Introduction

Take care of the earth and the water:
they were not given to us by our fathers,
but loaned to us by our children.

A nomadic shepherd's saying from Kenya

The issue of water

It will be water that shapes the new century, just as petroleum shaped the one that has just passed. Over the last century the population of the planet has tripled, while water consumption has increased by six or seven times. Consumption of water has increased at double the rate of the population, and as a consequence 30% of humanity does not have sufficient water and each year 7 million people die from diseases caused by polluted water. The forecasts are that in 2025 the world population will be about 8 billion and that the fraction with water scarcity will rise to 50% (Rosegrant et al., 2002). The deficit will be particularly severe in Asia and in sub-Saharan Africa, that is in those very countries that are today among the poorest in the world, but will occur also in regions that today are neither arid or even semi-arid.

In developing countries, where agriculture is an important component of the economy, irrigation uses from 75 to 90% of the fresh water derived from rivers or pumped from aquifers, but also in developed countries, where agriculture employs less than 5% of the inhabitants, agricultural water consumption is still very high, between 50 and 65% of the total. This means that the competition for water between agriculture and the other sectors is very high and destined to increase with population growth (Bonell and Askew, 2000).

It is predicted that the expansion of water demand will produce, each year, in the most critical months, the drying up of many rivers before they reach the mouth. The phenomenon is not new, however. Already, in the summer of 1972, the Huang Ho (Yellow River) ran completely dry for a few weeks close to its mouth (Brown et al., 1998). This phenomenon was repeated occasionally in the following years, but from 1985 it has occurred regularly every year. In 1997 the mouth of the river was dry for 226 days and for many months the river flow did not even reach Shandong, the last province that the river crosses on its journey to the sea. This is not the only case. The Colorado River rarely reaches the Gulf of California, because its waters are totally withdrawn to satisfy Arizona's thirst, and above all California's. The water volume that the Nile dumps into the Mediterranean is negligible by now, just like the volume that the Ganges brings to Gulf of Bengal (Brown, 2001).

For poor countries, to be able to have enough safe water is an essential condition for getting out of poverty. In rich countries the recovery of the water quality in rivers and lakes, which has been sacrificed in the past to economic progress, is an essential condition for

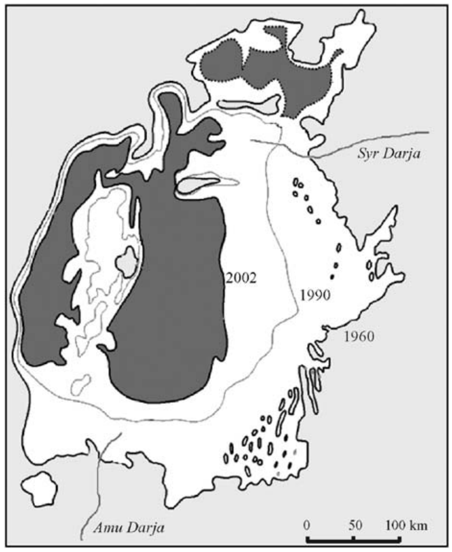

Figure 1: The progressive drying out of Lake Aral.

improving the quality of life. But to improve the quality and quantity of water available for human and environmental aims is a difficult task, since these objectives are often in conflict with each other. To increase availability, consumption can be rationalized (the volume of water dumped each time that a westerner uses the toilet is the volume that the average inhabitant of the third world uses in a day to drink, wash him/herself, wash, and cook) or the exploitation of the resource can be made more efficient.

In both cases the growing demand will increase the competition among water users at local, national and international levels. Ismail Serageldin, at the time vice-president of the World Bank and chairman of the Global Water Partnership, has declared more than once, and in no uncertain terms, that *the wars of the XXI century will be fought over water* (Homer-Dixon, 1996). He has been criticized a great deal for his thesis, but just as many have supported it (Starr, 1991; Bulloch and Darwish, 1993; Ohlsson, 1995). In 2003, at the Third World Water Forum, Klaus Toepfer, executive director of UNEP (United Nations Environment Programme), in presenting the Atlas of International Freshwater Agreements (Wolf, 2002b) indirectly confirmed this thesis. *The work* he revealed *shows the need to monitor, to adopt scientific rigor and diplomatic energy to assure that cooperation between the states be maintained and extended. Although 3000 treaties and agreements have been signed in the last century in 100 transnational river basins, another 158 are still without one*. These river basins collect 60% of the world's fresh water and host 40% of the population, and their number increases with political instability. The dissolution of the USSR, for example, made the Dnieper, the Don and the Volga international, and the Lake Aral river basin, in Central Asia, was left divided between five ex-Soviet republics. Tensions rose very quickly between these young nations over the sharing out of the waters of the Amu Darya and the Syr Darya, the two rivers that feed the lake and over the interventions aimed at improving the environmental and human disaster produced by its drying out (see Figure 1), which was the result of 40 years of massive derivations from these rivers to cultivate cotton in the deserts of Central Asia.

Until 1950 only one war generated by a dispute over water had been recorded, but in the following fifty years one quarter of such disputes have been hostile. This is a clear sign of growing tensions. In most cases the hostilities do not go beyond the verbal level, but unresolved tensions over water have nevertheless exacerbated relations and fuelled other reasons for hostility. In 37 cases military action has been taken, mostly limited to the destruction of dams. Almost all of these conflicts have developed in the same way: the construction of a big dam or a big project has created a prolonged period of regional instability and hostility, followed by a long and difficult process of dispute resolution (Postel and Wolf, 2001).

Competition is clearly not limited to nations, but arises also within them, between regions and economic sectors. Throughout the world, agriculture, cities, industry and environment compete for water and this competition affects in turn the relationships between political entities (cities and provinces) and their neighbours. For example, in Pakistan there is currently a bitter conflict between the regions of the Punjab and the Sind for the water of the lower Indus; and in Thailand between the north and the south of the country for the Chao Phraya, which feeds Bangkok. To satisfy the thirsty cities, water is often taken from agriculture. Sometimes, the farmers, who can no longer irrigate, react violently, as happened in 2000 in Shandong, when thousands entered into a bloody conflict with the police to block repairs to a large dam on the Huang Ho, whose leakage they had been using for some time to irrigate their fields. But even when it does not come to conflicts, the consequences are not the best because the farmers abandon the fields and go to increase the numbers of the unemployed masses in the overflowing and thirsty cities. This has happened in Pakistan, where the crisis of irrigated agriculture has produced an enormous emigration to the big cities, which in turn has led to repeated explosions of ethnic violence.

What can be done?

Unfortunately water cannot be produced in significant volumes within acceptable costs. The quantity of fresh water available is essentially invariable in time, which means that today, to satisfy 6 billion people, we have the same amount of annual flow (nearly 34 000 billion cubic metres per year) that was available 4000 years ago, when, in China and in Mesopotamia, the first great irrigation empires were formed and the population of the planet did not exceed 100 million inhabitants.

If we cannot increase the overall flow, we could try to increase the fraction of it that we use; however, this also is a blind alley, as today we capture little more than half (about 54%), and the residual is very difficult to acquire.

The possibility remains to reallocate the resource, both in space and time. To achieve this we need canals and reservoirs. In the last half century, the creation of these structures has proceeded at a frenetic pace. While in 1950 there were only 5000 'large sized'[1] reservoirs in the world, in 1994 there were more than 38 000 and together they intercepted 16% of the total flow of the rivers on the planet, with very significant economic and environmental effects (Silvester et al., 2000). It is not possible to construct a significantly greater number of dams, also because the marginal yield of the investment decreases rapidly, given that the best sites have already been used.[2]

[1] Defined as reservoirs formed by a dam higher than 16 metres.

[2] This situation is well reflected by the fall in financing for the construction of dams. For example, while in the period 1970–1985 financing from the World Bank for new dams represented 3% of the overall financing provided by the bank, the percentage drops to 2% in the ten years from 1986 to 1995, to decrease further to 0.9% in 2001 [www.worldbank.org].

Only one possibility remains: manage the water that we already have better. In other words, the conflicts will have to be resolved by moving the resource between bordering regions or between economic sectors. But, to avoid producing new conflicts, it must be done only with the agreement of the interested parties, in a collaborative way. Some have already begun to pioneer this way. The municipalities of some big cities that are particularly thirsty, such as for example Los Angeles and Beijing, subsidize the reduction of leaks in the irrigation system in peripheral agricultural areas, in exchange for the water that is recovered. In this way the farmers continue to farm and the cities obtain additional water at reasonable cost. Cooperation replaces competition.

The solution to the crisis will not come either from the 'State', or the 'market' alone, but, as the Second World Water Forum (GWP, 2000) concluded, from a change in the management paradigm with which water resources have been managed until now:

There is a need for profound change in the way water is managed, if we are to achieve any sense of sustainable water use in the near future. The empowerment of people at the local level to manage their water resources – the 'democratization' of water management – is essential.

This is therefore the path to follow for a better future: to adopt participatory decisions. We must transform the drawing up of the Plan or the Project from a technical act to a *political* process, in the noble sense of the word. A process in which all the *Stakeholders* must be involved: the institutions, organizations and individuals that are interested in the decisions to be taken; because, directly or indirectly, they will feel their effects, or because they have power to influence or thwart the decision. But this is not yet sufficient. Besides the plurality of the *U*sers, two other *U*s must be considered (as an effective slogan created by UNESCO says): the *Uncertainty*, that is intrinsic to the dynamics of water resources, and the complexity of its *Uses*. In other words, it is necessary to consider and integrate the physical aspects (hydrological, climatological, ecological), as much as the non-physical ones (technical, sociological, economic, administrative, legal), considering them from all the points of view from which the different users judge them. And since water does not respect administrative and political boundaries, management must be carried out at the level of the river basin, which is the natural hydrological and geological unit, crossing boundaries if it is transnational, and it must be extended to all the basins that are involved when inter-basin water transfer is being considered. For the same reason, the quality and the quantity of the resource must be considered jointly and simultaneously, because they are not two different problems, but simply different aspects of the same problem.

In summary: the point of view must be holistic and decisions integrated and participatory, so that they enjoy a wide consensus from the Stakeholders, or, as they say in jargon, *consensus is built* around them. This is the management paradigm that is proposed today and that is synthesized in the acronym IWRM: Integrated Water Resources Management (GWP, 2003). To put this into practice it is necessary to activate a decision-making process that

... promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner, without compromising the sustainability of vital-ecosystems. (GWP, 2003)

Such a process must begin from the periphery and move towards the centre, from the particular towards the general, briefly *bottom–up*, and not *top–down* as is traditional, to construct a viewpoint that is holistic and shared, which embodies all the viewpoints of the individuals as partial, but equally considered, viewpoints.

The adoption of the IWRM paradigm encounters a serious difficulty, which has been summarized by UNESCO in the following way:

Water management policy is generally based on outdated knowledge and technology. In many cases, procedures are followed where Stakeholders are unaware of what technical alternatives are available and scientists do not realize what is required. This 'Paradigm Lock' has come about because the two main groups have become isolated: scientists by the lack of proven utility of their findings, and Stakeholders by legal and professional precedents and disaggregated institutions. (Bonell and Askew, 2000)

To overcome this impasse UNESCO and the WMO launched the HELP programme[3] which has the aim of creating a global network of river basins in which the new paradigm is tested, demonstrating its utility in a concrete way.

Good intentions and examples are still not enough to get IWRM applied. Two other conditions must be satisfied: legislation must provide a normative framework that supports it and scientists must collect data, formulate procedures and make all of this available in information systems that allow the paradigm to be applied.

The appropriate legislation is absolutely necessary, even if alone insufficient, to manage our waters in a participatory way (Wolf, 2002a). The European Union has now equipped itself and in 2000 it enacted the Water Framework Directive (WFD) [Directive/2000/60/EC], which is totally centred around the new paradigm. For example, Article 13, dedicated to the 'River basin management plans', establishes:

1. *Member States shall ensure that a river basin management plan is produced for each river basin district lying entirely within their territory.*
2. *In the case of an international river basin district falling entirely within the Community, Member States shall ensure coordination with the aim of producing a single international river basin management plan ...*
3. *In the case of an international river basin district extending beyond the boundaries of the Community, Member States shall endeavour to produce a single river basin management plan ...*

Article 14 requires that the said plans be created through participation:

Member States shall encourage the active involvement of all interested parties in the implementation of this Directive, in particular in the production, review and updating of the river basin management plans.

As a consequence of participation:

- the capabilities of the Stakeholders are mobilized;
- advantages can be taken by their knowledge and experience of the system, making it easier to respond to the challenge of complexity;
- they are made actors, instead of passive subjects;
- they are made aware of the 'whys' and therefore become conscious individuals.

In order to make participatory decisions we need procedures and software systems that allow us to:

- evaluate the effect of the decisions ex-ante;
- facilitate dialogue and exchange viewpoints among the Stakeholders;

[3]http://icm.landcareresearch.co.nz/Library/project_documents/HELP~strategy~document.pdf.

- identify their alliances and conflicts;
- negotiate, i.e. to look for a compromise between the opposing needs, that might improve the conditions for everyone (a so-called *win-win alternative*).

The identification and reciprocal recognition of different viewpoints, the construction of a shared model with which to evaluate the effects of decisions for each viewpoint, and the dialogue created by these activities are often much more important than the decision itself, because they activate a social learning process.

What this book is about

The aim of this book is to introduce the reader to the water resource planning and management according to the IWRM paradigm, the adoption of which requires the use of dedicated software systems called *Multiple Objective Decision Support Systems*, commonly denoted with the acronym MODSS. Since the IWRM paradigm cannot actually be applied without the help of an MODSS the aim of this book is to describe the nature and structure of such a system in order to teach the reader how to design them.

The creation of an MODSS is an activity at the crossroads of the following three worlds:

1. The world of the physical, biological, economic, and social sciences which study and describe the processes that occur in a water system, both physical (hydrological, climatological and ecological) and non-physical (technical, sociological, economic, administrative and legal).
2. The world of methodologies, mathematical and non-mathematical, that allow us to describe those processes in a quantitative way and to define the decision-making and management procedures to govern them: System Analysis, Optimal Control Theory, Operations Research, Decision Theory and Alternative Dispute Resolution (ADR).
3. The world of Information Communication and Technology (ICT), which allows us to create the software system in which an MODSS takes material shape.

We will assume that the reader knows enough about the first point to follow the subject matter. Actually, we do not expect very much. Since our aim is to introduce the project methodology, we will simply consider the most elementary case, which is extremely frequent, in which water is used for irrigation, domestic and industrial supply. It is enough to know that water runs downstream and that both the scarcity of water (drought), and the excess of water (floods), cause damage. We will concentrate on the second and third points in the above list. On the second, in order both to illustrate how the models are built and how they are embedded in a decision-making procedure, and to define the latter, without entering into the more behavioural and psychological aspects, such as how the Analyst, i.e. the 'manager' of the decision-making process, should interact with the Stakeholders and facilitate the negotiations among them (only a few glimpses will be provided in Appendix A10). We will concentrate on the third point in order to show that the software system design has to be done not after but simultaneously with the identification of the procedure and the models, given that the nature of the available MODSS conditions the nature of the applicable procedure.

Since the designing of MODSS is carried out at the interface of these three worlds, we will not go into great detail on any one of them, but will concentrate on their relationships, showing where these worlds begin and which their more typical technical aspects are. The reader may find these *technicalities* developed further in the specialist treatises suggested through the text.

To be able to reach this goal, and contain the work within reasonable limits, reluctantly, some issues have had to be totally excluded.

What this book is not about

The reader will not find anything about water demand projections or population growth forecasts, two issues that certainly cannot be ignored when drawing up a Plan or Project. In fact, the Plan or the Project is written today but its effects come about in a future from which we are usually separated by many years (for example in the case of a dam, on average not less than ten years will pass between its commissioning and its coming into service). There will be no mention of water quality, certainly not because it is not important (this is the subject of the WFD!). We will simply consider the most basic intervention actions (delivery from a dam, construction of a reservoir or a diversion, definition of the MEFs[4]), completely ignoring more complex interventions, such as the rationalization of consumption, the upgrading of a river, or the establishment of an early warning system for floods or drought. As for the water systems that are considered, we will only deal with surface water (catchments, rivers, lakes, and canals) completely ignoring groundwater and coastal waters or distribution systems with pressure networks. We will not even speak about the design of the information system or data collection networks. The reason for all these exclusions is because it is not possible in an introductory book, to take for granted that the reader has the knowledge necessary to describe these systems and processes, and to evaluate the effects that the proposed interventions will have on them. At the same time, providing this information would render this work disproportionate and the thread of the presentation would be lost.

In any case these exclusions do not constitute a limit, as the reader will see that what is learned can be extended to include all that has been excluded, provided that the necessary notions for describing those systems, processes, interventions, and their effects, are given. This is possible because the decision-making procedure is totally independent from the water system and the interventions that are being considered, and can therefore be explained only using the simplest systems and interventions as examples. To convince the reader of the truth of this statement we prepared Appendix A1, in which we demonstrate how the baseline scenario (BLS) for the Seine-Normandy river basin could have been created accordingly to the WFD requirements using the PIP procedure. The reader will thus see that the notions provided in the following chapters can be useful even when water quality issues and spatially distributed (*distributed-parameters*) systems are considered.

The book goes into the methodological aspects of water resource planning and management in the light of the IWRM paradigm. Explanations are furnished with references to real Projects,[5] which are introduced through dedicated boxes, in which the problem and the solution are framed. We are conscious of the fact the theoretical exposition alone will not allow

[4] Minimum Environmental Flow.

[5] For didactic reasons, when necessary, we freely modified the system, the problems, the clients or the events with respect to reality, eliminating details that would have distracted the reader or adding elements that make the example more interesting. Therefore the Projects should be considered realistic, but not real, and what is presented, should not be attributed in any sense either to the real system or to the actors involved.

the reader to understand the complex articulations of the decision-making procedure and the practical problems that the Analyst must face. For this reason we have prepared a second volume: *Integrated and Participatory Water Resources Management: Practice* (Soncini-Sessa et al., 2007): in the following it will be referred to simply as PRACTICE. We advise, even if it is not strictly required, that it be read in parallel with this book, of which it could be considered an appendix for frequent consultation.

Who this book is for

When writing a book it is necessary to keep in mind the reader who it is being addressed. Our reader is a professional or a university student who has the basics for understanding problems of water resource planning and management. It is not strictly necessary, but it would be ideal, if the reader had some basic knowledge of hydrology. Further, we will ask for the basic elements of statistics and mathematics, which are usually provided in first year university courses, and lastly, basic knowledge of System Analysis and Mathematical Programming. Since all these notions are not always offered in scientific faculties, the reader who does not have some of them can fill this gap by reading Appendices A2–A4, A6–A8 on the CD that accompanies this book.

Reading pathways

The book is structured like a *matryoshka* and has a *top–down* order: the issues are at first presented at a high level and then developed in detail.

For this reason we suggest that readers begin with Chapter 1, which illustrates the decision-making process with which a Project is developed: from the formulation to the implementation of the alternative to be carried out. Even expert readers should not skip Section 1.3, in which the decision-making procedure (PIP) upon which the whole work is based is described. It is, in fact, not only the procedure that we propose for the development of a Project according to the IWRM paradigm, but also the key to reading the whole book, as it is explained in that section. Once the reader knows it, (s)he can proceed in a non-sequential way, if that is what (s)he wants to do.

Following the *matryoshka* structure, Chapter 2 provides an overall view of all the problems that the adoption of the PIP procedure poses: in other words, it is a conceptual map of the entire work. In particular Section 2.8 explains the subdivision of the book into parts and the organization of Appendices. Each Part opens with an introductory chapter that provides a high level description of it.

Going deeper into detail, Part B is essentially dedicated to modelling aspects. As one can easily understand, since not less than eighty percent of the literature is dedicated to it, this part could easily have dominated the others. To avoid making this mistake, we gave it a double, precise aim: to give the reader the cultural instruments to move in the vast world of modelling literature to search for what (s)he might need in the particular Project that is of interest to him/her, and to help him/her thoroughly to understand the links that run between modelling and the rest of the decision-making procedure. The consequence could be the dissatisfaction of those readers that are searching for a specific model of a given component, because they might not find it here. Appendices A5–A8 aim at mitigating this possible disappointment a little.

Part C is totally dedicated to the design of alternatives in the case where there is just one Project objective, while Part D is concerned with that case in which, as is usually the case in practice, there are multiple objectives. This division was created because not only it is didactically more efficient to introduce many concepts for the Single-Objective case and then extend them to the general case but mainly because Multi-Objective Design Problems are always led to Single-Objective Design Problem. In Part D the evaluation and the comparison of the alternatives find their place (Chapters 20 and 21).

Finally, Part E is dedicated to information technology. Just as for Part B, the aim of this Part is to provide a high level view of the particular requirements that the structure of an MODSS must respect to be effective, rather than to enter into great detail about the MODSS that exist today.

Parts B, C and E can be read autonomously from each other. Given that all of the terms are defined only when they first appear in the text a non-sequential reading could cause difficulties for the reader. To avoid this we prepared an analytical index in which the first reference is to the definition of the terms.

Didactic use

This book is born from the experience of more than twenty years of teaching undergraduate and post-graduate courses on *Natural Resource Management* at the Politecnico di Milano for the degrees in Environmental Engineering and Information Technology Engineering. It can be adopted as a reference text for both undergraduate and post-graduate courses. In undergraduate courses, Chapters 1–10, 16 and 17 can be used and the remaining chapters used in post-graduate courses. Thereby, at the undergraduate level the issues relative to structuring the problem and modelling the system are treated and some mention is made of techniques for the design, evaluation and comparison of the alternatives. These latter techniques are presented at the post-graduate level together with aspects of ICT. For courses in Information Technology, Part C can be used as a good example of an application of Optimal Control techniques in conditions of uncertainty and risk and Part E as an example of designing the architecture of an MODSS.

The attached CD

The CD is subdivided into the following sections:

- *Appendices* (A1–A10): these can be consulted by the reader to fill any methodological gaps or for a closer examination of particular issues.

- *Exercises*: these are divided into
  - *Theoretical Questions* (E1), which are subdivided for
    - *undergraduate* courses: mainly on Phases 0–3 of the PIP procedure and on the formulation of the Design Problem, i.e. on the material of Chapters 1–10, 17 and relevant Appendices;
    - *graduate* courses: mainly on Phases 4–7, i.e. on the material of Chapters 11–22, and on the more technical aspects of modelling presented in Appendices A1–A8.
  - *Simple applications of the algorithms* (E2), only for the graduate courses, mainly on the material of Chapter 12.

- *Projects* (P1–P10): the most 'artistic' part of a Project, the one that most heavily depends on the Analyst's experience, is the formulation of the Design Problem. To provide students with a more complete preparation and give some food for thought to professionals, a series of Projects is presented. The Projects are not completely developed in all their detail, because a complete description of all their phases would require an entire book (such as the book PRACTICE that deals with just one Project), but, after the presentation of the goal and the system that each of them is concerned with, the focus is the formalization of the Design Problem.

WEB site

To facilitate the updating of this work, a WEB site is available (www.elet.polimi.it/people/soncini) where the reader may find didactic material, updates and the errata–corrigenda prepared on the basis of the comments and suggestions provided by the readers.

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I would be grateful to anyone who would like to send me comments and suggestions to improve this work and I hope that no MODSS created with this book will ever be used to legitimize decisions that have been taken by someone a priori.

Milano, 30 June 2006

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Translator's note

In order to avoid boring forms like (s)he and his/her, which are used to acknowledge the fact that both men and women can be found performing all the roles described in this book, we chose to allocate (in a subjective, but seemingly fair way) each of our characters with a gender right from the beginning, and have been consistent throughout.

Valerie Cogan