In the end, water supply is only a financial resources problem, not a water availability problem.

Annex V

THE DETRIMENTAL EFFECTS OF GROUNDWATER OVEREXPLOITATION IN DEVELOPING COUNTRIES (DTCD POSITION PAPER)[1]

A. General

In the course of the last 20 years or so, groundwater resources have been extensively developed at a pace never before experienced, for urban, industrial and rural water supplies, as well as for irrigation and agropastoral purposes. The occurrence of droughts and launching of the International Drinking Water Supply and Sanitation Decade have accelerated the process. In many countries, especially in Western Asia, the search for "food security" and consequently for "water security" played an important role in the groundwater development proess. In fact boreholes are now constructed in large numbers whenever spring water or surface water is not permanently available nearby, and where supplies originating from traditional hand dug wells are insufficient in terms of quantity and quality.

It is well known that extraction of groundwater by means of motorized pumps results in lowering water levels in wells and boreholes and that the conservation of resources for the long term requires that pumping rates to not exceed the "safe yield" level. The concept of safe yield encompasses both hydrologic and economic parameters which may vary considerably according to local conditions.

Any extraction of groundwater from an aquifer depletes the water stored underground, transforming it either into waste water or evaporated water, depending on its use. If water is used liberally for irrigation, a part of the pumped water will infiltrate and recharge the aquifer. In the percolation process, however, chemical products used in modern farming, such as fertilizer (nitrates) and pesticides, may infiltrate the groundwater body.

The overall groundwater resource may be considered renewed if, within a year or at most a few years, the amount of water extracted is compensated by a recharge corresponding to water resources which previously had been lost to sea or inland areas where they evaporated. In many cases, groundwater extraction creates a transfer from a river without really developing a "new" water resource.

The depletion of the resource is measurable in terms of an increase of pumping drawdowns without total recuperation when pumping is discontinued over a substantial period of time. It is

[1] Prepared by the Water Resources Branch, Natural Resources and Energy Division, DTCD, United Nations, New York for the XXIII Congress of the International Association of Hydrogeologists and subsequent Workshop on Groundwater Overexploitation.

also measured in the increasing salinity of well water in coastal areas, fresh water depletion having induced the flow of sea water.

It occurs when one or several of the following adverse natural conditions are encountered:

1. In the case of "fossil aquifers", which were formed during the last pluvial Quaternary period (about 20,000 years ago), the resource cannot be replenished in a perceptible way, if at all, by infiltration of rain, stream or flood water. Fossil water is a one-time resource like oil and minerals. It is "mined" deliberately, and overdraft occurs when the depletion - the lowerin of water levels - develops faster than planned or expected.

2. In the case of aquifers with poor porosity and storativity, such as those formed in crystalline or non-carbonate rock, the small, localized resources or pockets of water can be entirely depleted within short periods of time by pumping. The sustainable yield of these aquifers is quite small.

3. In the case of arid, semi-arid and Mediterranean zones, groundwater has been developed extensively, while recharge from rain, streams and floods is insufficient to compensate for extraction. Even where storage and recharge conditions are extremely favorable, depletion wil occur and increase if groundwater extraction exceeds the limits of an assessed safe yield.

In most cases, damaging effects of extensive groundwater development can be summarily described as follows:

1. There is considerable lowering of water levels, reaching the bottom of existing wells, th rendering them inoperative, or reaching depths beyond which groundwater development is not viable in economic or technological terms.

2. Water quality deteriorates, mainly through salination in coastal or arid areas.

3. The land subsides as a result of the irreversible transfer of water contained in clays into dewatered sandy layers; or there is collapse of soft karstic limestone terranes, thus causing the sinking or collapse of entire land areas, or buildings.

Over the past 20 years, the Water Resources Branch of the Natural Resources and Energy Division (United Nations Headquarters, New York), through the execution of field projects, advisory service missions and compilation of reports on the groundwater situation in all countries, became acquainted with overpumping situations and their negative impact in developing countries around the world. A brief overview, necessarily incomplete and not entirely up-to-date, is provided below.

B. Asia

1. Eastern Mediterranean and Arabian Peninsula (figure 3)

In **Cyprus** and in **Turkey**, sea-water intrusion triggered by excessive pumping has been observed in a number of coastal areas.

In **Syria**, severe depletion has occurred, in certain parts of the Damascus Plain and locally elsewhere.

In **Iraq**, the salinity of aquifers of the Mesopotamian Plain has increased as pumpings are not matched by recharge from flood waters, as they used to be before the construction of dams on the Euphrates River.

In **Saudi Arabia**, depletion is occurring faster than planned in parts of the Saq Aquifer developed extensively for irrigation purposes. Depletion has also occurred in many other area including alluvial fill around Taif, Mecca and other urban areas.

In **Jordan**, the Disi aquifer in the south-east has been extensively developed for irrigation purposes. Although its safe-yield limits have practically been reached, as modelling studies indicate, further three-fold development is being contemplated.

In **Bahrain**, scores of artesian springs have dried up and sea-water intrusion has occurred in well fields.

In the **United Arab Emirates** the possibilities of the gravel plain aquifer north of Dubai have been exhausted and groundwater is being developed from deep aquifers.

In **Yemen**, extensive groundwater development for irrigation in the Sana'a plain has caused extensive depletion, raising concern over the source of water supply of the Sana'a metropolitan area.

2. Central South and Eastern Asia (figures 2 and 3)

In **Iran** extensive pumping, especially in sub-desertic areas bordering the central desert, ha resulted in the lowering of water levels. Hundreds of traditional draining galleries have dried up.

In the Baluchistan desert of **Pakistan**, the feasibility of artificial recharge is now being investigated as a means to compensate for depletion of aquifers. In the western desert of

Rajasthan (India), alluvium aquifers surrounded by a largely saline environment have become brackish as a result of overpumping.

In other parts of South Asia, severe depletion has occurred in the overdrawn hard rock are of the Indian peninsula, including Tamil Nadu (crystalline basement and its overburden), especially in the Madras area where groundwater has been developed both for irrigation and urban water supply, and Maharashtra (Deccan basalt traps). In the Punjab, alluvium aquifers have been depleted. Sea water has intruded the vulnerable limestone coastal aquifer of norther **Sri Lanka** (Jaffna). In **Bangladesh** the exploitation of deep boreholes has resulted in the dryin up of many shallow tubewells. In Dhaka excessive groundwater development from municipal well fields has resulted in high water costs, land subsidence, and sea-water intrusion in coastal areas.

In Eastern Asia overpumping in areas close to large urban concentrations has caused considerable subsidence in Bangkok (**Thailand**), in Shanghai (**China**) and to a lesser extent in Jakarta (**Indonesia**). In the metropolitan area of Manila (**Philippines**) the water level in boreholes drilled in volcanic formations has dropped by more than 100 metres in less than 20 years. In the **Republic of Korea** the Mesozoic aquifer complex of the urban industrial area of Taegu has been severely depleted. In many cases watertable aquifers in coastal areas are saline or have been salinized over the years and deeper confined aquifers have been largely depleted (Chantoung and Hopei province of **China**, coastal cities of **Viet Nam** and the **Philippines**). T unconfined aquifer of the vast Huang-Huai-Hai plain (320,000 km^2), representing one-third of the total plains territory of **China**, is showing signs of depletion and salinization in several areas. This aquifer is being tapped by well fields supplying large urban areas, including the Beijing metropolitan area, and by more than 600,000 irrigation wells.

C. The Americas

1. Central America and the Caribbean (figures 4 and 5)

In **Mexico** excessive pumping in the Mexico City basin area has resulted in subsidence wit spectacular effects. For example, ancient buildings including Guadalupe Cathedral have sunk several metres into the ground. In many areas of Mexico, a critical situation has developed in terms of lowering water levels and salinization, especially in the Hermosillo, Guaymas, Caborca, Mexicali and Santo Domingo areas in the north-west, the lake region (north-central), and the Celaya Valley in the central area. In the coastal areas of the north-west, water levels have fallen by more than 30 metres.

In the **Guatemala** Valley, where Guatemala City is located, excessive groundwater development has resulted in the depletion of water levels, mutual pumping interference of wells too narrowly spaced, and propagation of pollutants.

In **Nicaragua**, salt-water intrusion has developed near the shores of the Pacific Ocean and of Lake Managua, and mutual interference has been observed in extensively developed areas (Managua-Granada, León and Chinandega).

In **Panama** and **Cuba**, sea-water intrusion has occurred in some coastal areas.

In the **Dominican Republic**, water levels in the Azua plain and La Romana area have been dropping at a rate of 0.3 to 2.5 m per year and saline intrusion has penetrated inland to a distance of 5 km.

In **Haiti**, it is estimated that the main aquifer, that of the Cul de Sac Plain where Port-au-Prince, the capital, is located, is being developed locally beyond the safe-yield limit. Salt-water intrusion has occurred in the coastal area.

In **Jamaica**, coastal cavernous karstic aquifers in Clarendon and St. Catherine have been affected by overdraft and saline intrusion.

In **Trinidad**, northern gravel aquifers east of Port-of-Spain have been intruded by sea wate as have all the southern basin aquifers.

2. South America (figure 4)

In **Argentina**, salinity problems have developed in some areas along the Atlantic coast, in particular in Mar del Plata and Bahia Blanca. In the central plain, "pockets" of fresh water flo on salt water in lens-shaped bodies; excessive pumping has damaged that fragile resource in several areas.

In **Brazil**, the crystalline aquifers of the north-east are quickly depleted in most areas durin the dry periods, owing to their poor storage capacity. This creates emergency water situations and migrations of population. Well-interference problems are common to many urban areas in the south, the south-central, and north-east regions, the latter including Rio de Janeiro and Sao Paulo. Salt-water intrusion has occurred along the Atlantic coast (Recife Olinda). Subsidence due to excessive pumping has been observed in Brasilia.

In **Chile**, overdraft has developed in the area of the capital, Santiago.

In **Colombia**, overdraft has been observed in monitoring wells. Salt-water intrusion has developed on San Andrés Island and on the Atlantic Coast.

In the coastal valleys of **Peru**, groundwater levels have been declining by as much as a metre per year in certain cases. Sea-water intrusion has been observed in Chilca.

In **Suriname**, the salinity of well fields supplying the capital, Paramaribo, has increased du to high pumping rates.

D. Africa

1. North Africa (figure 3)

In **Morocco**, salt-water intrusion has occurred in coastal areas as a result of excessive pumping for municipal water supply and irrigation purposes. Owing to excessive agricultural and urban-residential development in the Marrakesh palm grove, water levels have been considerably lowered. As a result, traditional drainage galleries and irrigation wells have dried up. The process has been considerably aggravated by a succession of dry years. In the middle Sous Valley, east of Agadir, water levels have dropped to 100 metres or more below the surface, thus rendering pumping uneconomical for irrigation purposes.

Along the Mediterranean coastline of North Africa, the modest groundwater resources potential has been exhausted. For example, in the Cap Bon area of **Tunisia**, irrigation water originates from artificial groundwater storage of surface water from the Medjerda River; the coastal area of **The Libyan Arab Jamahiriya** is supplied by "man-made rivers", that is, large diameter pipelines tapping fossil groundwater from vast sandstone aquifers located up to 800 k away, in the Nubian desert.

In **Egypt**, including the Sinai Peninsula, the coastline is practically devoid of local water resources. Water is brought from the Nile by means of an extensive pipeline network. Also, pumping for irrigation in the Delta has generated local sea-water intrusion, and artesian well fields in the "New Valley" (Kharga, Dakhla oases) have been depleted.

2. West Africa (figure 3)

A number of major cities on the west coast of Africa, north of the equator, obtain their water supply from well fields situated not far from the seashore. Sea-water intrusion is always a threat and in most cases, pumping rates are reaching or exceeding the safe yield level. Water-level and water-quality monitoring networks have been set up in some cases. Data collected are processed through mathematical modelling exercises. Among the cities concerned the following are particularly important: Banjul-Kombo area (**Gambia**), Bissau (**Guinea-Bissau** Dakar (**Senegal**), Lomé (**Togo**), Cotonou (**Benin**), Douala (**Cameroon**), and the shores of **Nigeria** near Lagos, Mahin (Ondo State), and in Bendel State.

Inland overpumping is a matter of concern in several areas, including Bornou State in northern **Nigeria**, where the upper aquifer of the Chad Basin has been largely exhausted, and t plateaux of Kanem an Bathaga in **Chad**.

The Precambrian crystalline rocks underlying vast flat areas of western Africa (see figure 3 are poor aquifers in most cases, in terms of porosity and transmissivity. In fracture and quartzite areas, substantial yields are available, but in most cases they are not sustainable unles the aquifer is flanked by a nearby stream, marsh or pond. Most boreholes are fitted with handpumps which are not likely to deplete the aquifer. However, in countries like Burkina Faso, pumping tests which were carried out upon borehole completion have revealed that sever thousand wells could deliver substantial yields, to meet the needs of small towns, or small-scal irrigation.

The tests, however, were in general of short duration. It remains to be seen, therefore, whether the hopes generated for future development will be supported by tests of longer duration.

3. East and Southern Africa

The above statements apply to similar crystalline basement areas of East and southern Afri as well, particularly in **Uganda, United Republic of Tanzania, Botswana, Namibia, Malaw Mozambique** and **Zambia**.

In Djibouti, the well fields which supply the capital are situated in a volcanic region in the coastal area. Fears that salt-water intrusion may move inland have led to the setting up of a monitoring system. In addition, inland lacustrine aquifers in closed basins have been depleted.

In southern **Madagascar** natural conditions are extremely unfavourable, both because of extremely arid climatic conditions, and the geological setting, where karstic limestones prevail. As a result, sea-water intrusion has developed extensively. Elsewhere, alluvium aquifers, with little storativity, have been depleted.

E. Small Islands

Around the world, small islands and islands of modest dimensions are experiencing serious groundwater shortages, as a result of the increasing needs of local populations, tourism, and unsustainable groundwater development. That is the case, in particular, of the **Pacific atolls** (about 100 of which are populated), and other coralline low-lying islands such as the **Bahamas** (figure 4) and the **Maldives**; volcanic islands (**Cape Verde** [figure 3], **Comoros, Mauritius**); crystalline rock islands with alluvium overburden (Tortola in the **British Virgin Islands**, the **Seychelles**); and oolitic limestone islands (**Malta**).

F. Conclusions

1. General

A comprehensive survey of the extensively exploited aquifers in developing countries aroun the world, with comprehensive data collection including pumping water levels, hydrometeorologic and water quality data over the years, and sufficient data processing exercis would probably allow for the determination of simple principles to forecast their future evolutio in various physical and socio-economic environments.

In addition, the experience gained in certain countries in controlling and correcting pumpin patterns, in order to conserve the resource, would be of interest to others. In some countries, however, the issue of "overpumping" is politically sensitive, whether at the national or international level, and data may not be available. It should also be borne in mind that, as soo as news surfaces of the imminent depletion of a groundwater resource, it is accompanied by th risk of users rushing "to collect the last drop".

Be that as it may, it is to be hoped that, through international cooperation with industrialize countries where groundwater overdraft is widespread, and where preventive and corrective measures have been taken successfully, such as for the Ogallala aquifer in the United States, th availability of groundwater resources will be secured for the future in threatened areas of developing countries.

2. Related discussions in recent and upcoming international forums

The problem of overexploitation of aquifers is directly related to the environment and sustainable development of water resources. The United Nations Secretary-General, in his report to the Committee on Natural Resources at its twelfth session in March 1991, emphasized the need for integrated management of water (surface and groundwater) as a finite and fragile resource. This approach is particularly important to ensure the environmentally sound and sustainable development of water resources.

In recognizing the need for integrated management of water as well as for integrated land and water management, the Committee on Natural Resources also stressed the need to develop strategies and action plans at the global, national and river-basin levels - including local and community levels - particularly the need for the participation of all interests concerned. It also expressed support for the International Conference on Water and the Environment, which was to be held in Dublin in January 1992. This Conference was to aim at developing guidelines and time-frames to enable Governments to formulate those action plans, for integrated water resources development and management, as well as international action programmes.

Role of Women In developing countries, it is usually women who are primarily affected by problems arising from shortages of water. Consequently, women need to be increasingly involved in the protection and conservation of water resources. The crucial role of women in various aspects of water supply and sanitation was recognized during the Global Consultation o Safe Water and Sanitation for the 1990s, held in New Delhi in September 1990, and at meeting of the Water Supply and Sanitation Collaborative Council and the Steering Committee for Wat Supply and Sanitation.

Annex VI

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Annex VII

PROJECTS EXECUTED BY DTCD RELEVANT TO OVEREXPLOITATION OF GROUNDWATER

A. Africa

Benin: Water resources master plan (BEN-85-004)
Mathematical model study of the coastal aquifer to evaluate, in particular, the risk of sea-water intrusion through pumping.

Comoros: Assistance in water resources development (COI-86-001)
Study of the risk of sea-water intrusion in coastal wells under pumping.

Mali: Groundwater resources planning (MLI-84-005)
Studied the water balance of hard rock aquifers through detailed and long-term monitoring operations and mathematical modelling in order to determine the safe yield.

Morocco: Study of deep groundwater resources (MOR-78-004)
Through mathematical modelling, studied the potential impact on shallow aquifers of extensive pumping in deep aquifers.

Niger: Planning and management of groundwater resources (NER-86-001)
Through mathematical modelling the mining of non-renewable groundwater resources was studied according to several scenarios.

Togo: Groundwater research in coastal regions (TOG-71-S11)
The interface sea-water/fresh groundwater was identified through geophysical prospecti and the risks of sea-water intrusion induced by extensive pumping were evaluated.

Tunisia: Intensification of groundwater exploitation in northern and central Tunisia (TUN-69-528)
In this study a coastal aquifer vulnerable to sea water intrusion was studied. The safe yield was assessed.

United
Republic of
Tanzania: Hydrogeological map of Zanzibar and Pemba islands (URT-81-001)
Maps were prepared showing the areas vulnerable to sea-water intrusion were excessive pumping to be carried out.

Regional Project (Egypt-Sudan): Transnational project on the major regional aquifer of North East Africa (RAF-82-013)
Studied the potential of the "Nubian Sandstone aquifer", one of the major fossil aquifer in the world, now being mined in several areas, mostly in Egypt.

B. Asia and the Pacific

China: Groundwater resources evaluation of the Huang Hai Hai plain (CPR-81-036)
In the North China Plains under semi-arid conditions, groundwater is intensively developed for irrigation purposes. Studied the water balance, especially the recharge rate, through a mathematical model to determine the safe yield.

India: Hydrogeological and artificial recharge studies Madras (IND-78-029)
In the metropolitan area of Madras and its surroundings, groundwater resources are found mostly in alluvium and in crystalline basement rocks, weathered and fractured. They are extensively developed. Aimed at achieving sustainable groundwater development by adequate management including artificial recharge.

India: Artificial recharge studies in Gujarat (IND-78-033)
Studies areas of Gujarat Province where groundwater resources are overexploited.

Qatar: Assistance in groundwater development and conservation (QAT-82-001)
Qatar is a low-lying limestone peninsula, under desertic climatic conditions. Groundwat resources are limited and vulnerable to depletion and sea-water intrusion. Studied the ways and means to conserve that resource which, until recently, was overexploited.

Republic of Korea: Groundwater research and development (ROK-82-014)
Included pilot studies for determination of the safe yield of exploitation in three hydrogeologic environments: crystalline rock/alluvium, sedimentary complex, volcanics

Regional Projects (Pacific Island Countries): Water resources assessment development and planning in Pacific islands (INT-86-R30 and RAS-87-009)
Many coastal areas exposed to sea-water intrusion induced by the pumping of groundwater were studied.

C. Latin America and the Caribbean

Argentina: Development and control of groundwater hydraulic basins (ARG-70-013)
The safe yields of several aquifers were assessed.

Bahamas: Water resources development and management (BHA-78-003 and BHA-86-004)
The Bahamas Islands are low-lying and quite vulnerable to sea-water intrusion.

Bermuda: Groundwater resources development (BER-79-002)
A mathematical model was established and operated to determine the safe yield of coas aquifers exposed to sea-water intrusion.

Costa Rica: Groundwater surveys in three selected areas (COS-65-502)
Sea-water intrusion in coastal areas, occurring through overexploitation of groundwater resources was studied at several locations.

Haiti: Strengthening of services for groundwater (HAI-79-001)
A mathematical model of the aquifer of "Plaine du Cul de Sac", the largest plain in Haiti, was established and operated to determine the sustainability of the extensive and increasing development of groundwater.

Paraguay: Groundwater development in the Chaco (PAR-72-004)

In the Chaco, groundwater resources are saline or brackish with the exception of alluvi river beds recharged by floods. The potential of that alluvium was studied and the safe yield limits assessed so as to prevent the overexploitation of groundwater, which would endanger its quality.

Regional: (Caribbean Islands) Water resources development and management (CAR-79-R01 an RLA-82-003

Many coastal areas exposed to sea-water intrusion induced by the pumping of groundwater were studied.