Sustainable Use of Water in Agriculture

Indicators and Trends for Water Resources Conservation

Marie Curie Training Course
Venezia (Italy), September 5-9, 2009

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Proceedings of the 3rd training course "European Sustainable Water Goals"
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Contents

5	**Michela Miletto**	Foreword
7	**Eriberto Eulisse, Melike Hemmami and Esther Koopmanschap**	Preface
12	**Shaminder Puri**	Introduction. Why Worry about Transboundary Aquifers in Promoting Sustainable Agriculture?
21	**Claudio Gandolfi**	Modelling Tools for the Harmonization of the Water Framework Directive and the Common Agricultural Policy
31	**Bernard T. Nolan and Kerie J. Hill**	Determining Groundwater Vulnerability to Nitrate Contamination from Agricultural Sources
43	**Bruna Gumiero, Bruno Boz and Paolo Cornelio**	River Restoration and Sustainable Agriculture in the Venice Lagoon Basin: the Nicolas project
53	**Luis S. Pereira**	Irrigation Water Use, Conservation and Saving. Issues to Support a New Paradigm of Water Uses
65	**Josep Mas-Pla and Anna Menció**	Estimating Water Balances for a Sustainable Use in Agricultural Basins
77	**Guido D'Urso**	Teledetection Techniques for Sustainable Agricultural Development
87	**Laura Riesgo**	Water, Economy and Sustainable Agriculture
97		*Abstracts and Authors*
112		*DVD Contents*

Foreword

It is a pleasure to introduce the conference proceedings of the 3rd Marie Curie training course "European Sustainable Water Goals", titled in 2009 "Sustainable Use of Water in Agriculture: Indicators and Trends for Water Resources Conservation". This event, organized by the University Ca' Foscari of Venice in cooperation with the Water Civilizations International Centre, is part of the Marie Curie Programme aimed to support transnational research networks and to enable junior and experienced researchers to benefit from the experience of leading international experts.

I welcome this opportunity to present the World Water Assessment Program of the United Nations (WWAP), established by UNESCO in 2000 and, since 2007, hosted in Perugia, Italy.

The creation of WWAP responded to a call of the Commission on Sustainable Development, in 1998, to all UN agencies to combine their efforts with a view towards monitoring and periodically reporting the status of global freshwater resources in order to provide policy recommendations, enhance assessment capacity at a national level and inform the decision-making process. Since its establishment, WWAP effectively coordinates this periodic assessment and publishes every three years the authoritative World Water Development Report (WWDR) which results from comprehensive UN-wide cooperation of the 26 agencies of UN-Water, working in partnership with governments, international organizations, non-governmental organizations and other stakeholders.

It may be appropriate to recall here three key messages of the 3rd UN World Water Development Report (WWDR3), presented in Istanbul in the occasion of the 5th World Water Forum in March 2009:

- Properly managing freshwater resources is an essential component of growth, social and economic development, poverty reduction and equity - all essential for achieving the Millennium Development Goals
- Leaders in the water domain have to disseminate the processes outside their domain and manage water resources to achieve agreed socioeconomic objectives and environmental integrity. Nevertheless leaders in government, the private sector and civil society will determine the direction that actions take

- Management of the world's freshwater resources requires reliable information about the state of the resource and how it is changing in response to external drivers such as climate change and water and land use. Worldwide, water observation networks provide incomplete and incompatible data on water quantity and quality for properly managing water resources and predicting future needs"

In sum, water resource management - and first of all in the agricultural domain, the largest freshwater user - must be a component of decisions that lead to socio-economic development within a context of environmental sustainability. Decision-makers may lack the information about the current situation and the way it may change, which they need to take decisions. This requires a system of useful indicators based on reality and a framework of scenarios about possible futures to guide them.

The World Water Assessment Program of the UN is striving to respond to these needs, and inform decision making at all levels by translating science and disorganized information derived from many national and regional networks into a coherent set of trends and policy recommendations.

In a changing and unpredictable world impacted by increased climatic variability, ever growing demographic pressures, and forceful global economic drivers, WWAP's global monitoring of the state of our precious freshwater resources, combined with targeted efforts of the scientific community, is increasingly relevant to the achievement of those fundamental sustainability targets that the international community has adopted.

Michela Miletto
Deputy Coordinator
World Water
Assessment Program

Preface
Water for Sustainable Agriculture

Eriberto Eulisse, Melike Hemmami and Esther Koopmanschap

Quel que soit l'angle sous lequel on voudrait parler de l'eau, il convient de le faire comme il faut, car les avantages en sont multiples et innombrables
Qûtâmâ, Nabatean Agriculture[1]

In his Nabatean Agriculture, the Agronomic Encyclopaedia dealing with the origins of the Mesopotamian school of agriculture and its economic and agrotechnical conceptions, Qûtâmâ reveals how a holistic approach is a necessary requirement for any progress in agricultural development and agrarian sciences. Today, a similar vision is the foundation not only of one of the most innovative environmental legislation, i.e. the European Water Framework Directive (WFD), but also of strategic Declarations such as that made in Madrid (2005) to inaugurate a "New Water Culture". In this sense, the treatise of Qûtâmâ prefigures *ante litteram* a perspective of what nowadays we would be inclined to define as "sustainable use of water in agriculture", which is also the title of this 3rd ESWG conference volume.
Moreover, Qûtâmâ may be considered as a forerunner of an interdisciplinary approach. When he was compiling his treatise (ca. 10th century AD), the art of managing water in agriculture was a prerogative to wise experts whom today we would call agronomists, but also hydraulic engineers, hydro geologists, mathematicians and even philosophers. Spiritual digressions and the same concept of aesthetic beauty were not alien to their scientific interests. A similar approach towards water was genuinely holistic and interdisciplinary.
During the 20th century, in contrast, the specialization of science seems to have prevailed over any other interests, leading to a "productivist" irrigation management approach that does not consider *a priori* any holistic vision.
Structuring a holistic and interdisciplinary perspective is a complex operation that can not be taken for granted. However, at a time characterized more and more by water scarcity, this would seem an essential premise to talking about "sustainable" use of water in irrigation. Since globally the greatest usage of water is in agriculture ("water for food"), it is important to pay special attention to the ways in which the "sustainability" concept is outlined in scientific literature.

[1] Quoted from T. Fahd, "Un Traité des Eaux dans al-Filâha an-Nabatiyya (Hydrogeologie, Hydraulique Agricole, Hydrologie)", in: *La Persia nel Medio Evo*, Accademia Nazionale dei Lincei, Roma, 1971.

"Sustainable use of water" is an expression often mentioned or referred to. Everybody has some often vague idea of what it means. Scholars from different disciplines conceptualize the sustainability of water uses in different ways, and sometimes even without clarifying their purpose or their methodical assumptions. Too many studies and scientific approaches do not even mention what definition they refer to. Some experts in the field of water think about it from an ecological perspective (water to sustain ecosystems, or "water for nature"). Others think about sustainable use of water in social ("water for people") or economic terms ("water for profit", including "water for food"). As a consequence, the term "sustainable" is ambiguous in itself.

The word "sustainability" may mask different and even conflicting meanings. As an example, what would seem today the "sustainable" perspective of an agronomist or a hydraulic engineer may not be considered as such by an ecologist, who uses different parameters to evaluate the sustainability of irrigation withdrawals from rivers. This same volume bears witness to the diverse disciplinary approaches that do not make reference to a single definition of sustainability.

Another common misconception that may be noticed in scientific literature is that the term "efficiency" does not necessarily equal "sustainability". As stressed in a recent publication edited by the European Commission, DG Environment, the case of Israel offers a paradigmatic example. Indeed Israel has a highly efficient water system that includes water recycling and desalination. Up to 80% of Israel's "grey water" is re-used for agriculture. Nonetheless, water levels in the country's rivers and lakes continue to decline. In such a context, as emphasized in a recent volume aimed at disseminating some of the best European LIFE projects, "management plans should place more limits to water extraction so that more *sustainable* water levels are maintained". This perspective is likely to require significant changes to consumption patterns in many semi-arid countries, but also requires tough political decisions to be made. According to DG Environment, "agricultural patterns (cropping systems) also need to change", especially where "water intensive crops are presently being grown in places suffering from water scarcity".[2]

Shifting to more efficient and sustainable water irrigation systems: are farmers sufficiently aware of the need of this shift and can farmers shift that easily? Implementing water policies aimed to "sustain" in semi-arid environments (as in the Mediterranean) water demanding crops, such as corn: are these far-sighted policies? And when the Common Agricultural Policy (CAP) itself stops nourishing irrigation practices that are neither sustainable nor locally "traditional"?

[2] European Commission (DG Environment), *Water for life, LIFE for water. Protecting Europe's Water Resources*, European Union, Brussels, 2010: 11.

To assess these issues correctly it is necessary to adopt a univocal definition of the term sustainability. "Sustainable development" is an expression that was first used in 1987. As referred to in the Brundtland Report of the United Nations, in order to be "sustainable", development has to meet "the needs of the present without compromising the ability of future generations to meet their own needs".[3] In the critical evolution of this definition, it has been stressed that three dimensions are essential to give shape to development that is genuinely sustainable. The economical, social and environmental dimensions have to go hand in hand to guarantee an effective sustainability of development in the long term.

By introducing, in the evaluation of water quality, a series of parameters that consider not only chemical but also biological and hydromorphological aspects, the WFD has fully inherited this very concept of sustainability: in principle, no economic development can compromise further the ecological status of European water bodies.

The WFD, the normative framework that is laying the foundations for a common European policy of integrated water management, is today enlisted among the most innovative environmental legislation worldwide. Its main objective is the protection of water quality for the generations to come, that is the preservation of the water cycle against further degradation of aquatic ecosystems from the impact of large hydraulic infrastructures, depletion and pollution of water bodies, and wetland desiccation. Nonetheless, the WFD answers (and solves) only partially to some environmental and social contradictions generated by the "productivist" irrigation management approach and by the CAP.

In Europe, as an average, all water uses are split as follows:[4] agriculture 64%; industrial 24%; civil 12%. These data, however, mask considerable regional differences among member states. Indeed if in Europe, as an average, agriculture accounts for approximately 65% of all water uses, in southern Europe this proportion rises to more than 80%. In such a context of increasing water scarcity, the issue of sustainability is fundamental - especially in Mediterranean countries - for any further development of integrated water resources management plans.

Since current management models of irrigation require significant adaptations regarding water scarcity, also in the light of climate change impact on water resources, the "sustainability" of water uses in the Mediterranean agriculture is a real challenge. Such a critical area also explains the selection of papers included this year in the 3rd ESWG volume.

According to the European Environmental Agency (EEA, 2009), the agricultural water use across Europe has increased over the last two decades "driven in part

[3] See www.un-documents.net/ocf-02.htm.

[4] COM 2007, 414.

by the fact that farmers have seldom had to pay the 'true' cost of water". The Common Agricultural Policy (CAP) would bear part of this responsibility, having in some cases provided "subsidies to produce water-intensive crops using inefficient techniques". The EEA notes also that while recent reform of the CAP is reducing the link between subsidies and production in the agricultural sector, "the demand for energy crops has the potential to increase once again unsustainable agricultural water usage in future years".[5]

Other negative effects of CAP policies are today quite evident. For years indeed the CAP has favoured mainly the industrialised sector of agriculture, to the detriment of small farmers and natural ecosystems. According to Ruf and Valony (2007), CAP policies have produced major social, economic and also environmental contradictions, because of an unequal distribution of water resources for irrigation, causing serious precariousness in Mediterranean small farmers.[6] In this process the state, far from being absent, has often expropriated ancient water rights to favour precisely those who over-consume, therefore generating a *hiatus* as to how water for agriculture has been managed by local communities over the centuries.

It is worth noticing that those farmers who deliver the greatest biodiversity benefits are, very often, small farmers working under the most difficult circumstances.[7] These farmers indirectly support European biodiversity. High Nature Value Farmlands are also largely contributing to Europe's Nature 2000 network and land maintenance. Nevertheless, small farmers are quite vulnerable. They have been weakened in the last decades by the same CAP policies and have been forced, as a consequence, to abandon their "traditional" activities. Across Europe, many "traditional" landscapes which have been rich in biodiversity are being lost in the last decades due to land abandonment, change of land use and even processes of cultural loss (or "deculturation" processes).

The predominant approach to water use in Mediterranean agriculture has caused not only a consistent loss of landscape memory, traditional knowledge and techniques, but has also generated degraded ecosystems with an obvious chain-reaction. As has been stressed by Gumiero, Rinaldi and Fokkens (2009), among others, "losing diversity in species (flora and fauna) means losing the significant economic and social benefits that ecosystems can provide, like provision of food and other products, and even creation of work places, diversification of local economies and

[5] European Environmental Agency, *Water resources across Europe - Confronting water scarcity and drought*, Report n.2, EEA, Copenaghen, 2009.

[6] Ruf, T. and Valony, M. 2007. «Les contradictions de la gestion intégrée des ressources en eau dans l'agriculture irriguée méditerranéenne», in: *Cahiers Agricultures*, 16 (4), 294-300.

[7] This has been demonstrated in the case of Turkey in: Redman, M. and Hemmami M., 2008. *Agri-environment Handbook for Turkey*, Bugday, Ankara.

improvement of life conditions".[8]
Recent CAP reform is making an attempt to overcome these contradictions by taking into account both the critical state of surface water and aquifers all around Europe, and the increase of demand on irrigation that is expected in the coming years. Programmes devoted to shifting to more efficient irrigation systems are also supported through Agri-Environment projects. It is important to implement these programmes, since they may boost the cultivation of local crop varieties that are more adapted to a specific region and/or require less water.
If present agricultural patterns or cropping systems need to change, especially in the Mediterranean, cultural factors should be considered an essential ingredient of this renewal. As Holst Warhaft points out (2010), it would seem not only "impossible to address the problems of water in the Mediterranean Basin without an understanding of the cultural factors that affect the way people in the region use water, but that culture, in its broadest and narrowest sense, including its historical and contemporary manifestations, can and should be enlisted in the effort to redress the current water crisis".[9]
Such a process necessarily entails that the predominant engineering approach aimed at increasing water availability, e.g. through new dams and innovative wastewater treatments (to produce water for increasing demands on irrigation), should go hand in hand with "conservation strategies" prioritizing *water savings*, that is with stoppage of water-wasting crops in water scarce environments (i.e. in line with a "water for life" approach).
Innovative technologies are definitely essential in this process, but a new ethical perspective, or a new "water culture", is even more crucial. "*Achieving sustainability, equity and democratic governance in water management*" - as stated in the New Water Culture Declaration (2005) - "is one of the main challenges for the international community in the 21st century, and we believe that the scientific community must become involved in this debate through an interdisciplinary effort. Taking on this challenge requires far-reaching changes in our scales of values, our conception of nature, our ethical principles, and in our lifestyles; in short, there is a need for a cultural change that we have termed the birth of a "New Water Culture". A New Culture that must assume a holistic approach and recognise the multiple dimensions of ethical, environmental, social, economic, political, and emotional values embodied in aquatic ecosystems".[10]
Again, a holistic approach based on dialogue among disciplines and on the recognition of the varied cultural dimensions and functionalities related to water that, as the compiler Qûtâmâ recalls, brings forth multiple and countless advantages.

[8] Gumiero B., Rinaldi M. and Fokkens B., *Proceedings of the 4th International Conference on River Restoration*, Venice, 2009.

[9] Holst Warhaft G. and Steenhuis T. (eds), *Losing Paradise: the Water Crisis in the Mediterranean*, Ashgate, 2010.

[10] See http://www.unizar.es/fnca/euwater/index2.php?x=3&idioma=en.

Introduction
Why Worry about Transboundary Aquifers in Promoting Sustainable Agriculture?

Shaminder Puri

Most global, regional and sub regional assessments today concur that there is an increasing global water scarcity aggravated by climate change and the associated increasing amplitude in its seasonal and inter seasonal variability (UN, WWDR; see Miletto in this volume).

The many modelling studies have not yet been able to provide definitive future scenarios (IPCC 2007). Nevertheless, current field observations are starting to make it clear that rapid changes are afoot. These changes are a complex mix of direct human impact - such as through the rapid modifications of large tracts of land - or indirect, through the greenhouse gas accumulation in the atmosphere.

Therefore it is clear that for sustainable agriculture the input of water has to be considered a critical factor since water has to be available at the point in time that a crop reaches its wilting point and in quantities that ensure the yields are not significantly affected (see Pereira in this volume). Then, it follows that a reliable source of water has to be available, and can be deployed on-line, to satisfy such needs.

With reliable rainfall patterns, deploying such resources can be planned into water resources management operations. However, with increasingly less reliable rainfall patterns, the management of water resources for reliable agriculture becomes more problematic (CGIAR Alliance 2002). If this level of complexity occurs at the basin level and within the jurisdiction of one water organisation, it can still be resolved to some extent. When water resource basins or aquifer systems transcend across national boundaries, then the degree of complexity increases several fold.

Given that 40% of global water resources occur in the transboundary context, and that many of the major agricultural developments of the world occur in transboundary basins (Nile, Mekong, Indus, Ganges, Tigris, Euphrates, to name a few), then it becomes clear that such water resources merit the attention of the concerned communities to ensure that tools and methodologies are available for sustainable agriculture (Puri and Aurelii, 2009).

The purpose of this introduction to the 3rd conference volume is to address water resources in transboundary aquifers, although reference will also be made to analogous river basins (see Figure 1).

Figure 1. Some of the major Aquifers in the world are shown, illustrating their transboundary extents. Source: UNESCO Atlas of Transboundary Aquifers (Puri and Aurelii, 2009).

Environmental security for productive landscapes

Landmark studies such as the Millennium Assessment have shown that environmental security is a basic building block also for human survival. Globally ecosystems are at risk and increasing pressures on them mean that many of them, defined in any one of the many classifications, are moving into conditions where their resilience to shocks is reducing.

The ecosystems at the centre of productive landscapes provide security for mankind though at the cost of security to the diversity that is normally found in many of the natural systems. The reduction in the biodiversity of productive landscapes is an eventual threat to environmental security. Development, expressed through economic progress, often has the net effect of reduction in biodiversity and thus reduces their resilience to potential shocks. After the recent economic crisis, the opportunities that may have been possible to design the recovery incorporating the rebuilding of sustainability are still available. The crisis related to food production in order to provide the global demands has gone through shocks and the lessons learnt provide a sound basis for concerted future action.

Water as an essential ingredient in most natural and built ecosystems, is the raw material in its multiple roles and manifestations and thus defies institutional classification. Therefore, for the purposes of this introduction it may be noted that water is the input to hydro-energy generation as well as the raw material for irrigation to sustain agriculture.

One of the sources for seeking such security is through the sound management and deployment of water held in aquifers. Among some of the benefits of aquifers is the availability of effectively 'free storage' in the subsurface that can be replenished and exploited to respond to the shocks discussed above (see Puri and Struckmeir 2010).

Aquifers as a resource to mitigate shocks

At national level, aquifers provide reliable water resources. Sometimes, however, aquifers have been extensively exploited in some countries to the extent that groundwater is close to exhaustion (e.g. Indus Plains, aquifers of NW China, Ogallala Aquifers of the Mid-West US, Mexico and to some extent also countries in the Middle East and North African Region). Despite this, there remain many regions of the world in which aquifer resources provide major resources, and these are being utilised, though not always with the planning that may be required in the context of the coming climatic shocks of deep periodic droughts. Adoption of sound national policies is certainly a key requirement and among them the need to have appropriate institutional structures, in particular in the arid zones.

Some of the key drivers that have to be taken into account in water management, especially in arid zones, are based on the current hydrologic variability and the related levels of risk, with the expectation that these will intensify in association with climate variability. To achieve better economic performance in sustainable agriculture in spite of the greater variability, higher investments are required for risk aversion (see Alvarez in this volume). These factors will influence the decisions that are made to lessen the vulnerability to hydrological shocks (see Nolan in this volume).

Nevertheless there are constraints to investment choices that are made: if the risks relevant to the rewards are too high, then there is an aversion to making risk reduction choices. In the case of investment in infrastructure for use of aquifer resources, the main source of risk is the lack of sufficient information on the yield of the aquifer in times of need - some of these situations of insufficient knowledge relate to the institutional structures. Where poor information and awareness of the potential users is the norm, sound investments that might make the agricultural investments sustainable, are not made.

Bottom-up assessments

In order to gain an understanding of the dynamics of investments in the use of water from aquifers, a "bottom-up" approach would suggest that it can be conducted at three levels: (1) at the level of the individual farmer; (2) at the level of industrial and urban conurbations; and (3) at the country level, which also equates to the transboundary level. A detailed assessment is beyond the scope of this paper, but the following sections outline the key issues that underlie the assessments.

At the first level, an individual farmer and potential groundwater resource user in arid zones can mitigate the hydrological risk through the adoption of coping strategies, such as shifts of crop mix, alteration of production technologies, or through taking out of crop insurance. If these coping strategies are found to be uneconomic, then the water user is also not likely to invest in land improvement, capital intensive input or in new production technology. This is compounded when the individual is unable to access investment capital. On the other hand, if the institutional structures can provide the required information about the availability of water resources in the aquifers under the lands where agricultural sustainability is to be enhanced, then coping strategies can be modified and there may not be the need for radical changes in the current practices. A rather better planned programme of changes can then be instituted. At this level, the constraints of a transboundary resource are not significant since very small users are involved.

At the level of urbanised and industrial conurbations, where many more interests than those of an individual need to be amalgamated into the decision process the Industrialist and the richer urban dweller would mitigate their risks by investing in orientated coping strategies e.g. through the construction of private boreholes. However, this has downsides, such as the fact that when the wealthy choose to drop out of the public system, utilities cannot achieve economies of scale, with the result that poor maintenance systems take hold and deterioration in infrastructure may accelerate. The usual response to these problems in many situations is the need to raise tariffs. Urban conurbations that lie rather closer to international boundaries are likely to be affected by the transboundary issues (e.g. the City of Geneva is reliant on the recharge of water from the French district of Haute Savoie).

Finally, at the national level and also at the transboundary level, in order to reduce the impact of high vulnerability, countries will try to adapt food security policies e.g. food supply would be assured through trade and industrial production, decrease in the uneconomic agricultural production or increase in agricultural imports. As these measures are rather more political and relate to national policy packages, at the country level, managing hydrological risks requires engagement at state level of top political leadership. The reason that top level engagement is required is that large scale infrastructure with transboundary impacts may be at issue, and this involves too many complexities at State level.

An observation worth making here is that these policy packages can be even more complicated when a country has several climatic zones and thus faces different hydrological risks, so that a single set of nationwide regulations may not apply. For example, the hydrological policies in Kazakhstan along its southern arid borders are the same as those with the northern borders, where there are temperate conditions and water shortage is not an issue. In summary, the management and the benefit of aquifers for assuring agricultural sustainability is a several-level issue, and is related to the different perceptions of risk at each of these levels.

Food grown in foreign lands: a new transboundary impact paradigm?

Prior to the onset of the economic crises of 2008, there was growing evidence of a new paradigm in food security, i.e. that of acquiring land in foreign territories to grow food for return back to the investor country. Although many countries established close mutual relations in the past to assure food import, the new paradigm is different in that food importing countries seem to have a direct role in the agricultural activities (see “Food grown in foreign lands”, The Economist, May 2009; IISD 2009). It is not the purpose of this paper to provide an analysis of the new paradigm, but it is important to note that this approach provides a new line of thought in terms of transboundary impact assessment. Compared to the previous ideas that only countries sharing a river basin could have a mutual impact, this new approach might suggest that a third country may impact, through its investments policies, the water resource balance in basins other than its own (Puri, 2006). An interesting observation can also be made here. When juxtaposing some basins and aquifers where sizeable foreign investments have taken place, it may be noted that some of them have been classified as being ‘at risk’ when viewed from the perspective of potential for water related conflicts (see Miletto in this volume, and UNESCO PccP) (see Figure 2).

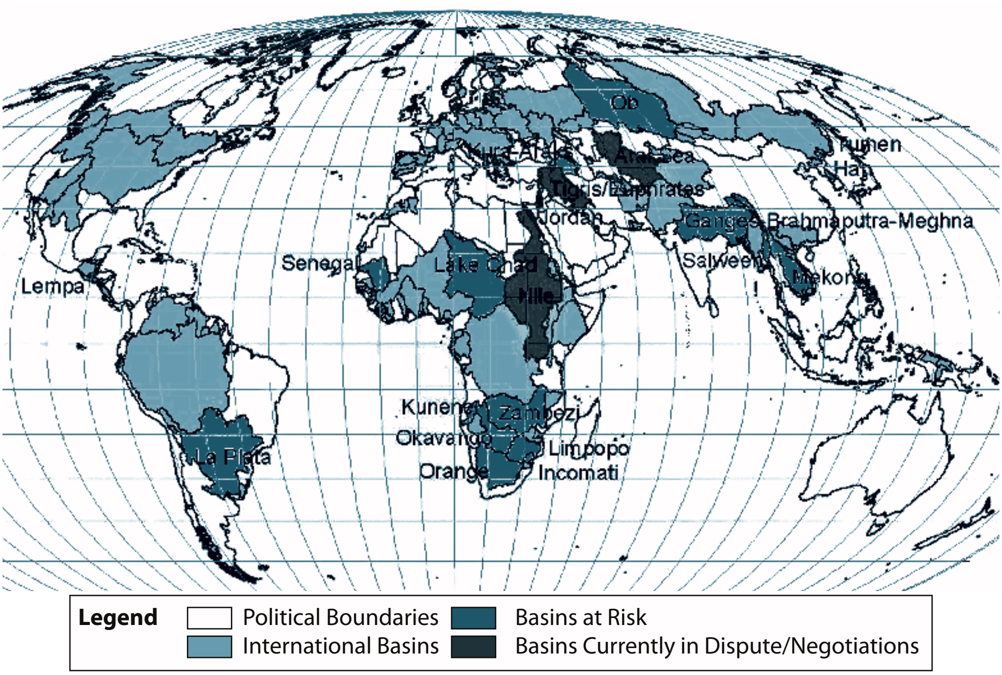

Figure 2: Basins and Aquifers considered at risk from the resource balance and mutual relations (based on UNESCO PccP). Source: www.unesco.org/water/pccp

Institutional factors in transboundary aquifer manageement

As implied earlier, the sound management of transboundary aquifers for sustainable agriculture is a function of their sound management at the national level. At the national scale the actors that are involved in an institutional 'web' can be represented in the sketch Figure 3.

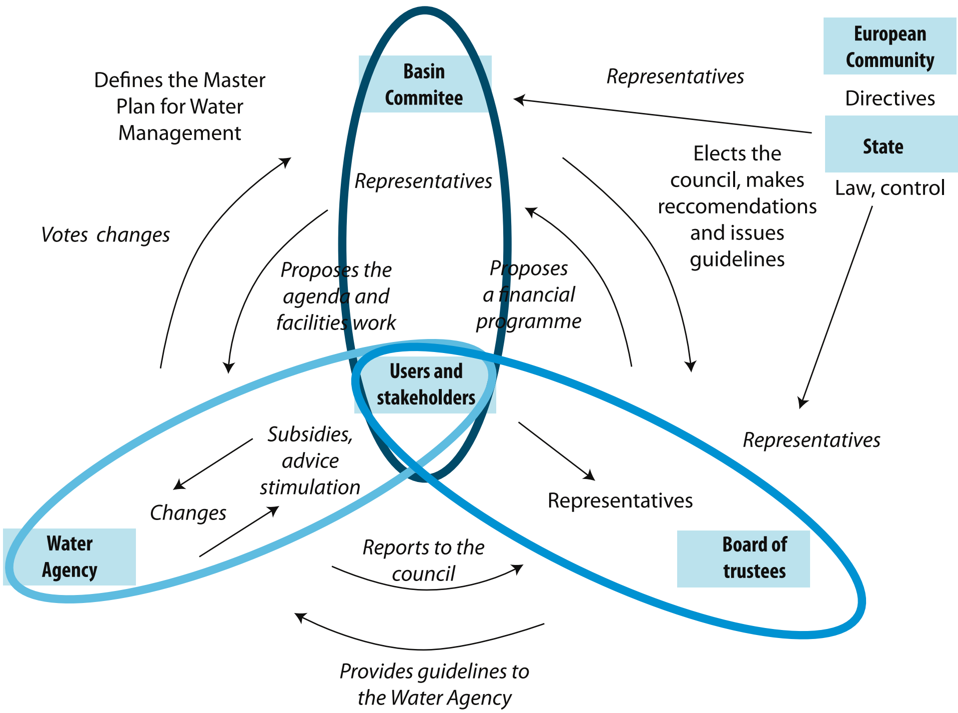

Figure 3. The web of actors within the institutional web at the national scale.

At the centre of such a web, one can notice the water users and the stakeholders who interact with various sets of institutional groups: here the dynamic is based along radial lines. In addition there are also forces at the perimeter of such a system, linking the institutional groups and also creating synergies and, at times, conflicting pressures. The institutions involved in these conditions can be analysed in order to better define their functions.

"Institutions" are structures that are based on some rules and a hierarchical structure of technical and administrative cadres. The technicians and administrators operate along a series of norms and standards that may be structured either in a rigid manner or with certain flexibility. Irrespective of whether they operate within rigid rules or less well defined ones, their group behaviour includes a variety of informal norms that coordinate human behaviour.

These formal and informal rules can be said to be essential for sustainable and equitable development. When the institutions that have been established function well, they enable people to work with each other to plan a future for themselves, their families and their larger communities. When the institutions are weak, i.e. they follow their rules in an inconsistent manner or are simply unjust, there is mistrust and uncertainty in the community. This in turn encourages people to "take" rather than "make" and it undermines the joint potential for community activities and in this case the sustainable development of agriculture.

Some of the key functions of institutions can be summarised as follows. Institutions should pick up signals about community needs and problems - particularly from the fringes of the groups that they are set up for to regulate. This involves generating information, giving citizens a voice, responding to feedback, and fostering learning. The institutions must balance interests by negotiating change and forging agreements. They should enable this by avoiding stalemates and conflicts. The institutions must execute and implement solutions by credibly following through on any agreements that they make.

Nevertheless there are the barriers to the good performance of institutions. Some of these relate to dispersed interests. By the nature of things, concentrated interests are often given too much weight, as may be found in the assignment of property rights for land and water, and in the operation of governments. When societies and processes are unequal and undemocratic, it is more difficult to coordinate dispersed interests and forge credible commitments.

Many studies have been conducted by social scientists on how to overcome barriers to the good operation of institutions. Generally change in the culture of an institution is simply too difficult to make through the so called normal channels. Sometimes the change of pace in social and economic development offers opportunities for change.

The economic crisis of 2008 - 2009 was such an opportunity, when the global pressures were sufficiently great that change could have been introduced to achieve improvements such as a new paradigm in water resource management. Some of the structural changes that are brought about through urbanization, through the demographic transition, and through the redistribution of wealth (particularly increments of new wealth) have been found to be able to release dynamic forces and opportunities for institutional change.

At this time also the initiatives to channel information can serve as catalysts for change. Information can empower people by giving them more voice in public services and allowing greater transparency and accountability in the activities of

governments and firms. Time will show whether the recent global economic crisis was a missed opportunity or whether smoother transitions are more constructive.
The above observations are also the foundations for the sound management of transboundary waters and the webs of stakeholders and institutions that operate within the jurisdictions of neighbouring water sharing states. It is self evident from the above discussion that if the ‘webs’ in two neighbouring states are driven by rather different pressures, then the possibility to coordinate shared water usage is made more difficult. Sustained agriculture for example in the great transboundary alluvial aquifers in the Indo Gangetic - Brahmaputra Plains will require that the institutional webs of the two sharing states have some common factors. This example applies also to the very extensive alluvial, aquifers in the Mekong.
Apart from the major alluvial aquifers, there are also the aquifers of arid zones such as the Nubian Aquifer system, the North Sahara Aquifer System and the Rum-0SAq Aquifers, where a similar analysis would provide the basis for sustainable agricultural development.

Concluding remarks

In the overview to this volume, it is important to highlight that the issue of water management is intrinsic to human and environmental security and will remain so, as complexities in the global interactions continue to operate. Some of the legal and institutional tools discussed above have been effectively utilised at the national level; for them, to work in the same way at the international level, it is logical to analyse all the functions of water related regulations, and to seek balance and regulatory harmonisation across jurisdictional boundaries where shared water resources are used (see Gandolfi in this volume).
Indeed it would seem that governments have not yet fully recognised the needs for institutional harmonisation across state boundaries. While inter-state interactions in water resources sharing states would need priority action, it can be noticed a new paradigm of third states that seems to have an increasing influence where ‘food grown is grown of foreign land’, i.e. where the investing state has an implicit impact on local water management. Consequently, taking the overall perspective, bi- and multi-lateral agencies need to strengthen their capacity to deliver the global water related goals for achieving sustainable agriculture.

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Modelling Tools for the Harmonization of the Water Framework Directive and the Common Agricultural Policy

Claudio Gandolfi

After a few years, following the official release of the Water Framework Directive (WFD, 2000/60/EC) on 22 December 2000, agricultural activities have emerged as one of the crucial issues for achieving the WFD objectives (CIS-WFD, 2004). Therefore, linking agricultural policies and the implementation of the WFD is considered one of the highest priorities in the European Union (European Commission, 2003). The recent reform of the European Common Agricultural Policy - known as Mid Term Review (MTR) - has increased the opportunities to support farmers in addressing some environmental issues. The MTR affects the farmers' behaviour by guiding their production choices for the future that, in turn, will influence the water demand for irrigation.

Due to the importance of these issues, a lot of research has been done on the assessment of agricultural policies' effects on land use. In addition, a number of models have been developed to forecast farmers' behaviour as a consequence of agricultural policies, both at sector and regional level (Heckelei & Britz, 2001; Britz et al., 2003; Offermann et al., 2005; Barkaoui & Butault, 2000; Judez et al. 2001, 2002). A large amount of literature also exists focusing on the assessment of irrigation water requirements (Todorovic and Steduto, 2003; Bormann et al., 2003; Ishigooka et al., 2008; Heinemann et al., 2002; Fortes et al., 2005). However, the examples of conjunctive modelling of the two aspects are much more limited.

This paper presents some results of the TwoLe project (www.twole.info), funded by the Fondazione CARIPLO. The author acknowledges the contribution of the whole TwoLe team to this project.

The work presented in this paper points out some innovative aspects. The study does couple not only an economic model and a spatially distributed hydrological model, but also it incorporates the two models in a wider procedure aiming to support the process of water resources planning at basin scale, based on the IWRM paradigm (Soncini Sessa et al., 2007).
While the economic model defines different land use scenarios deriving from the effects of agricultural policies on farmers' production choices, the hydrological model assesses the crop water requirements and determines the consequent variations of irrigation water demand at the basin scale. Finally, the modified pattern of irrigation demand of each land use scenario is incorporated into a multi-objective optimisation procedure, which generates a set of efficient water management policies. The stakeholder involvement is a central component in all phases of the process, including setting the optimization objectives and selecting the performance indicators for the different uses of water resources within the basin.
This paper focuses on the first two phases of the process, i.e. describing the characteristics of the economical and hydrological models and presenting the results of their application to a basin in Northern Italy, the Adda river basin.

Methodology

The proposed methodology is based on the combined use of two different models:
- an economic model used to predict the likely land-use scenarios following the CAP reform;
- a spatially distributed hydrological model for the assessment of irrigation water requirements for each of these scenarios and for the simulation of irrigation water use.

The economic model is based on the Positive Mathematical Programming algorithm (PMP, Howitt, 1995) and identifies different land use scenarios, deriving from the effects of the CAP measures on farmers' production choices, including the effects of market prices of agricultural products and, eventually, other specific constraints (e.g. on water availability and feed needs for breeding).
The hydrological model assesses the crop water requirements for each land use scenario, taking into account the spatial distribution of land use changes, as well as the spatial variability of physiographic and meteorological conditions within the basin.
Finally, the set of irrigation water demand scenarios that is obtained is taken into account to develop the Plan of Measures as required by the Water Framework Directive.[1] Also, the hydrologic model is used to predict impacts on the irrigation supply and crop yield.

[1] The Programme of Measures includes all the measures aimed to achieve the objectives set in the River Basin Management Plan.

Economic model and land use scenario generation

The economic model is based on the theoretical requirements of the Positive Mathematical Programming (PMP) as formalized by Howitt (1995a). The aim of the PMP is to calibrate an optimisation algorithm on the basis of the observed behaviour in a sample of farms during a reference period (baseline). The PMP is applied here under the assumption of a profit maximizing equilibrium in the baseline situation, while using the observed production levels as the basis upon which the coefficients of the non-linear objective function are measured. The PMP implementation follows three steps, as outlined below.

First, a Linear Programming (LP) model is defined, where the land allocated to each production process is used as a calibration constraint. The marginal cost values of the soil factor in each activated production process are obtained from the dual structure. The aim of the linear model is to obtain a vector of differential marginal costs that, together with a vector of accounting costs, indicates the variable marginal cost given by all calibration constraints, which, in this specific case, are represented by the land factor. It is then possible to derive the vector of the activity levels.

The second step uses duals to calibrate the parameters of the non-linear objective function. The third and final step of the PMP methodology is the calibration of a non-linear model, whose optimal solution has the same apportioning of land among the various production processes observed in the baseline period. The objective function of the model is then included in a non-linear programming problem identical to the one of the previous step, but with constraints deriving from the calibration. This model is then used to simulate scenarios of production choices, as described in the paragraph "Implementation of the economical model and scenario generation" (p. 25).

Hydrological model and crop water requirements model

The hydrological model is a distributed-parameter, conceptual model, which allows the simulation of the irrigation water distribution and the computation of the hydrologic balance in the root zone on a daily basis. The model includes three main modules, devoted to specific tasks: water sources, conveyance and distribution and, thirdly, soil-crop water balance.

The water balance module (Galelli et al., 2009) accounts for the space variability of soils and crops, as well as of meteorological and irrigation inputs, by subdividing the irrigation district with a regular mesh: soil and crop characteristics as well as meteorological inputs and irrigation supply are homogeneous in each cell of the mesh but may vary from cell to cell. Each individual cell identifies a soil volume which extends from the soil surface to the lower limit of the root zone, and a one-dimensional representation of the hydrological processes is adopted within it. The soil volume of each cell is subdivided into two layers: the upper one (evaporative layer) represents the first few centimetres of the soil; the bottom one (transpira-

tive layer) represents the root zone. The two layers are modelled as two non-linear reservoirs in cascade, by solving the water balance equations of each reservoir with a daily time step.
The model can be used both to simulate the behaviour of the irrigation system and of crops when the water availability is limited, and to compute the crop water requirements. In the former case, the daily volumes available for irrigation in each day of the simulation period need to be provided as inputs and the model computes the irrigation supply to each cell and all other terms of the hydrological balance, which, in turn, can be used to compute the values of crop water stress or yield response. In the latter case, it is assumed that there are no limitations to the water availability and the model computes the daily values of the irrigation water requirements in each cell of the district, over the whole simulation period. Land use, crop and soil parameters, along with the time series of the relevant meteorological variables are needed to run the model simulations.

Case study application

The study area is the basin of the Adda river, in Northern Italy, which in its 7,000 km^2 includes the regulated Como Lake (Figure 1). The basin is characterized by a great variety of water uses: in the alpine portion, upstream of the lake, hydropower production is the main use: 20 reservoirs -with a total storage capacity of 500 106 m^3 - supply water to hydropower plants with a total nominal capacity of 90 MW. The lake is a key resource for tourism and sailing activities, while a public navigation service provides a connection between the shores. In the southern plain, an ancient and complex network of canals provides water to a 3,500 km^2 wide irrigation district, where intensive agriculture coexists with highly developed industrial and commercial activities and with a considerable population (about 1,500,000 inhabitants). Finally, flood protection and environmental issues are important both upstream and downstream of the lake and a significant portion of the river valley is included in regional parks.
The Como lake has been used for sixty years as a regulated multipurpose reservoir, with an active storage capacity of 250.106 m^3. Its management has been primarily aimed at the satisfaction of water demands for irrigation and at flood control, both on the lake shores and on the outflowing Adda river. Due to changes of the legal and hydrological conditions, the conflict between these objectives has become a burning issue.
The present study aimed to verify the feasibility and the benefits of incorporating the methodology presented in the previous section in the River Basin Management Planning process, as required by the Water Framework Directive 2000/60, in order to account for the future land use scenarios in the area following the MTR implementation and to predict their impact on the irrigation demand.

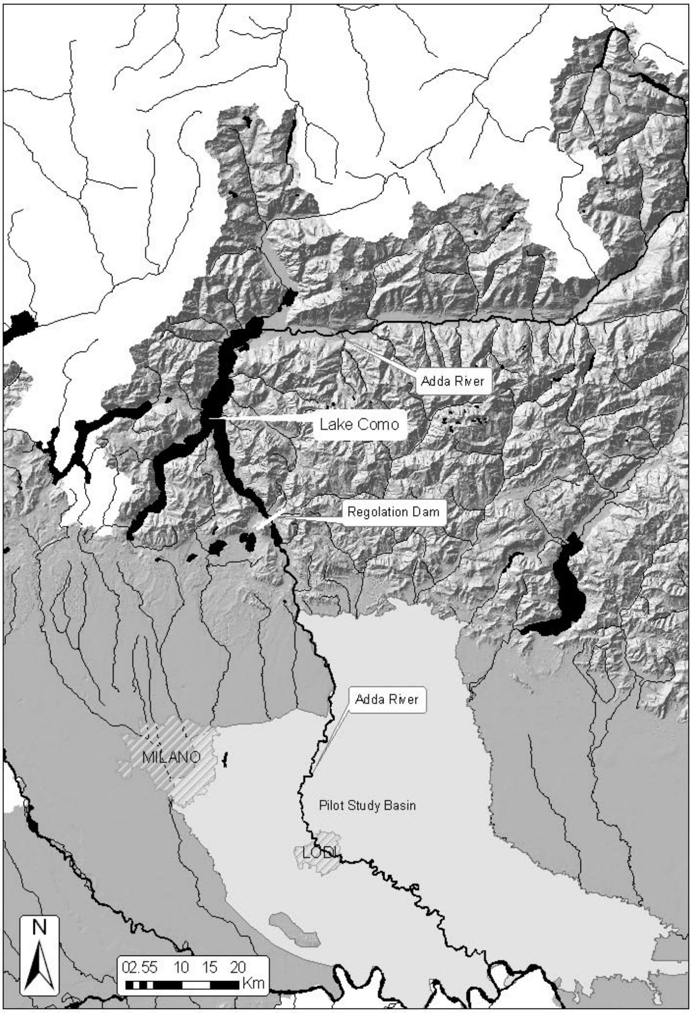

Figure 1. The Como lake - Adda river system. The irrigation district is shaded in light gray.

Implementation of the economic model and scenario generation

The analysis has been carried out using farm business data from the European Union Farm Accountancy Data Network (EU-FADN). EU-FADN data were then integrated with farmers' land use request for CAP payments, which are included in the Agricultural Information System of the Lombardy Region (SIARL in the Italian acronym). The prevailing farming activity is specialist dairy farming and the main crops grown are grain corn, silage corn, alfalfa, forage crops and soya bean, covering approximately 90% of the whole UAA (Utilised Agricultural Area). The dairy farming and crop production data have been included in the analysis. The total agricultural area is divided in smaller regions, based on the classification of the Italian National Institute of Statistics (ISTAT in the Italian acronym), which identifies fifteen units that are homogeneous according to their territorial and agricultural features. These units are called Agrarian Regions (Figure 2).

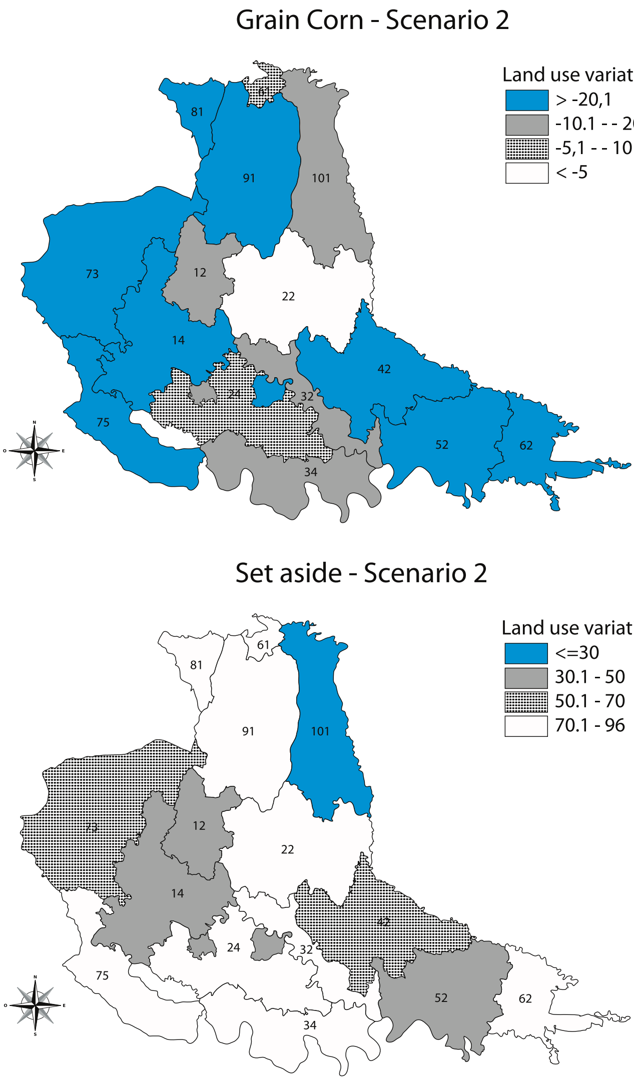

Figure 2 - Borders of the Agrarian Regions (numbers indicated are ISTAT codes of the Regions) and colour-coded representation of land use variations (%) between baseline and scenarios for grain corn and set-aside.

The economic model was first calibrated for the baseline situation (year 2004 land use) and then used to generate a number of different possible land use scenarios, each of them differing in the change of selected exogenous variables in the PMP formulation (Figure 2). Changes included varying cereal prices (corn, wheat, barley), as well as milk price. As an example, one of the scenarios (scenario 2) is based on the expectation of a 15% fall in grain prices, as well as in the price of oil plants and plant protein crops, and includes, as a possible effect of the single payment on animal husbandry, a drop in milk price of 20 %. The land use obtained for scenario 2 shows: i) a considerable reduction in the cultivation of corn crops, both grain and silage; ii) a parallel growth in the production of other forage crops and other cereals; and iii) a sharp increase of set aside.

Irrigation water requirements

The model implementation for the Adda irrigation district was based on a careful collection and collation of all the available physiographic, meteorological and hydrometric data, as well as on a thorough investigation of the irrigation management rules and criteria. The model was used for the estimation of the crop water requirements of both the baseline conditions and the scenarios generated by the economic model.

Figure 3 compares the average values of the seasonal irrigation water requirements of each Agrarian Region for baseline and scenario 2. The variations range between 3 and 14 %, with the highest values deriving from the combined effects of crop type changes within the irrigated areas and of the increase of non-irrigated areas. The simulation results also show that the variations are not uniformly distributed within the season: they are generally smaller or even positive at the beginning, while they become larger and negative in July and August, when the requirements reach the peak values. The main driver of this latter variation is the decrease of corn, while the slight increase of the demand in the early season is due to the increase of grassland and alfalfa. This behaviour is more or less pronounced in the different Agrarian Regions, but is clearly reflected in the time pattern of the daily irrigation requirements of the whole area, which show a moderate but significant deviation from the present conditions all through the irrigation season (Figure 4).

The predicted reduction of crop water requirements was taken into account in the water resources planning process, since the less stringent demand from the irrigation sector may enhance the satisfaction of other users of the water resources system. The analysis of Scenario 2 has shown that the decrease of irrigation demand may allow, for example, a significant reduction of the flooding episodes in Como or the doubling of the minimum flow that is currently maintained in streams for ecological reasons, preserving the same value of the irrigation performances indicator.

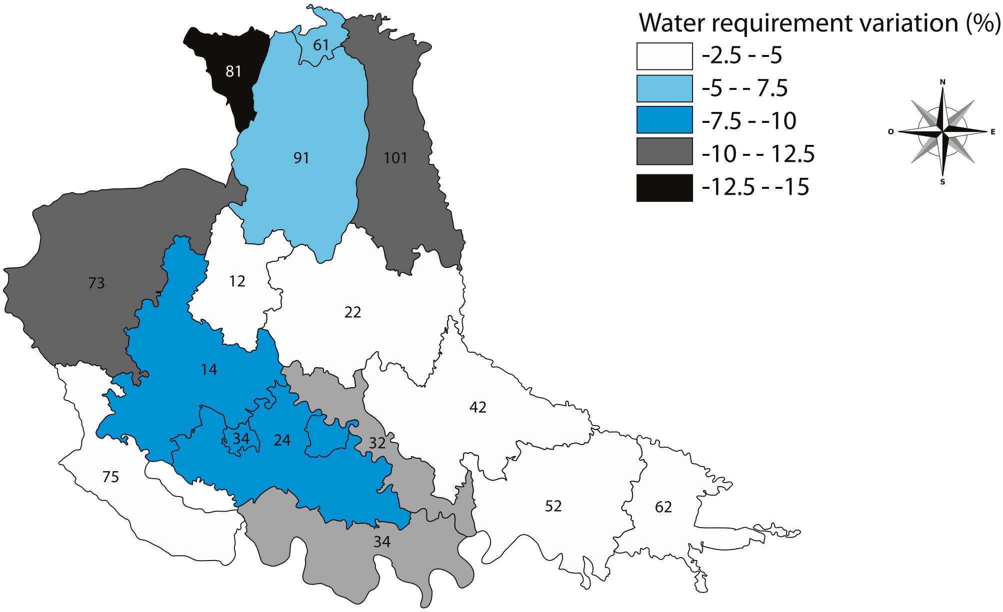

Figure 3 - Variation of irrigation requirements (%) in the summer season between baseline and scenario 2.

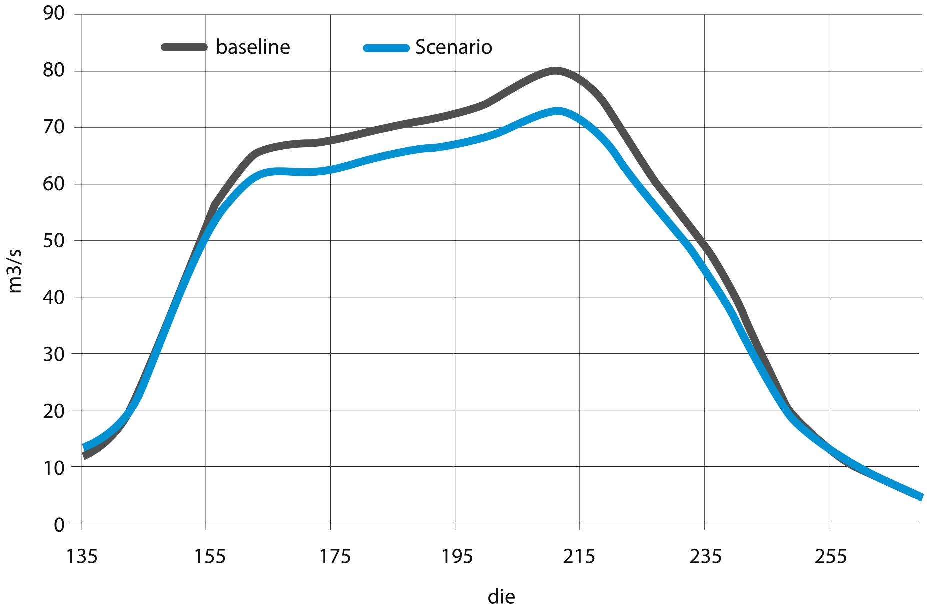

Figure 4 - Variation of the total average irrigation requirement between baseline and scenario 2 (years from 1993 to 2005).

Conclusions

The approach followed in this study represents an attempt to include the predictable effects of agricultural policies in the planning process of water resources at the basin scale. The discussion of the results involves two aspects. The first one is specific to the Adda basin case study, while the second is general, and refers to the potential and limitations of combining economic, hydrologic and management modelling and optimization tools.

In the Adda case study, the economic model has highlighted how the CAP acceleration, driven by the Mid Term Review may produce an adjustment on the agricultural sector, as a consequence of farmers' reactions to the *single payment*, which heavily affects their crop preference.

On the whole, as a reaction to a general fall in agricultural prices, farmers tend to shift to more extensive land uses, as well as to a greater productive diversification. The predicted changes in land use type and distribution have a significant influence on the irrigation water requirements, with a generalized decrease of their average value, which may exceed 10% in some areas. In turn, the decrease of the irrigation demand can be exploited to achieve a higher degree of satisfaction of other users of the water resources system.

The second relevant aspect of this study is related to the innovative approach presented in the paper, that combines economic, hydrologic and management modelling and optimization tools. Since pressures due to agricultural activities have a major role in the status of water resources systems throughout Europe and many other countries, the evaluation of the effects of agricultural policies on water resources is a key problem in water resources planning and management.

The Adda case study has shown that complexity associated with using a set of different modelling and optimization tools to support the water resources planning process can be managed. However, such an effort is justified, providing an effective support to the river basin planning process, only if stakeholder involvement takes place from the very early stages, when the planning objectives and the performance indicators are defined, and the relevant processes that need to be accounted for by the simulation models are identified.

Indeed, in the TwoLe project one of the first activities was to identify and contact 271 potential stakeholders, whose participation was then achieved through 4 plenary meetings, a number of targeted meetings with specific groups of stakeholders (e.g. agricultural) and communications through the project website. Different techniques for the elicitation of knowledge were applied, including questionnaires, structured interviews, conceptual maps, brainstorming. The result was that 45 out the 271 subjects, actively took part in the project activities, contributing in different ways to define objectives and indicators and share data and information on the water resources system's characteristics.

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Determining Groundwater Vulnerability to Nitrate Contamination from Agricultural Sources

Bernard T. Nolan and Kerie J. Hitt

Groundwater is an important resource that provides drinking water for at least 1.5 billion people worldwide, according to the U.S. Agency for International Development. Nitrate is a widespread contaminant in ground and surface waters and is steadily accumulating in aquatic ecosystems. Globally, human production of nitrogen (N) has increased significantly since 1950 and currently exceeds nitrogen fixed by natural processes by about 30%. These increases are primarily related to increased food and energy production. Fertilizer is the largest contributor of anthropogenic N worldwide, with other major sources comprising animal manure; atmospheric inputs of N oxides emitted by utilities, industry, and automobiles; and leguminous crops that fix atmospheric nitrogen. Nitrogen is transformed to nitrate in the soil and that which is not assimilated by plants or denitrified can readily leach to groundwater. Nitrate that accumulates to high levels in groundwater is a human health concern. The World Health Organization has promulgated a guideline of 50 mg/L as nitrate (equivalent to 11 mg/L as nitrate-N) to protect against methemoglobinemia or "blue baby syndrome." In the United States, the maximum contaminant level for nitrate in drinking water is 10 mg/L nitrate-N. For consistency, all nitrate concentrations in this paper are reported as N.

Systematic monitoring is the most effective way to determine nitrate occurrence in groundwater. For example, monitoring of 2,130 wells by the U.S. Geological Survey's National Water Quality Assessment Program (NAWQA) indicated that shallow groundwater (typically <5 m) beneath agricultural land had higher nitrate concentration (median = 3.4 mg/L as N) than shallow groundwater beneath urban land (1.6 mg/L) and deeper groundwater typically used for drinking (0.48 mg/L). However, it is impractical and unaffordable to monitor everywhere, such that water-quality data are of limited availability. Data gaps can be addressed with models that use spatial data on chemical inputs and environmental characteristics to predict contaminant levels in unmonitored aquifers. This paper emphasizes parsimonious statistical models that are calibrated to observed chemical concentrations. Because such models typically have far fewer parameters than mechanistic models, they can be readily applied at large spatial scales. Statistical models, therefore, are appropriate for determining the vulnerability of aquifers to nonpoint source contaminants dispersed over broad areas. Here, aquifer vulnerability is defined as the coincidence of stressors (e.g., N loading) and factors that represent the inherent susceptibility of the underlying aquifer (e.g., well-drained soils). N loading refers to fertilizer, manure, and atmospheric inputs of N to the land surface.

In this paper we summarize three modeling approaches: logistic regression (LR), nonlinear regression (NLR), and classification and regression trees (CART). The models use readily available explanatory variables compiled in a geographic information system (GIS) representing the sources, transport, and fate of nitrate in groundwater. LR and NLR have the advantage of less process complexity (i.e., fewer parameters) compared with mechanistic models (e.g., MODFLOW, MODPATH) and, therefore, less intensive data input requirements. CART is entirely data-driven and features decision rules in lieu of model parameters. Each of the modeling approaches (LR, NLR, and CART) is described in more detail below along with examples from the NAWQA Program.

Logistic Regression

Logistic regression differs from classical, linear regression in that the modeled response is the probability of being in an ordered category, rather than the observed quantity of a response variable. Model parameters are estimated by the method of maximum likelihood instead of ordinary least squares. LR is well-suited to analysis of nondetects, which can be ranked relative to other concentration categories.

The log of the odds ratio, or logit, transforms probabilities into a continuous, unbounded variable that is a linear function of the explanatory variables. The resulting equation is

$$\log\left(\frac{P}{1-P}\right)=\beta_0+\beta_1X_1+\beta_2X_2+\ldots+\beta_kX_k \qquad (1)$$

where $\left(\frac{P}{1-P}\right)$ = the odds ratio; P = the probability of exceeding the threshold value; β_0 = the intercept; and $\beta_k X_k$ = k^{th} slope coefficient and explanatory variable such as percent land cover or depth to the water table.

The nonlinear logistic transformation converts the predicted values of the response variable back into probability units that are constrained between 0 and 1, where $P(Y=1)$ is the probability that the response variable exceeds the LR threshold:

$$\mathrm{P(Y=1)} = \frac{e^{(\beta_0+\beta_1 X_1+\beta_2 X_2+\ldots+\beta_k X_k)}}{1+e^{(\beta_0+\beta_1 X_1+\beta_2 X_2+\ldots+\beta_k X_k)}} \tag{2}$$

The likelihood ratio test statistic or "model chi-square" (G_M) tests the overall statistical significance of the LR model:

$$G_M = -2(L_{\mathrm{int}} - L_{\mathrm{model}}) \tag{3}$$

where L_{int} = log-likelihood of the intercept-only model and L_{model} = log-likelihood of the model with one or more explanatory variables. G_M is approximately chi-square distributed in large samples and the null hypothesis is that the additional parameters in the full model equal zero. The Wald statistic tests the statistical significance of individual coefficients in the model and is the ratio of the estimate of the slope coefficient to its standard error. It follows approximately a normal distribution in large samples and its p-value indicates whether the slope coefficient is significantly different from zero. Wald and G_M statistics were used in this research to build an optimal model, and the Hosmer-Lemeshow (HL) statistic was then used to assess model goodness-of-fit. In the HL test, data are ranked from low to high by values of the predicted probabilities and typically grouped into ten "deciles of risk" to compare observed and predicted probabilities.

The LR model was calibrated to groundwater data from 1,280 shallow wells (depth to water typically less than 5 m) in the conterminous U.S. between 1992 and 1995. A LR threshold of 4 mg/L nitrate was specified, meaning that the model predicted the probability of exceeding 4 mg/L nitrate in groundwater. Explanatory variables evaluated during LR modeling comprised N loading from various sources and aquifer susceptibility characteristics that potentially affect nitrate mobility and fate, such as percent well-drained soils and depth to a seasonally high water table. N load and land use data were compiled within 500-m circular buffers around sampled wells. Other data, such as soils and geology, varied little within well buffers and thus reflected conditions at the scale of the monitoring network or the aquifer. Note that all explanatory variables were available as GIS data layers throughout the spatial domain (i.e., the conterminous U.S.) to enable prediction in unsampled areas.

Six explanatory variables remained in the LR model after calibration (Table 1); thus the national scale model was very parsimonious. The G_M p-value was <0.0001, indicating that the final model was highly significant. Wald p-values in Table 1 indicate that each explanatory variable's slope coefficient was highly significant ($p \leq 0.002$ for all variables). The p-value of the HL goodness-of-fit statistic was 0.22, indicating reasonable fit to the observed data (with this statistic higher p-values do not support rejection of the null hypothesis that the model adequately fits the data). The model correctly predicted nitrate contamination status for 68% of the wells. Observed and average predicted probabilities were highly correlated for deciles of risk (R^2 = 0.875). The LR model was validated with an additional 736 wells that were sampled during 1996 - 1999. Observed and average predicted probabilities for deciles of risk were reasonably well correlated for the validation data set (R^2 = 0.793).

The LR model was used to create a map showing the probability of nitrate exceeding 4 mg/L in groundwaters of the U.S. (Figure 1a). The explanatory variables in Table 1 were recompiled within 1-km grid cells, and Equation 2 was used to predict the probability of nitrate exceeding 4 mg/L for each grid cell. The mapped probabilities reflected regional patterns of groundwater nitrate response to N sources and aquifer-susceptibility characteristics. The likelihood of nitrate contamination was high in the central U.S. and in selected areas of the western and mid-Atlantic states. These areas tend to have high N fertilizer loading and well-drained soils overlying unconsolidated, coarse-grained deposits. In the southeastern U.S., the probability of nitrate contamination was low even though N loading can be high. High organic carbon content in poorly drained sediments of outer Coastal Plain areas results in denitrification, a bacterially mediated process that converts nitrate to N_2 gas.

Nonlinear Regression

Whereas logistic regression predicts the probability of exceeding a specified contaminant concentration, it is frequently desirable to predict contaminant concentrations for comparison with water quality criteria such as human health standards. Multiple linear regression (MLR) can predict contaminant concentrations, but experience has shown that the uncertainty of the predictions is large when MLR models are applied at large spatial scales. Also, unless the response variable has been appropriately transformed, MLR can predict negative values, which is physically unrealistic. To address these limitations, an NLR model (Ground WAter Vulnerability Assessment or GWAVA) was developed based on average values of N loading and aquifer susceptibility characteristics within monitoring networks. Data from individual wells were spatially averaged within networks to minimize

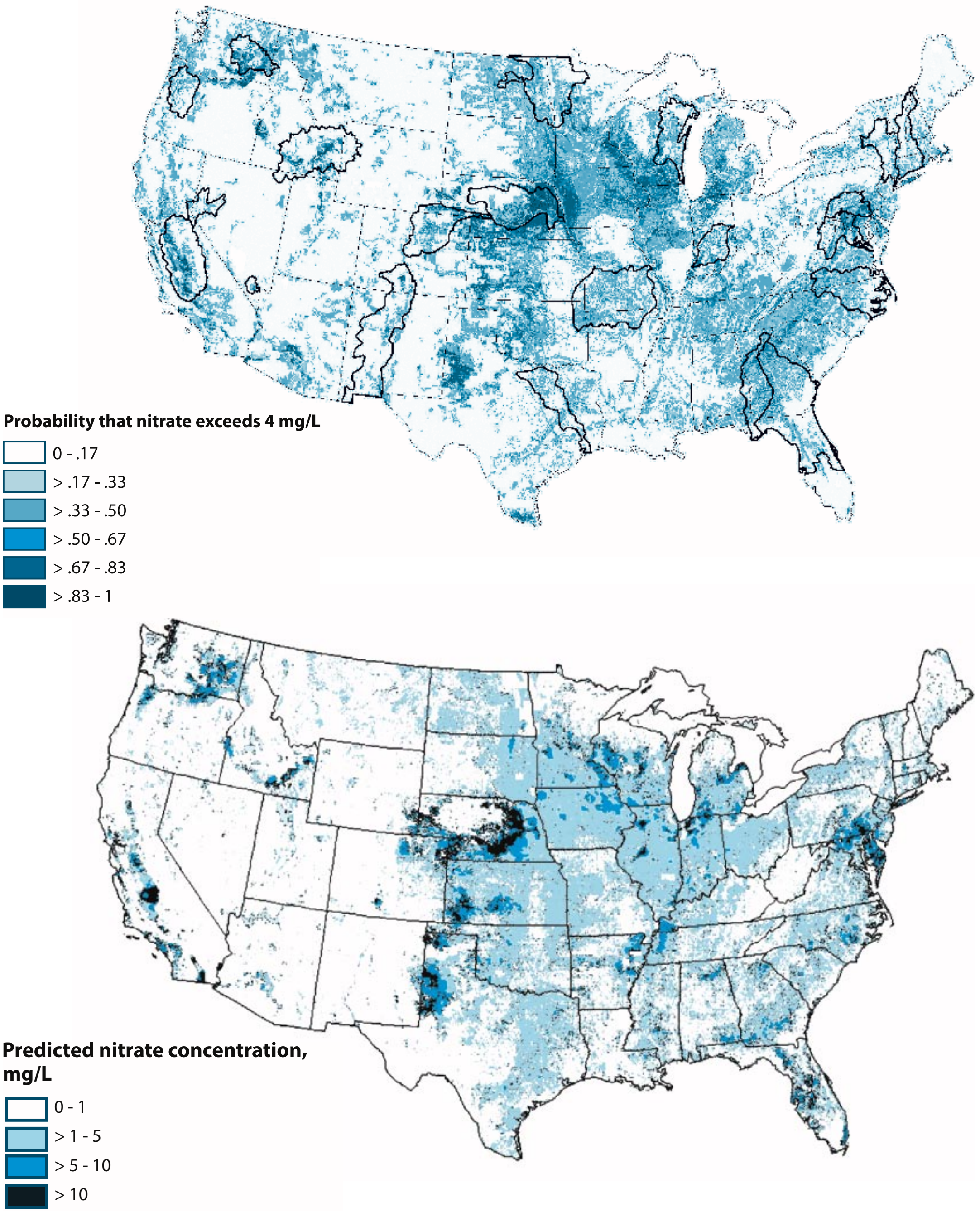

Figure 1. Aquifer vulnerability determined by (a) logistic regression as the probability that nitrate exceeds 4 mg/L in shallow groundwaters of the United States; and (b) by the GWAVA nonlinear regression model as nitrate concentration in shallow ground water. Black outlines in Figure 1a indicate NAWQA study basins.

small-scale variability so that the large-scale influences of N loading, climate, and aquifer characteristics could be more readily seen. The nonlinear model is more "mechanistic" than LR and MLR because it segregates nitrogen (N) sources and physical factors that enhance or attenuate nitrate transport and accumulation in groundwater. Finally, the multiplicative exponential structure of the model constrains predictions of contaminant concentrations to ≥ 0 mg/L. The form of the GWAVA model is

$$c_{gwi} = S_i \bullet T_i \bullet A_i + \varepsilon_i \tag{4}$$

where

N sources: $S_i = \sum_{n=1}^{N} \beta_n X_{n,i}$

Transport: $T_i = \exp\left(\sum_{j=1}^{J} \alpha_j Z_{j,i}\right)$

Attenuation: $A_i = \exp\left(\sum_{k=1}^{K} -\delta_k Z_{k,i}\right)$

and c_{gwi} = observed mean nitrate concentration in groundwater associated with network polygon i, mg/L; $X_{n,i}$ = average N loading from source n in network polygon i; $Z_{j,i}$ = average transport factor j in network polygon i; $Z_{k,i}$ = average attenuation factor k in network polygon i; βn = coefficient for N source n; α_j = coefficient for transport factor j; δ_k = coefficient for attenuation factor k; and ε_i = model error for network polygon i. Two versions of GWAVA were developed: one for shallow groundwater, and one for drinking water wells. The shallow groundwater model is described here.

Because GWAVA is nonlinear in the parameters, ordinary least squares cannot be used for parameter estimation; instead, an iterative procedure was implemented using PROC MODEL in SAS statistical software. Model performance was evaluated through the coefficient of determination (R^2), mean square error (MSE), p-values associated with the estimated coefficients, and analysis of model residuals.

The GWAVA model was calibrated to 97 shallow groundwater monitoring networks comprising 2,306 wells sampled during 1991 - 2003. Most of the wells were in agricultural and urban areas, but a few represented other land uses such as mining. Over 100 explanatory variables were evaluated, including management practices such as the extent of agricultural drains. The final model consisted of the variables in Table 1 and had MSE = 2.96 and R^2 = 0.801. The latter statistic

Variable	Estimated coefficient	p-value
Logistic regression model		
Intercept	-5.541	<0.001
N loading from fertilizer, kg/ha	0.004	<0.001
NLCD cropland-pasture, percent	0.016	<0.001
ln(1990 population density), ln(people/km^2)	0.229	<0.001
Well-drained soils[a], percent	0.025	<0.001
Depth to seasonally high water table, m	1.088	<0.001
Presence or absence of unconsolidated sand and gravel aquifers	0.424	0.002
Nonlinear regression model (GWAVA)		
Nitrogen source (β)		
N loading from farm fertilizer, kg/ha	0.227	0.002
Confined manure, kg/ha	0.405	0.004
Orchards/vineyards, percent	1.960	0.023
Population density, people/km^2	0.007	<0.001
Cropland/pasture/fallow, percent	0.147	0.014
Transport to aquifer (α)		
Water input[b], km^2/cm	38.16	0.009
Carbonate rocks, binary indicator	0.563	0.001
Basalt and volcanic rocks, binary indicator	0.518	0.105
Drainage ditch, km^2	-6.48	<0.001
Slope, percent	-0.039	0.001
Glacial till, binary indicator	-0.814	0.001
Clay sediment, percent	-0.048	<0.001
Attenuation (δ)[c]		
Fresh surface water withdrawal, megaliters/day	-1.08	<0.001
Irrigation tailwater recovery, km^2	-8.33	<0.001
Histosol soil type, percent	-0.019	0.100
Wetlands, percent	-0.032	0.036

Table 1. Explanatory variables and estimated coefficients in the calibrated regression models.

[a] Sum of percentages of STATSGO soil hydrologic groups A and B in groundwater study area

[b] Ratio of irrigated land to precipitation

[c] Although the negative sign is embedded in the attenuation term in equation 4, it is repeated here for consistency with how the other variables in the table are presented.

indicated that much of the variation in groundwater nitrate concentration was explained by the model. The model was then used to predict nitrate concentration in shallow groundwaters of the U.S., after recompiling the explanatory variables in Table 1 for 1-km^2 grid cells representing the conterminous U.S. Areas with high N loading, low-to-moderate clay content, high water input, and low denitrification potential had the highest predicted nitrate concentration (Figure 1b). The most extensive areas of high nitrate concentration (> 10 mg/L) were predicted to occur in the High Plains (primarily Kansas, Nebraska, and Texas), and areas of predicted, moderate contamination (> 5 to ≤ 10 mg/L nitrate) were fairly extensive in the northern Midwest. The High Plains aquifer is extensive and comprises portions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.

Parameter coefficients in Table 1 reveal processes influencing nitrate transport and accumulation in groundwater. All of the N source parameters had positive signs, indicating that nitrate concentration in shallow groundwater increased as N loading increased. Transport parameters had positive or negative signs depending on whether they increased or decreased the amount of nitrate delivered to groundwater. Parameters having a positive sign included water input and selected rock types. Nitrate concentration was predicted to increase with increasing water input, represented in the model as the ratio of irrigated land to precipitation. Carbonate, basalt, and volcanic rocks commonly contain solution channels and/or fractures that enhance the flow of water and chemicals in aquifers. In contrast, all of the attenuation parameters had negative signs. Fresh surface-water withdrawal suggested dilution in irrigated areas overlying highly transmissive rocks. For example, some irrigation districts in the northwestern U.S. apply surface water to thin soils overlying fractured basalt, which can recharge large amounts of low-nitrate water to the aquifer. Areas with histosols and/or wetlands have potential for denitrification. Histosols contain large amounts of organic matter in the upper profile, and wetlands indicate reducing conditions. In combination, these factors suggested denitrification in poorly drained soils with high organic carbon content.

Classification and Regression Trees

CART performs recursive, binary splits of data by the explanatory variables to find decision rules that group observations having a similar response value (e.g., high or low nitrate concentration). Results are expressed graphically as "trees" with branches terminating in nodes that are considered homogeneous clusters of observations. Because decision rules replace equations, there are no model parameters; therefore, statistical assumptions are more relaxed than for LR and NLR. CART makes no assumption regarding the underlying distribution of the data and does not require linear or monotonic relations. It accepts both categorical and continuous predictor variables and automatically incorporates interactions among predictors.

CART was used in this research to explore additional, site-specific factors such as trace elements, dissolved oxygen, and well characteristics that are potentially related to nitrate in groundwater. Note that these data were available only at sampled wells, which precluded their use in the above LR and NLR models. Whereas the latter models used explanatory variables that were available throughout a region to generate vulnerability maps, CART was used to enhance understanding of site-specific processes.

Data analyzed by CART comprised 2,257 shallow wells in agricultural and urban areas of the conterminous U.S., which is very similar to the data set used for NLR. We used a recursive partitioning procedure in JMP statistical software to find the level of the explanatory variable that maximized the difference in sum of squares between a parent node and its two child nodes. The procedure is interactive and has no global stopping criterion; therefore it is possible to over-fit the data. Cross validation can be used to verify model structure.

In the following example, CART was used to explore relations between the dependent variable (groundwater nitrate), nationally available variables used in LR and NLR, and site-specific variables. Each box of the resulting tree is a node and the level at which the optimal partition occurred is indicated by the values below the node (Figure 2). For example, iron concentration in groundwater yielded the optimal partition of the overall data set. The left-hand child node represents observations with iron ≥ 62.98 μg/L (i.e, nitrate reducing conditions), and the right-hand node represents observations having iron concentration <62.98 μg/L. Each of the child nodes was further partitioned until sum of squares differences between the parent and child nodes were minimal.

After iron, partitions occurred on dissolved oxygen and N from farm fertilizer (Figure 2). Iron and dissolved oxygen indicated that redox chemistry was an important control for nitrate in groundwater. The sampled aquifers typically are stratified by groundwater age and redox zones that are defined by predominant electron accepting processes such as nitrate reduction, manganese-oxide reduction, and iron-oxide reduction. The coincidence of high iron and low mean nitrate concentrations (see box outline on left branch of the tree) indicated a progression of redox transformations. On the right side of the tree, nitrate concentration increased with increasing farm fertilizer N and calcium content, low manganese concentration, and more well-drained soils (mean nitrate concentration = 34.1

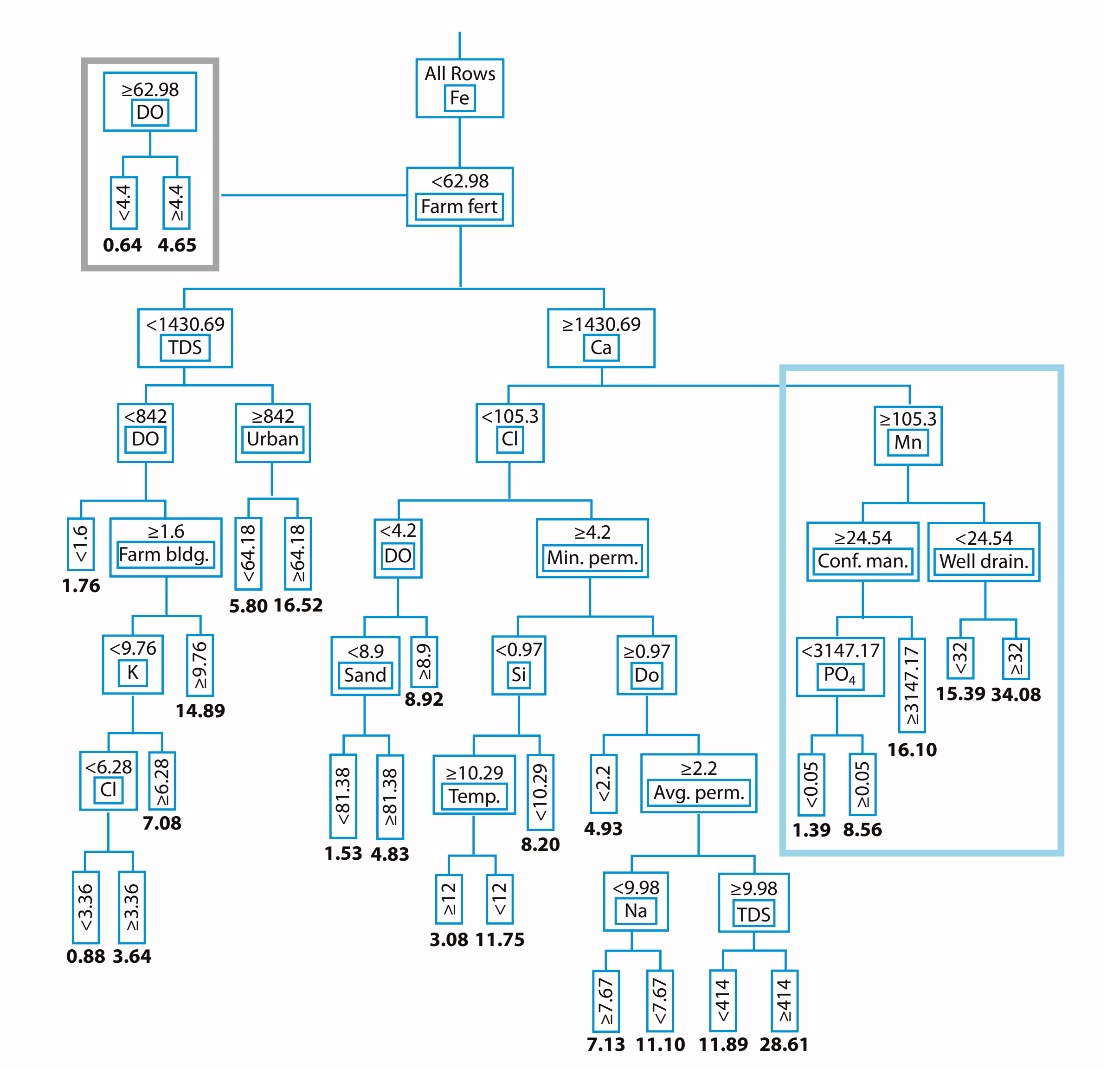

Figure 2. Classification tree from CART analysis of the shallow groundwater data set. The mean nitrate concentration (mg/L) of terminal nodes is shown outside the boxes in bold type. Variables are defined as follows: Fe, iron (µg/L); Mn, manganese (µg/L); Ca, calcium (mg/L); Cl, chloride (mg/L); K, potassium (mg/L); Na, sodium (mg/L); PO4, orthophosphorus, (mg/L); Si, silica (mg/L); DO, dissolved oxygen (mg/L); TDS, total dissolved solids (mg/L); temp., temperature, °C; sand, percent in monitoring network; well drain., percent hydrologic group A soils in monitoring network; farm bldg., percent area of farm buildings in 500-m radius well buffer; farm fert., kg of farm fertilizer in well buffer; conf. man., kg confined feedlot manure in well buffer; urban, percent urban land in well buffer; min. perm., permeability of least permeable soil layer, in/hr; avg. perm., average permeability of soils, in/hr.

mg/L) (see box outline on right branch of Figure 2). CART also provided a listing of variable importance based on the amount of variation in nitrate concentration explained. Iron, manganese, and farm fertilizer N were among the most important variables in the data set, underscoring the strong interdependence between N loading, redox conditions, and groundwater nitrate.

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River Restoration and Sustainable Agriculture in the Venice Lagoon Basin: the Nicolas Project

Bruna Gumiero, Bruno Boz and Paolo Cornelio

The Nitrates Directive, as linked with the Water Framework Directive (WFD or Directive 2000/60/EC), is aimed to provide good water quality and enhance the status of all European water bodies. Reduction of ammonia and nitrate emission should lead to a higher quality of groundwater and prevent the eutrophication of freshwater and marine systems.

Agriculture is a predominant source of nitrogen emission in the European environment. In most agricultural systems the input of nitrogen is higher than the amount removed with the harvested crops. This situation results in leaking of nitrogen to groundwater and surface waters. The nitrate concentration in a number of areas with intensive agriculture exceeds the maximum value for drinking water of 50 mg/l.

The control of nitrate pollution can take place at two levels. Firstly there is the control of input nitrate within the agricultural environment. The second way of action may be found in increasing the complexity of the landscape, not necessarily all over the catchment but in specific zones, especially within the river corridor, by buffer zones.

While actions to inform and train farmers have resulted in much better fertilisation management and agricultural practices, further work is still needed to achieve water quality goals in all EU waters. Many Member States need to increase efforts in a number of areas, including monitoring and identifying pollution hotspots as well as developing tougher action programmes.

A European Commission report of 11/2/2010 (IP/10/154) reveals that nitrate levels in water across the EU are decreasing. However, despite these encouraging

trends, the report reveals a number of regions where nitrate levels are at alerting levels. One of these regions is the northern part of Italy.
The Venice Lagoon is a wide, shallow coastal basin extending for about 50 km along the north-western coast of the Adriatic Sea. A large portion of the catchment of the Venice lagoon is within one of the main Italian reclaimed areas for agriculture. The lagoon has been substantially modified by human activities over the last century through the artificial control of the hydraulic dynamics of the lagoon. Moreover, the land use of its catchment is mainly agricultural (67%). As a consequence, over the past decades, nutrient loads delivered to the Venice Lagoon have attracted considerable concern.
The local government (Regional Authority) established a series of targets to reduce the level of nitrogen and phosphorous entering the Lagoon thanks to a special law (L. 139/1992) aiming to enhance the water quality of water draining into Venice Lagoon. The aim of the targets was to establish eutrophication protection measures as well as to improve the overall quality of the water entering the lagoon.

The Zero River project

The Drainage Authority (Consortium) Dese Sile, which is located in the drainage area of the Venice Lagoon, manages three key rivers contributing 40% of the freshwater flowing into the Lagoon. The Consortium Dese Sile in the last decade has been active in a number of activities, among which a big project aimed at developing a catchment strategy to reduce nutrient loads entering the Venice Lagoon from its rivers.
One of those rivers is the Zero river that joins the Dese river just before the latter flows into Venice Lagoon. Zero is a krenal river,[1] 41.5 km long, with a 7.283 ha watershed, 94% of which is used for agriculture and 6% for urban areas. The watershed is mostly covered by herbaceous cultivations (maize, soybean, wheat).
To achieve this goal, the Consortium planned a major river restoration project for the Zero River. In particular, for two of the main rivers managed by the Consortium, i.e. the Dese and Zero river (the Zero river, as mentioned earlier, being a tributary to the Dese river). The restoration project resulted in a nutrient load reduction of 150 tons/year of N_{tot} and 40 tons/year of P_{tot} which correspond to a reduction of 12 and 17% respectively.
The main objectives of the Zero Project were:

- Reduction of nitrogen and phosphorus loads into the Venice Lagoon
- Reduction of the hydraulic risk (by facilitating water infiltration, reducing superficial runoff and increasing the total stored volumes)
- Increase of the nature value of the river (biodiversity)
- Improvement of the multiple uses of banks and adjacent areas

[1] Groundwater-fed stream type.

The Zero River project has entailed the re-engineering and the restoration of the last 11 km of the homonymous river before its flowing into the Dese river. The project has been conceived as part of the long-term flood defence of this vulnerable area (Figure 1).
River banks along this section are below the 13.50 m threshold required and therefore are liable to fail as a flood defence structure when both high flows within the river and high tides occur. Since this work was planned, the Consortium saw this as an opportunity to develop a new channel section that could increase the ecological value of the river as well as increase the nutrient retention capacity of the riverine environment.
Other than banks widening, the main restoration actions carried out included: increase of aquatic vegetation on river terraces, creation of lateral and inflow wetlands (ponds and lakes) and creation of a wooded riparian area (buffer area) irrigated by the river.

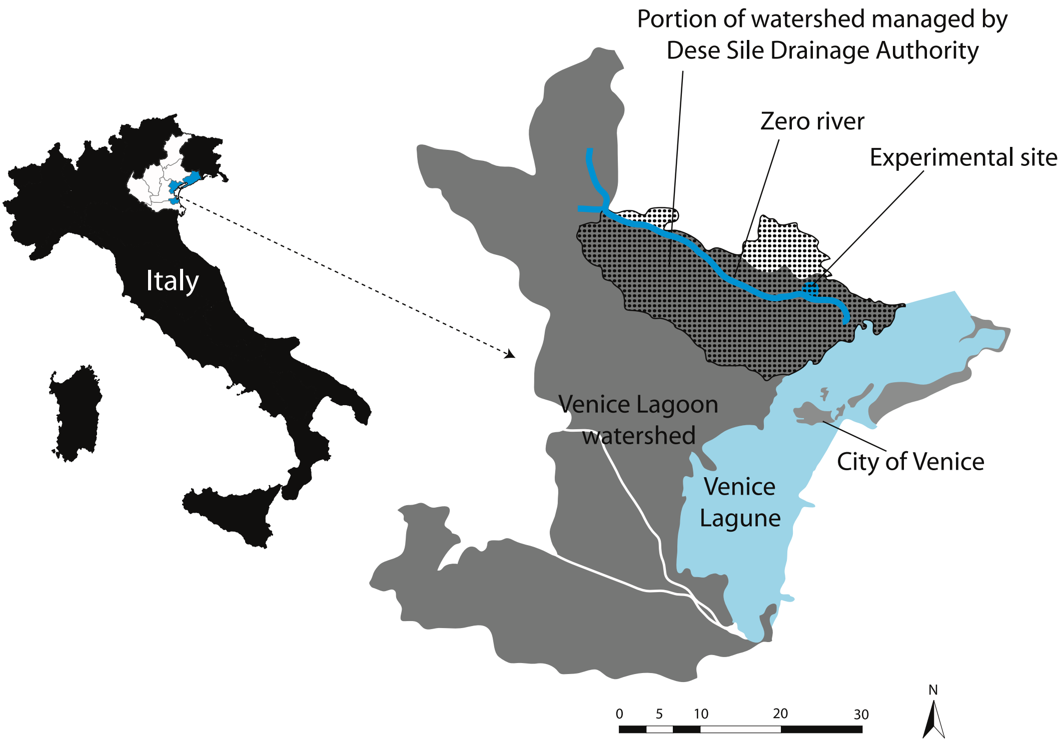


Fig. 1. The experimental site, located on the left bank of the terminal reach of Zero River, in the watershed draining into Venice Lagoon. This portion of basin is managed by Dese Sile Drainage Authority. In March 2010 the Dese Sile Drainage Authority joined the Acque Risorgive Drainage Authority, see www.acquerisorgive.it.

In particular the Consortium Dese Sile restored and created a series of natural key habitats:

1. The freshwater lake “Lago Pojan”. This is a riverine lake, with the same function as an in stream wetland, with an approximate surface of 2 ha, and 4 m depth.
2. The freshwater pond with watergate “Nodo Carmason”. One of the project objectives was to reduce the length of saline water intrusion within the Zero river, thus enabling water to be abstracted from the river for agricultural purposes. To achieve this, a gate was built 3.2 km upstream from the confluence of the Zero and Dese rivers. The height of the gate can be regulated in order to prevent tidal water to flow upstream, but at the same time to permit the discharge of freshwater to the tidal section of the river. The final effect of the gate is the creation of a 6.7 km long section of freshwater that behaves like a pond characterized by near static water height and slow moving water for the majority of time.
3. A terrace in freshwater section. Within the freshwater section of the Lower Zero River, the project foresees a Phragmites thicket of 1.5 m minimum width to limit bank erosion and to facilitate nutrient retention. These functions may be limited but the conservation and ecological value of this community will be significant for the invertebrate communities and fisheries interest.
4. A series of rainwater- and groundwater-fed shallow lakes, called “Cave Cavalli”. These were created in an area previously used for the extraction of clay. The lakes are 1 to 4 meters deep, with a water surface of over 30 ha. Part of the Zero River water passes through the quarry and utilises the potential nutrient retention capacity of the lakes before entering into another series of drainage ditches which ultimately discharge into the Dese river.
5. A wetland next to the tidal gate. Within the Zero project, a provision has been made for a small wetland to be created next to the Zero tidal gate. The main function of the wetland is to allow ecological continuity from the tidal river to the freshwater section. The wetland consists of a sedimentation pool followed by 0.7 ha of Phragmites thicket. This system allows to receive the river low flows and acts as a small but significant filter for freshwater before it passes into the tidal section.
6. A riparian woodland. This is an extensive area of land which is historically reclaimed where the crop fields are lower than Zero River. Thanks to the collaboration between the Consortium Dese Sile and Veneto Agricoltura a cultivated area of about 30 ha was converted into a forested buffer strip, irrigated with freshwater from the Zero river, so that the wet woodland could operate similarly to a natural riparian woodlands. The area was divided in plots of the same size (0.35 ha each) and structure, and each plot was watered through a ditch system carrying water (through a lifting system) from Zero River.

7. A saline wetland. The Zero river downstream from the tidal gate will be subject to the largest degree of engineering work in order to increase the flood defence value of banks. Nonetheless, there are still opportunities to enhance the ecological value of the tidal river. The project allows a minimum of 6 m of Phragmites to colonise the river banks and help minimise the erosion of the new banks from tidal wash and the effects of boats passing along the river. In addition to providing bank erosion control, the Phragmites/Scirpus vegetation complex helps the nutrient erosion.

In order to allow the estimation of nutrient retention capacity of the above actions, the nutrient mass balance was investigated for each of them (research conducted by Quest Environmental) with the model STELLATM 5.0 (Haycock, unpublished data). The simulated scenarios showed that the most efficient system was represented by the wooded riparian area.

The ability of riparian forests in retaining nitrogen has been studied since the early 80's. The effective removal of nitrate within riparian zones is dependent upon the presence of conditions conducive to high de-nitrification rates as well as to the maintenance of a stable vegetation structure. Two processes, vegetation/microbial uptake and de-nitrification, work together to provide a buffer zone that can protect aquatic ecosystems from agricultural excessive nitrogen loadings.

The spatial distribution of riparian forests relative to agricultural fields is likely to affect their functioning and sustainability in controlling nitrogen fluxes. Equally the connectivity between these riparian buffer and landscape sources of nitrogen fundamentally influences their efficiency at landscape level. Indeed, farming systems constitute the key driving force in undermining or enhancing both spatial distribution and connectivity of riparian ecotones within the agricultural landscape.

Hence, the spatial and functional sustainability of riparian ecotones under varying farming practices needs to be evaluated in order to propose the most efficient landscape design to reduce nitrogen fluxes under given climatic and farming constraints.

The efficiency of a riparian zone in regulating nitrogen fluxes is not a function of the surface area of the riparian zone, but rather a function of the hydrological length of contact between the riparian zone and the upland drainage basin. Such a function results from the contact between water and soil sediment, which increases nutrients retention and processing. Therefore the best strategy is to prioritise and conduct riparian protection and rehabilitation throughout all rural catchments, particularly near headwaters.

The experimental site “Nicolas”

The above mentioned 30 ha forested buffer area, within Zero River project, was planted in spring 1999 mainly for timber production, except for a tree strip of purely nature value, covering a surface of 4 ha, which was planted between the productive area and the riverbank. All forested area is irrigated for 10 months/year with water from the Zero River.
A pilot experimental system - to monitor in particular the buffering efficiency of the wooded areas on non-point pollution sources of nitrogen - was built within this much wider forested buffer zone. The experimental site was called “Nicolas” because the entire experimental design (analytical methods, the location of sampling sites and sampling frequency) followed the one adopted by the different Institutes involved in the European Research Project NICOLAS (“Nitrogen Control by Landscape Structures in Agricultural Environment”).[2]
The objectives of the experimental site monitoring (carried out since 1999) were to:

1. Increase knowledge on the processes which allow the riparian forest to act as buffers strips, thus reducing the concentration of the main nitrogen compounds which are carried by the water flow running through them
2. Quantify the amount of the reduction in nitrogen load, and the trend of the reduction during the maturation phase of the riparian forest system
3. Identify the most appropriate management strategies of the buffer strips and water flow in order to choose those typologies, planting techniques and maintenance operations which would maximize the efficiency of the buffer systems

The experimental site covers a total area of around 0.70 ha, divided into two adjacent plots, symmetrical with respect to a drainage ditch which divides them, each one 15 m large and about 200 m long. One-thousand forested samplings of trees and shrubs were planted in each plot (Figure 2).

The structure of the experimental field is characterized by ridges and furrows facilitating sub-superficial water flow throughout the entire field from the inlet point, represented by water pumped through the ridges, to the parallel network of furrows localized at lower elevation.
Analyses carried out before starting to monitor allowed classifying the soils texture category as “silty clay loam” (USDA classification “Soil Survey”), characterized by horizontal and vertical homogeneity until a calcareous layer at around 80 cm depth.

[2] Project funded by DG XII, Environment & Climate (ENV4-CT97-0395). Project coordinator: Université de Rennes I, France. Partners: University of Durham, United Kingdom; INRA, Rennes, France; University of Utrecht, Netherlands; University of Barcelona, Spain; Polish Academy of Sciences, Poland; University of Bucharest, Romania; Ecole Polytechnique Fédérale de Lausanne, Switzerland; Consorzio di Bonifica Dese Sile, Italy; Quest Environmental, United Kingdom; California State University, USA; Royal Holloway Institute for Environmental Research, United Kingdom.

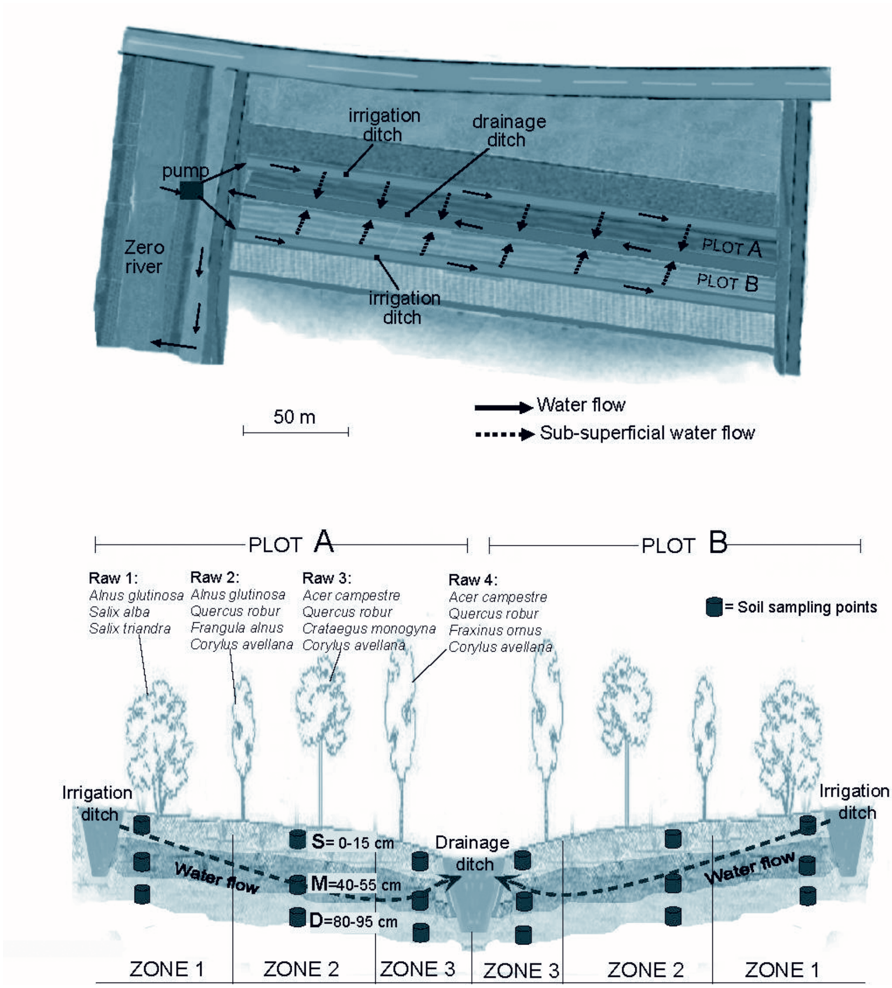
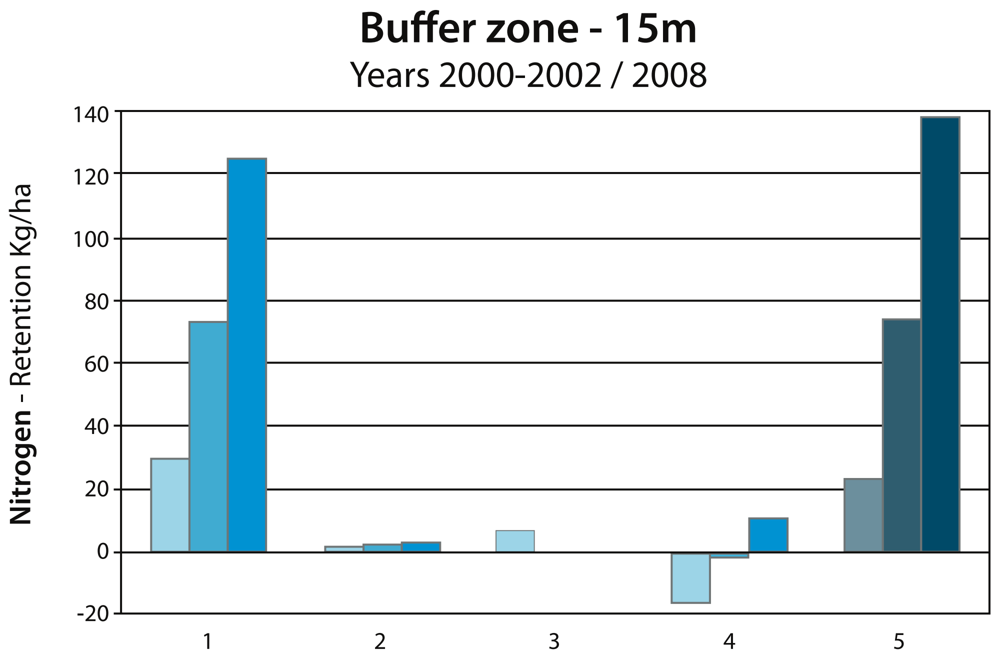


Fig. 2. Plan (above) and section (below) of the experimental site: each of the 2 plots is watered through an irrigation ditch carrying water from the Zero River. Soil setting allows a difference in elevation among the irrigation ditches and the drainage ditch, resulting in a sub-superficial flow of water running through the wooded buffer strips.

Quality of incoming water is checked with a conductivity-meter and an automatic sampler. The monitoring station has 36 piezometers which are used to measure the sub-superficial water level, and to collect water samples.

The experimental site was monitored in two periods; first for three years from 2000 to 2002, and then again during 2008. Thanks to this second monitoring opportunity it was possible to evaluate the long term efficiency of the site.

As regards the different nitrogen compounds, the nitrates retention capacity increased strongly from 46% to 83% from the first to the third year, and remained constant at the highest value in 2008. Ammonia, on the other hand, had higher annual variability, with the output sometimes exceeding the input, but with the trend of reaching the same input and output levels. Organic nitrogen output during the first three years of monitoring was always higher than the input, but with



	RETENTION 2000			RETENTION 2002			RETENTION 2008		
N-NO3	30,0	kg/ha	46%	73,20	kg/ha	83%	125,7	kg/ha	82%
N-NO2	1,8	kg/ha	86%	2,40	kg/ha	84%	2,8	kg/ha	76%
N-NH4	6,9	kg/ha	35%	0,00	kg/ha	-7%	-0,6	kg/ha	-5%
N-Organic	-15,9	kg/ha	-177%	-1,50	kg/ha	-13%	10,7	kg/ha	23%
N-Total	22,8	kg/ha	33%	74,1	kg/ha	55%	138,7	kg/ha	64%

BZ 15m	2000	2002	2008
Irrigation volume	77 m^3/day ha	154 m^3/day ha	205 m^3/day ha

Fig. 3. The mass balance and percentage of removed nitrogen during the monitoring period.

a progressive reduction of the output. On the other hand, a reduction of 24% was recorded during 2008. Overall, total nitrogen retention progressively increased from 33% in the first year to 55% in the third year, reaching 65% in 2008 (Gumiero et al., 2008; Boz & Gumiero, 2009).
With regard to the mass balance, the system was able to remove 75 kg/ha/y of total nitrogen after only three years. In 2008, thanks to a much higher soil permeability, more water was pumped in the system (higher irrigation volume); as a consequence, the buffering capacity reached about 150 kg/ha/y (Figure 3). Nevertheless, the achieved nitrogen removal was lower than the STELLA simulation, because in the model the estimated nitrogen concentration for the Zero River was about 10 mg/l, whereas the observed value was 3 mg/l during all monitoring activities.
All de-nitrification data confirm the high efficiency of the system, with a mean value higher than 300 kg/ha/y. The measurements of potential de-nitrification (de-nitrification enzymatic activity), by soil incubation without limiting factors (nitrogen and carbon), showed a strong potential increase in de-nitrification rates (about 2000 kg N/ha/y) (Haycock et al., 2005; Gumiero et al., 2008; Gumiero et al., in press).
Besides the efficiency in nitrate removal, a clear improvement on soil quality was recorded over time. A significant higher percentage of organic carbon was recorded in the upper soil layer, but it will take a longer time to reach the deeper layers.
Another important goal was achieved thorough this project: the enhancement of biodiversity.
The wooded area can be considered an oasis within a biological desert. It is represented by a diversified trees, shrub and herbaceous communities on the riparian zone, in addition to the reeds and macrophytes living in the permanently-wetted ditches. Such diverse vegetation creates important habitats for fauna, mainly amphibians, dragonflies, terrestrial invertebrates and birds.
Finally, the microbial analysis showed more diversified and active microbial communities than those of the neighbouring arable land.
In general, river restoration, as in the case of the Zero River project, can be a strategic tool to reduce nutrient input to other "sensitive" adjacent ecosystems like lakes, lagoons or coastal water.
At the same time, river restoration can contribute to reach other important goals, such as: reduction of hydraulic risks thanks to the widening of river sections, improvement of the nature value (due to the high naturalness of the restored habitats), and improvement of the multiple uses of banks as well as of the landscape value of adjacent areas.

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Irrigation Water Use, Conservation and Saving. Issues to Support a New Paradigm and the Sustainability of Water Uses

Luis S. Pereira

Many civilisations developed throughout the world in water scarce environments. In the 20th century, the idea of progress questioned the traditional know-how, a knowledge that has been often replaced by modern technologies and management imported from different environments and cultures. Today irrigation management faces difficult challenges due to the fact that irrigators have a different perception of problems, practices and objectives from the non-farmer managers. Traditional institutions and practices lost importance and new centralized institutions were created followed by investments and new technologies. Nevertheless, a turn in re-valuating traditional irrigation is starting and a new perception of advantages of traditional know-how begins to be acknowledged.

In this perspective, it is necessary to develop a new approach for a better understanding of what is water use in agriculture and why performance should be improved responding both to the needs of societies and farming's objectives. In this sense, the same concepts of "performance" need to be differently defined, understood and applied.

The terms "water conservation" and "water saving" are generally associated with the management of water resources under scarcity. The term water conservation refers to every policy, managerial measure, or user practice that aims at conserving or preserving the water resources, as well as combating the degradation of the water resource, including its quality. Differently, water saving aims at limiting or controlling the water demand and use for any specific purpose, including the avoidance of water wastes and the misuse of water. In practice both perspectives are complementary and inter-related. However, these terms should not be used synonymously. In addition, questions related to preservation of and improving water quality are essential in water conservation.

Water use, consumptive use, water losses, and performance

The performance of water supply systems and water use activities are often expressed with terms related to efficiency. However, there are no widely accepted definitions of this term, since "efficiency" is used with different meanings according to different water use sectors. In this sense, a more consistent conceptual approach is required (Pereira et al., 2009).

The term efficiency is often used in irrigation and is commonly applied to each irrigation sub-system: storage, conveyance, off- and on-farm distribution, and on-farm application sub-systems. It can be defined by the ratio of the water depth delivered by the sub-system under consideration and the water depth supplied to that sub-system. In case of on-farm application efficiency, the numerator is replaced by the amount of water added to the root zone storage and the denominator is the total water applied to that field. However, in reality an efficiency indicator refers to a single event and should not be applied to a full irrigation season without adopting an appropriate up-scaling approach.

These ratios relate to individual processes and their use as a bulk term does not provide information on the processes. A scheme on processes involved in irrigation water use is given in Fig. 1. For non-irrigation water systems, the term efficiency is less used but could be similarly applied referring to the various processes involved.

The term "efficiency" often leads to misconceptions and misunderstandings. A common misconception is the fact of considering that increasing irrigation efficiencies are almost synonymous with creating more available water. However, there is the need to quantify the fraction of water used (diverted from a given use) that is beneficially consumed, and the fraction that is not used for consumption and is available for reuse or becomes degraded after use. For the latter case, improving efficiencies would represent a reduction in water losses and contribute to the conservation of the available resource. In many cases, the non-consumed fraction is not degraded and is used by other systems downstream; then, improving efficiencies would not be advantageous to the total system.

According to the present trend, the term efficiency for irrigation water conveyance and distribution is abandoned and new service performance indicators are adopted. In fact, it is recognized that impacts on agricultural yields, farmers' incomes, and farm water management largely result from the quality of the water delivery service. Indicators referring to the reliability, dependability, adequacy,

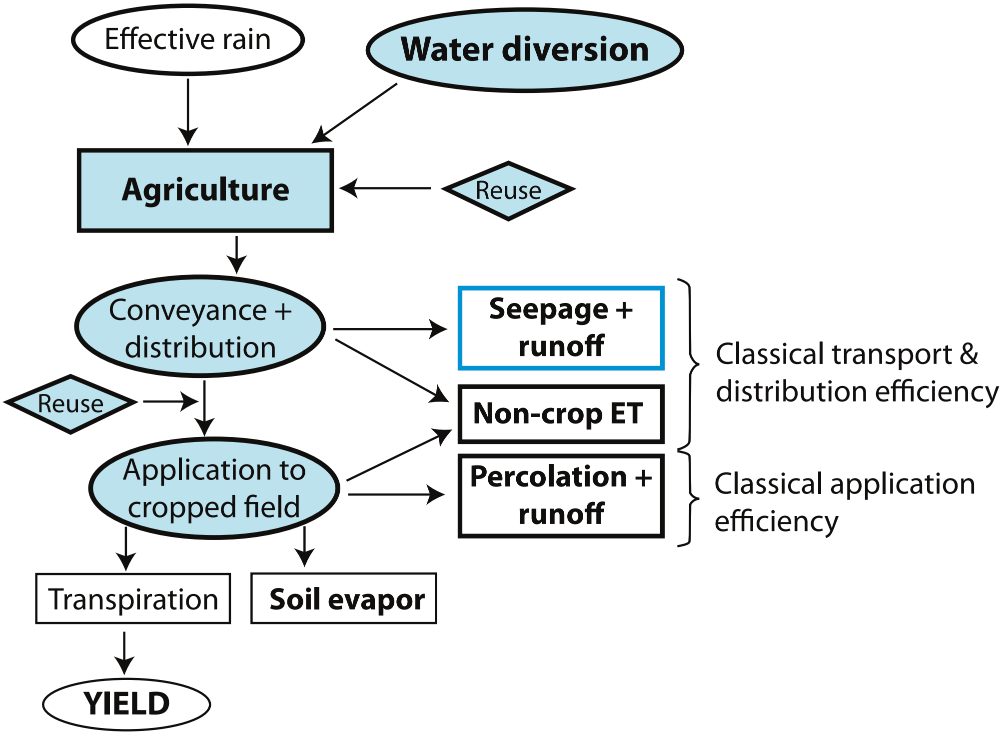

Figure 1. Processes influencing the irrigation efficiency off- and on-farm: in grey boxes, the processes leading to the crop yield; in white boxes, those leading to water wastes and losses.

or equity of deliveries may be used for that purpose. These and other indicators are measures of the capacity of collective water systems for timely water delivery with appropriate discharges, pressure head, time intervals and duration to satisfy the farm requirements throughout the irrigation season and independently of the location of the gate or hydrant. Similar water service indicators are also used for other non-irrigation networks.

The term application efficiency is still used to characterize the management of a given event. However, it must be adopted together with an indicator of the uniformity of water application to the field because when a system does not provide for uniform water application, efficiency is necessarily low and percolation through the bottom of the root zone is high.

Another expression commonly used is "water use efficiency" (WUE), but again no common definition is adopted. In crop production, the term WUE is applied with precise meanings, such as the WUE yield, which is the ratio of the harvested biomass to the water consumed to achieve that yield. In plant physiology and eco-physiology WUE expresses the ratio between assimilates produced during a cer-

tain period of time and the corresponding plant transpiration. In this case, WUE expresses the performance of a given plant or variety in using water. To avoid misunderstandings, the term "water use efficiency" should be only used to measure the performance of plants and crops, irrigated or non-irrigated. The term "water productivity" (WP) should be adopted to express the quantity of product or service produced by a given amount of water used.
Also, new concepts to distinguish more clearly between consumptive and non-consumptive uses, and beneficial and non-beneficial uses, are to be developed. Similarly, the differences between reusable and non-reusable fractions of the non-consumed water diverted into an irrigation system or subsystem are to be clarified. These consist of alternative performance indicators that are much more relevant than "irrigation efficiency" when adopted in regional water management for the formulation of water conservation and water saving policies and measures. These concepts and indicators refer to irrigation and non-irrigation water uses.
When water is diverted for any use only a fraction is consumptive use. The non-consumed fraction is returned after use with its quality preserved or degraded. Quality is preserved when the primary use does not degrade its intrinsic quality

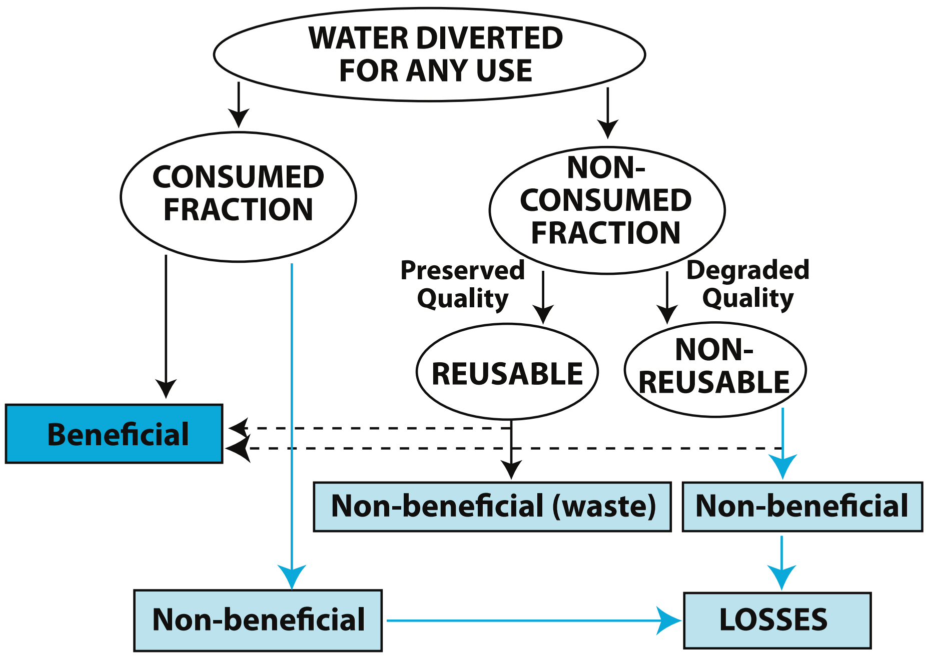

Figure 2. Water use, consumptive and non-consumptive use, beneficial and non-beneficial uses, water wastes and losses.

to a level that does not allow further reuse, or when water is treated after that primary use, or when water is not added to poor quality, saline water bodies. Otherwise, water quality is considered degraded and water is not reusable (Fig. 2)
Both consumed and non-consumed fractions concern beneficial and non-beneficial water uses. These are beneficial when they are fully oriented to achieve the desirable yield, product, or service. Alternatively, when that use is inappropriate or unnecessary, it is called non-beneficial. Reusable water fractions are not lost because they return to the water cycle and may be reused later by the same or by other users. They are not losses; but are wastes since they correspond to water unnecessarily mobilized. Contrarily, the non-beneficial water consumed or returned to poor quality, or saline water bodies, or that contribute to degradation of any water body, are effectively water losses (Fig. 2).

Beneficial and non-beneficial water uses

It is important to recognize in the water economy perspective both the beneficial and non-beneficial water uses (Fig. 3). In crop and landscape irrigation, the bene-

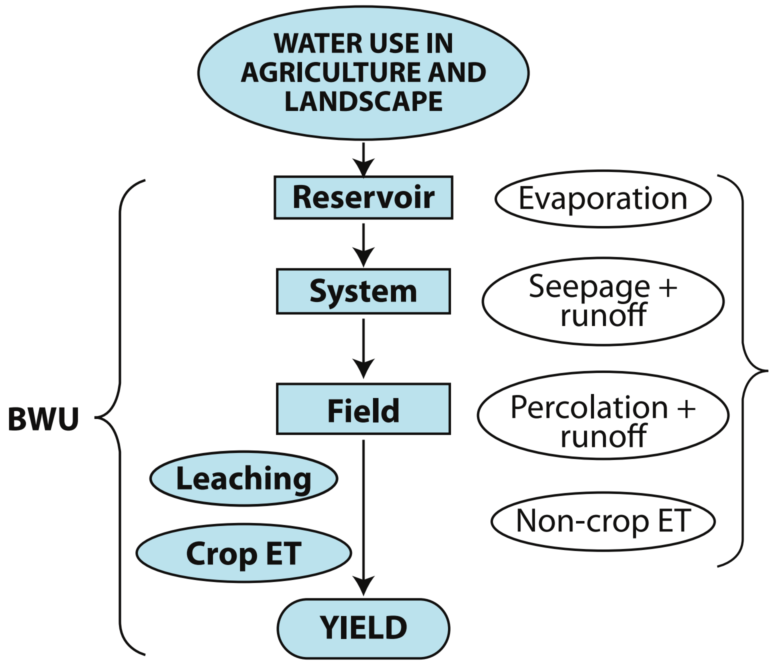

Figure 3. Beneficial and non-beneficial water use (respectively BWU and N-BWU) in crop and landscape irrigation.

ficial uses are those directly contributing to an agricultural product or a delightful garden, lawn or golf course. Non beneficial are those uses that result from excess irrigation, poor management of the supply system, or from water misuse.
These concepts may also be applied to the use of water in industry, urban regions, energy production and other activities. Then beneficial uses include all the activities and processes leading to achievement of some production or service which results in some good or benefit, such as washing, heating, cooling, or generating energy. The uses are not beneficial when water is used in non-necessary processes, is misused or is used in excess of the requirements.

Efficient water use

Assuming the concepts above, it is important to recognize what is meant by "efficient water use". To support this concept, a few main ideas are explained in Fig. 4. First, it is required to identify the water pathways in any water use, to distinguish

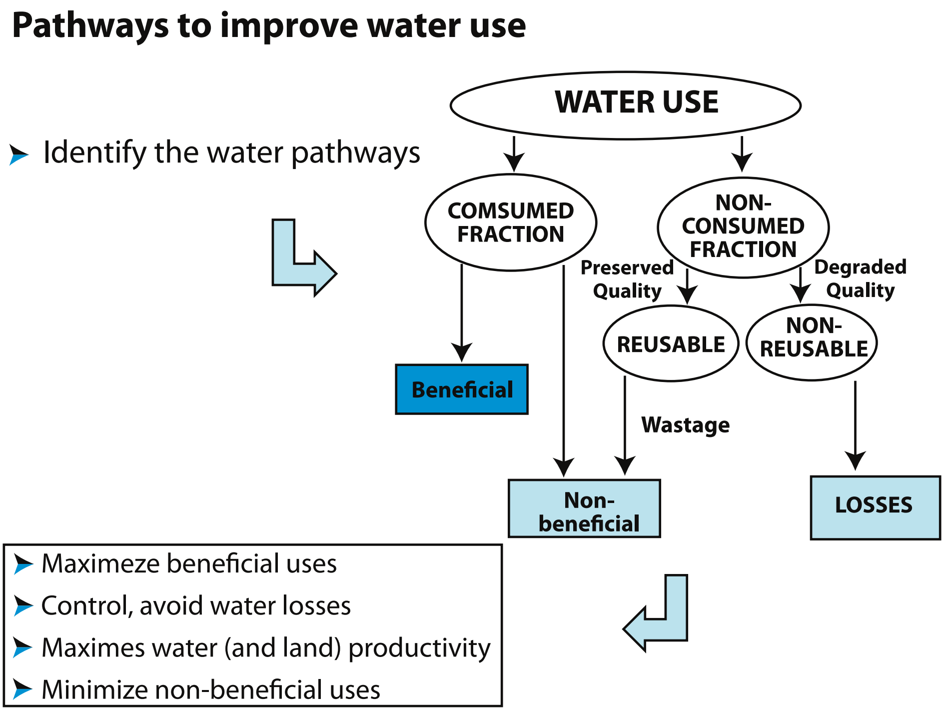

Figure 4. Pathways to improve the efficient use of water.

what is consumptive and non-consumptive water use, what is a beneficial or a non-beneficial water use, and which fractions are really losses or just wastes. This requires that productive and non-productive processes, i.e. oriented to achieve the water use goal, are recognized. Then, a water use is more efficient when beneficial water uses are maximized, the water productivity is increased, and water losses and wastes are minimized.

Assuming the concepts above, it is possible to define water use indicators adapted to any water use or system, for irrigation or non-irrigation users, and to adopt them to make the use of water more efficient, i.e. aiming at improved performances from the perspective of water resources conservation. These indicators may be useful for water resources planning and management under scarcity. They may be combined with process indicators, including those which relate to the quality of service of water systems.

The indicators refer to the three water use fractions (Fig. 2), i.e. the consumed, reusable and non-reusable fraction, and to the respective beneficial and non-beneficial water use components. These indicators can be characterised in equations that express the ratios summarized in Table 1, referring to the main processes of water use in agriculture. Similar concepts may be used for the non-irrigation sectors - municipal and domestic, industry, energy, recreation - since the aims of efficient water use are similar (Table 2).

	Consumptive	**Non-Consumptive but Reusable**	**Non-Consumptive and Non-Reusable**
Beneficial uses	• ET from irrigated crops • Evaporation for climate control • Water incorporated in product	• Leaching water added to reusable water	• Leaching added to saline water
Non-beneficial uses	• Excess soil water evaporation • ET from weeds and phreatophytes • Sprinkler evaporation • Canal and reservoir evaporation	• Deep percolation added to good quality aquifers • Reusable runoff • Reusable canal seepage and spills	• Deep percolation added to saline groundwater • Drainage water added to saline water bodies
	Consumed fraction	**Reusable fraction**	**Non-reusable fraction**

Table 1. Beneficial and non-beneficial water use and its relation to consumptive and non-consumptive uses in irrigation (ET = Evapotranspiration).

	Consumptive	Non-Consumptive but Reusable	Non-Consumptive and Non-Reusable
Beneficial uses	• Human and animal drinking water • Water in food and process drinks • Water incorporated in industrial products • Evaporation for temperature control • ET from vegetation in recreational and leisure areas • Evaporation from swimming pools and recreational lakes	• Treated effluents from households and urban uses • Treated effluents from industry • Return flows from power generators • Return flows from temperature control • Non-degraded effluents from washing and industrial processes	• Degraded effluents from households and urban uses • Degraded effluents from industry • Degraded effluents from washing and process waters • Every non degraded effluent added to saline and low quality water
Non-beneficial uses	• ET from non beneficial vegetation • Evaporation from water wastes • Evaporation from reservoirs	• Non-degraded deep percolation from recreational and urban areas added to good quality aquifers • Leakage of non-degraded water from urban, industrial and domestic systems added to good quality waters	• Deep percolation from recreational and urban areas added to saline aquifers • Leakage from urban, industrial and domestic systems added to low quality waters and saline water bodies
	Consumed fraction	**Reusable fraction**	**Non-reusable fraction**

Table 2. Beneficial and non-beneficial water use and its relation to consumptive and non-consumptive uses in non-irrigation user sectors.

Water productivity

Nowadays, there is a trend to call for increasing water productivity (WP) as a main issue in irrigation. The attention formerly given to irrigation efficiency is now transferred to water productivity. However, this term is used with different meanings in relation to various scales (Fig. 5).

Water productivity in agriculture and landscape irrigation may be generically defined as the ratio between the actual crop yield (Ya) and the water use, expressed in kg/m3. For landscape, a convenient definition of Ya has to be adopted because irrigating gardens, lawns or golf courses produces qualitative yields. The denominator may refer to the total water use (TWU), including rainfall, or just to the irrigation water use (IWU). This results in two different indicators:

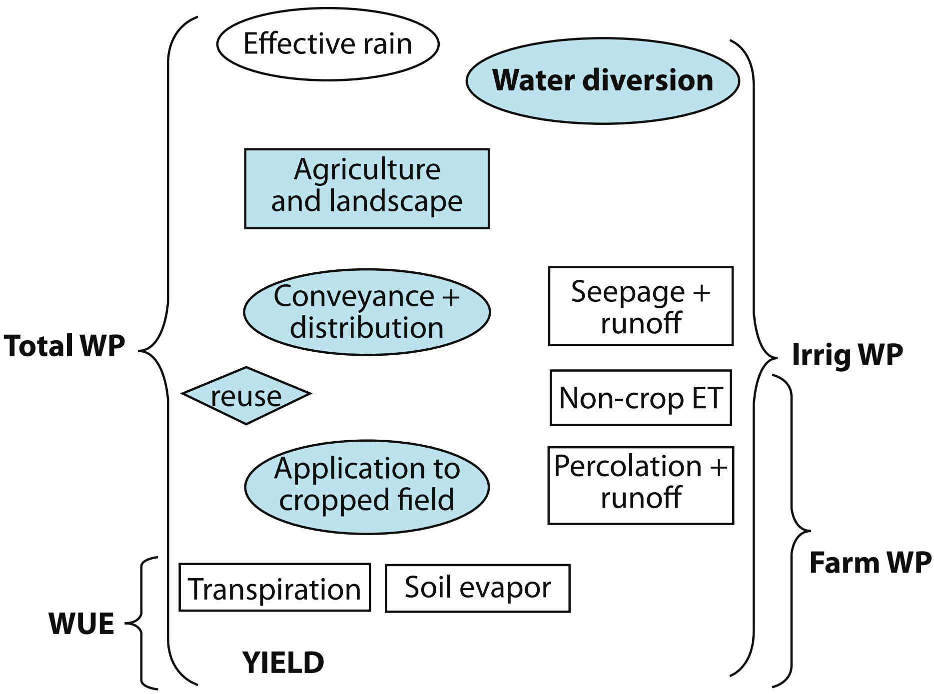

Figure 5. Water productivity in agriculture at various scales: a) the plant, through the water use efficiency WUE; b) the irrigated crop at farm scale (Farm WP); c) the irrigated crop, at system level (Irrig WP); and the crop including rainfall and irrigation water (Total WP).

$$WP = \frac{Y_a}{TWB} \tag{1}$$

and

$$WP_{Irrig} = \frac{Y_a}{IWB} \tag{2}$$

The meaning of indicators is necessarily different. The same amount of grain yield depends not only on the amount of irrigation water used but also on the amount of rainfall water that the crop could use, which relates to rainfall distribution during the crop season. Moreover, the pathways to improve crop yields are often not so much related to water management as to agronomic practices and the adaptation of the crop variety to the cropping environment. However, a crop variety for

which WUE (ratio between assimilates produced during a certain period of time and the corresponding plant transpiration) is higher than that of another variety has the potential of using less water than the second when achieving the same yield. Therefore, discussing how improving WP could lead to water saving in irrigation, requires the consideration of various different factors: a) the contribution of rainfall to satisfy crop water requirements, b) the management and technologies of irrigation, c) the agronomic practices, d) the adaptability of the crop variety to the environment, and d) the water use efficiency of the crop and variety under consideration.
Replacing the numerator of equations above by the monetary value (€) of the actual yield Ya, the economic water productivity (EWP) is expressed as €/m^3.

$$EWP = \frac{Value\ (Y_a)}{TWU} \tag{3}$$

The economics of production may be better expressed when both the numerator and the denominator are given in monetary (€) terms, respectively the yield value and the TWU cost, thus yielding the economic water productivity ratio EWPR:

$$EWPR = \frac{Value\ (Y_a)}{Cost\ (TWU)} \tag{4}$$

EWPR is useful for analysing impacts of water prizes, production costs and yield values (Rodrigues and Pereira, 2009). Improving this ratio implies finding a balance between production and yield costs, as well as appropriate soil and water conservation and irrigation practices. This is not easy to achieve and explains why farmers may retain low irrigation performances and poor conservation practices if related costs for improvement are out of their economic capacity.
An analysis of water productivity suggests that the costs for reducing the N-BWU may be the bottleneck in improving water productivities: to reduce N-BWU implies investment in improving the irrigation system that may be beyond the farmers' capacity, particularly for small farmers. This calls for attention towards the need for support and incentives for farmers when a society requires that they decrease their water demand and increase water productivity. In collective and cooperative irrigation systems part of the difficulties results from poor system management and inadequate delivery services, which are often outside the control of the farmers.
The concept of water productivity is also applicable in other water user sectors. It must be adapted to the specificities of each sector and activity. The term water productivity probably needs to be used or defined separately for each production or service process. Similar to WP being expressed in kg of grain per m3 of water

used in the case of irrigation, it is also possible to express WP in meters of fabric per m3 of water in the textile industry; kWh produced per m3 of water in energy generation; m2 of lawns irrigated per m3 of water in recreational areas; or m2 of area washed per m3 of water in commercial areas.
Differently from agriculture, where water use and related costs (including equipment, labour, and energy) may constitute a large percentage of production costs, water costs in other user sectors are often a small fraction of the production costs, but often include wastewater treatment and water recycling. Therefore, the rationale behind water productivity for most sectors and activities is very different from the rationale in agriculture.
In urban supply systems consumption data are usually available in terms of litres/person/day, and there is the need to have these numbers continually decreasing. In all the above cases, for farms, factories and domestic supply operations, there should be more policies and incentives aimed at bringing water consumption to the lowest possible level for each unit of production or activity in all areas, i.e. increasing the water productivity in all uses.

Conclusion

Water saving and conservation require adopting clear and well defined concepts and indicators in order to support the identification and definition of appropriate pathways for efficient water use. By making use of appropriate concepts, it is possible to develop conceptual approaches and use decision support systems (DSS) that help finding appropriate solutions for design and management of farm irrigation systems, as well as for conveyance and distribution systems. The proposed indicators have proved to be adequate in a variety of assessment studies and to define the attributes of design and management DSS applications.
The analysis has shown that improving irrigation performances is not only a matter of irrigation technologies; indeed serious efforts are necessary in supporting farmers to improve crop husbandry, irrigation management, as well as in upgrading their irrigation systems. In parallel, while upgrading the conveyance and distribution of systems, a major economic and institutional effort has to be taken up for improving the service to farmers, e.g. supporting training and non-structural betterment.

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Estimating Water Balances for a Sustainable Use in Agricultural Basins

Josep Mas-Pla and Anna Menció

At the beginning of the XXI century, agriculture is considered as one of the main priorities in front of environmental changes that scientists envisage for the next decades. At a large scale, climate change is considered a menace for food production worldwide, and the trigger of human conflicts originating from demographical growth, water scarcity, and globalized markets that threat local production.

Water scarcity is not just a problem in developing countries where food availability, and therefore social stability and wealth, is linked to accessibility to water resources. Developed countries also face a population growth that implies a larger pressure on environmental factors and especially changes in land use (WWAP, 2009). Preserving agricultural environments, as a characteristic feature of natural as well as social landscape, is considered necessary to achieve a regional equilibrium and to promote economic activities in the primary sector. Nowadays, specific environmental regulations are applied to limit an indiscriminate access to water resources and their unplanned uses, with the aim to preserve its quantity and quality as a fundamental issue to reach sustainability; the European Water Framework Directive, for instance, is such an environmental regulation.

Regardless the development stage of a country, agriculture is often the activity that requires the largest amount of water (Gleick, 2009). Therefore, water management

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oriented to protect water resources, as well as to warrant its availability for all human activities, must consider agricultural water demand in any hydrological plan. In this paper, water agricultural needs based on the crop requirements defined by plant evapotranspiration and soil properties are introduced. Supplying this amount of water depends on the water balance at a local spatial scale. Such a balance defines the water volume that needs to be diverted from streams or withdrawn from aquifers. Nevertheless, a full regional perspective is required to understand/know/identify whether such water resources exploitation is sustainable in the frame of the hydrological budget within the basin. Therefore, the concept of the water balance is revisited to provide an insight of the effects of water uses on the whole hydrological system and its alteration on its budget.

Agricultural water supply

Efficient irrigation of crops depends on a number of natural factors that determine the amount of water needed to obtain a successful production. Those factors are the soil type and the hydrological properties of the vadose zone (unsaturated zone), the rainfall input and the temperature regime, and finally, the type of crop. It stands that an approach to determine the agricultural water supply depends on soil, weather, and biological data. When seen from a regional perspective, geological information is also of relevance to define water resources management strategies.
Soil type and its hydrological features are essential to set up irrigation control. Field capacity is defined as the amount of soil moisture or water content held in soil after excess water has drained away by gravity, and that remains available for growing crops. Water retention is related to capillarity and it depends on the grain size of the soil and its sorting. Similar terms are “available water capacity”, or “available water content”. After a rainfall or irrigation period, a downward flow is created that increases the soil water content. Humidity is afterwards redistributed according to capillarity forces that retain a percentage of the water. The excess water then drains off, recharges the aquifer and increases its stored resources, and produces an elevation of the water table.
Soil water content depends then on the drainage capacity of soils and on the rainfall frequency and intensity, which depends in turn on the weather regime. Soil water inputs are given by infiltrating rainfall, and water outputs by gravity drainage and water losses by evaporation and plant transpiration. These last two terms constitute what is known as “evapotranspiration”, which includes all the water that returns to the atmosphere from the land-surface due to physical and biological processes. The crop type determines then the amount of water that is transpired and lost as a groundwater resource. The depth of the root zone of each plant is also important as it defines the thickness of the soil layer necessary to store water at the field capacity to satisfy the crop water needs.

Therefore, in agricultural development, the amount of irrigation to be supplied to a given crop is given by the equation:

Irrigation = Evapotranspiration - Rainfall - Soil Fluxes

If soil fluxes as lateral flow or capillarity rise in the vicinity of the water table are disregarded, the amount of irrigation depends on the rainfall input, and evapotranspiration output. While rainfall rates are widely and easily registered, water evapotranspiration losses are more difficult to calculate, and their estimation is based on distinct expressions that combine hydrometeorological factors and crop characteristics.

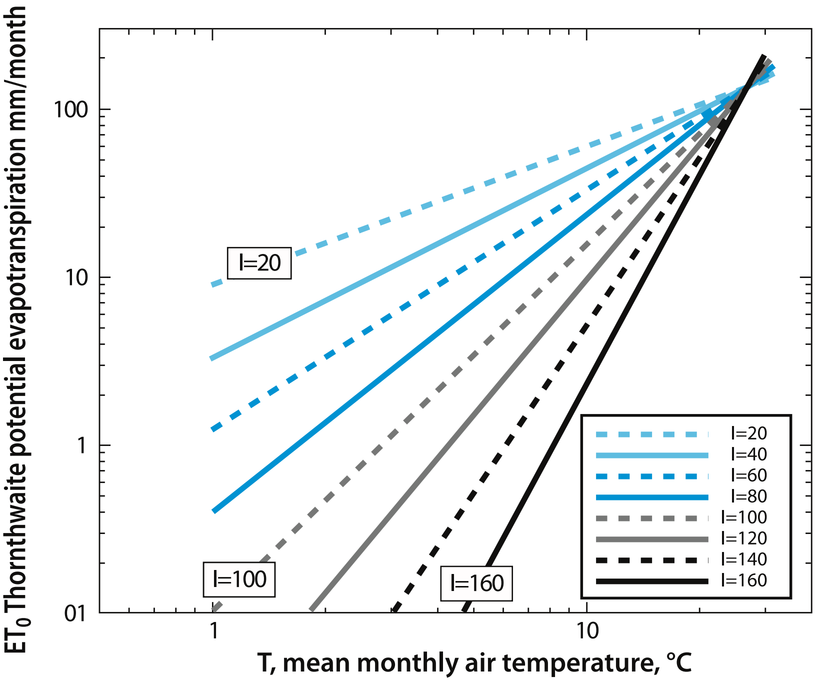

Figure 1. Graphical solution of the Thornthwaite equation for reference evapotranspiration, as a function of the mean monthly air temperature for various values of annual thermal index, I.

One of the most well known expressions for the estimating evapotranspiration is the Penman-Monteith equation (Allen et al., 1998). This equation requires daily mean temperature, wind speed, relative humidity, and solar radiation; that is, it includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters are measured or can be readily calculated from weather data.

Other equations as those derived by Coutagne, Turc or Thornthwaite, among others, are also interesting even though they estimate monthly evapotranspiration instead of daily values (Dingman, 2002). Those equations rely on few hydrometeorological data (temperature, rainfall, net radiation) that are available at most of the weather stations. For instance the Thornthwaite equation, which is widely accepted, relies only on the mean monthly temperature (see Figure 1):

$$ET_0=16\beta\,(10\,\frac{T}{I})^{\alpha}$$

where ET_0 is the monthly evapotranspiration (in mm), T is the average monthly temperature (in °C), and I is the annual thermal index, estimated as the sum of the monthly thermal indexes, in; that is:

$$I=\sum_{n=1}^{12} i_n=\sum_{n=1}^{12}\left(\frac{T}{5}\right)^{1.5}$$

Also, α is a factor that depends on the annual thermal index:

$$\alpha=0.49239+1792x10^{-5}I-771x10^{-7}I^2+675x10^{-9}I^3$$

and β is a latitude correction factor that varies monthly (e.g. Dunne and Leopold, 1978).

The Penman-Monteith and Thornthwaite equations, among many others, calculate the reference (or potential) evapotranspiration; that is, the total amount of water that will be transferred to the atmosphere assuming a uniform cover of grass without restrictions of water availability. Therefore, the equation estimates the maximum amount of water that needs to be supplied to the crop to ensure its growth and a good production.

Actual reference evapotranspiration needs to be adjusted by multiplying ET_0 by a crop coefficient (*Kc*) that integrates the effects of characteristics that distinguish field crops from grass. The value of this coefficient depends not only on the crop type, but also on the crop growths stages. Details are given by Allen et al. (1998).

Therefore, water needs for agricultural uses can be estimated by adding the demand of every crop times the surface occupied. For a single field, or a set of crops, irrigation water is computed as the difference between the rainfall rate and its evapotranspiration. This allows estimating the whole irrigation needs in an agricultural basin.

Nevertheless, evapotranspiration equations are also used to estimate the maximum water demand for the entire basin area, assuming that it provides the water needed for a uniform vegetation cover. This approximated approach is commonly used for basin water budgets, independently of the land use. If most of the basin area is devoted to agriculture, determining the area of each crop, using the appropriate crop coefficients, will provide a quite exact estimate of the water needs. On the other hand, if land-use is diverse, the evapotranspiration term of the basin water budget is also useful to compute the whole natural losses of water to the atmosphere. The complete water budget and its comparison to human water demand are explained in the following sections.

Estimation of water demand in a hydrological basin

Up to this point, let's consider that in a basin the total demand of water is given by distinct human uses: agriculture (that may be assumed as the main factor), industry, and domestic uses. In this case, the water-budget must estimate how much water is available considering the hydrogeological features of the basin. This calculation is fundamental to answer a simple, but tricky question: 'where does the water in the budget come from?', that also means: 'is all the yearly recharge within the hydrographic basin enough to supply a mean demand?'. By answering these questions, we have a better insight to address the issue of sustainability of water resources in the basin.
Indeed, the water mass-balance in a hydrographic basin is expressed as,

Inputs - Outputs = Variation of Stored Water Resources (1)

being, Inputs = Rainfall + Groundwater Flux In
and Outputs = Evapotranspiration + Surface Runoff + Groundwater Flux Out + Consumptive Water Use

It is important to recall that a percentage of the diverted or withdrawn water returns back to the basin, and therefore only the consumptive use must be accounted for.

Two examples

Usually, an annual water mass-balance in a basin is usually presented as,

Rainfall - (Evapotranspiration + Surface Runoff + Water Uses) = Recharge (2)

Notice that the term "recharge" is used instead of "variations of stored water resources", which indeed are similar. However, "recharge" may also be understood as the amount (rate) of water that "replenishes" the aquifer, and therefore can be exploited for human uses. This is, in fact, the key-issue of the so-called water-budget myth (Bredehoeft et al., 1982; Bredehoeft, 1997, 2002; Alley and Leake, 2004; Devlin and Sophocleos, 2005).

Two examples about water budget at distinct basins in Catalonia provide an interesting insight to the usual expression of the water-balance (see equation 2 and Table 1). Each component of the water-balance has been estimated as the mean of their annual values, using rainfall and temperature (to estimate *ET*), and runoff values from the gauging station at the lowest reach of the river basin.

Component	Arbúcies Basin	Onyar Basin
Basin area (km2)	110	295
Rainfall recharge	100	227
Evapotranspiration	64	215
Surface runoff	26	54
Recharge	+10	-42
Human water demand	0	12
Final balance	+10	-54

Table 1. Mass-balances (in hm^3/year) for two distinct basins in Catalonia.

The results of both water-budgets are astonishing if they are understood by their own. For the Arbúcies basin, we have an annual increase of the recharge of +10 hm^3. At that rate of increasing resources, we can foresee a second Universal Flood! Contrarily, for the Selva Basin a negative natural recharge of 42 hm^3 occurs, or of 54 hm^3 if groundwater withdrawal rate for human uses is considered. Indeed, it means that groundwater reserves are progressively drying. Even the IPCC has never considered the effects of climate change in Western Mediterranean to be of such a magnitude, in a sense! In other word, one can understand that by using annual averages it is possible to create a conceptual mistake in the evaluation of the hydrologic cycle.

So, where is the error? The miscalculation mainly lays on failing to remember the role of groundwater flow terms into and out from the basin. If recharge is positive, it doesn't mean that it accumulates in the aquifer. It simply denotes that the magnitude of those terms will be modified; for instance, increasing the underground discharge out of the basin's subsoil. If negative, it means that there will be some extra groundwater flow into the basin that equilibrates the withdrawn resource. Nevertheless, the balance in equation (2) is still valid when considered at a soil scale, and that infiltration and droughts may occur, which just means a change of the soil stored resources with time.

Let's explore in the following section the water balance in detail at basin scale, based on mean values of the mass-balance components.

Revisiting the water mass-balance for a hydrologic basin

Indeed a hydrological basin is not a closed system. Groundwater flows to and from the surrounding basins have a strong influence on the whole water budget, in particular when groundwater exploitation is intense. Appropriately, Bredehoeft et al. (1982) compared a basin with a circular island in the middle of the ocean to illustrate the effect of pumpage upon the aquifer –i.e. the basin– boundaries (see Figure 2).

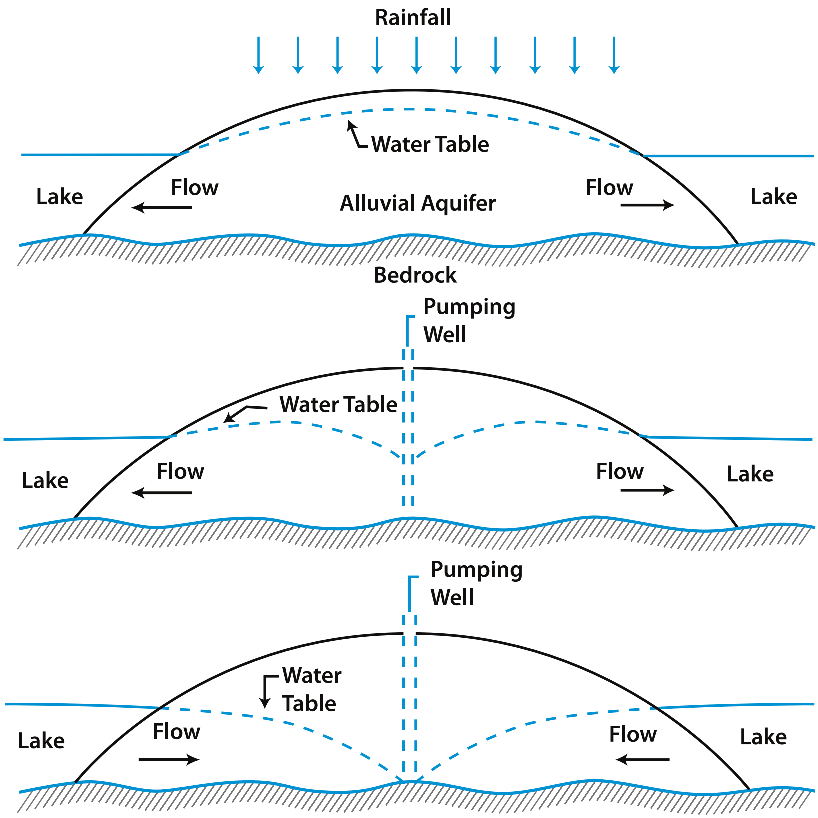

Figure 2. Cross-section of an island in a fresh-water lake formed by an unconfined alluvial aquifer, underlain by bedrock of low permeability with rainfall recharge (top), influenced by a pumping well whose cone of depression has reached the coast line (center), and illustrating how pumpage generates an incoming flow from the lake (bottom). After Bredehoeft et al. (1982).

In this sense, under long-term natural pre-development conditions, average inflow to and outflow from the basin will be balanced; that is, no changes in storage (V) are expected (dV/dt = 0; e.g., Bredehoeft et al., 1982; Devlin and Sophocleos, 2005). Under these circumstances,

$$P + GW_{in} = ET + SR + GW_{out} \tag{3}$$

where P is rainfall, ET is evapotranspiration, SR is surface runoff, and GW_{in} and GW_{out} stands for groundwater flow into and out of the basin boundaries. From meteorological and runoff data, the magnitude of P, ET and SR can be estimated for the whole basin; for instance, in terms of water volume per year. Knowing these values, the following cases may occur:

1) $P - (ET+SR) = 0$, that is $GW_{in} = GW_{out}$
2) $P - (ET+SR) > 0$, that is $GW_{in} < GW_{out}$
3) $P - (ET+SR) < 0$, that is $GW_{in} > GW_{out}$

Therefore, the hydrological basin can no longer be considered a closed system and, more importantly, the estimation of P-(ET+SR) term (in other words, the surface water balance) provides some information about subsurface mass-balance in the basin boundaries.
Under development conditions, new terms need to be added to the right-hand side of equation (3):

$$P + GW_{in} = ET + SR + GW_{out} + Q + dV/dt$$

where Q stands for the net groundwater abstraction (i.e. pumping), and dV/dt refers to water removal rate from aquifer storage per unit time. Indeed the time term is fundamental for further analysis. If $dV/dt < 0$, there is a continuous resource depletion, and therefore overexploitation of the aquifer occurs. Otherwise, if $dV/dt = 0$, this second possibility could be addressed in two distinct ways: 1) pumping is safe as no decline is observed in groundwater levels, but the modified flow system results in impacts upon some parts of the water cycle; or 2) pumping is also safe and sustainable, understood in its broader sense, because the new state preserves hydrologic dynamics, water quality, ecological functions and socioeconomic values (Sophocleos, 2000; Custodio, 2002; see Figure 3).
Hence, assuming that the basin doesn't suffer from a loss of storage, the response of the basin mass balance will be distinct depending on the magnitude of P-(ET+SR) and the groundwater withdrawal rate, Q. In particular:

1) $P-(ET+SR) > 0$, meaning that $Q-\Delta GW$ is a positive magnitude, let us say α. As $Q > 0$, and depending on the relationship between Q and α, different possibilities exist for the outcome of $\Delta GW=GW_{in}-GW_{out}$. For instance,

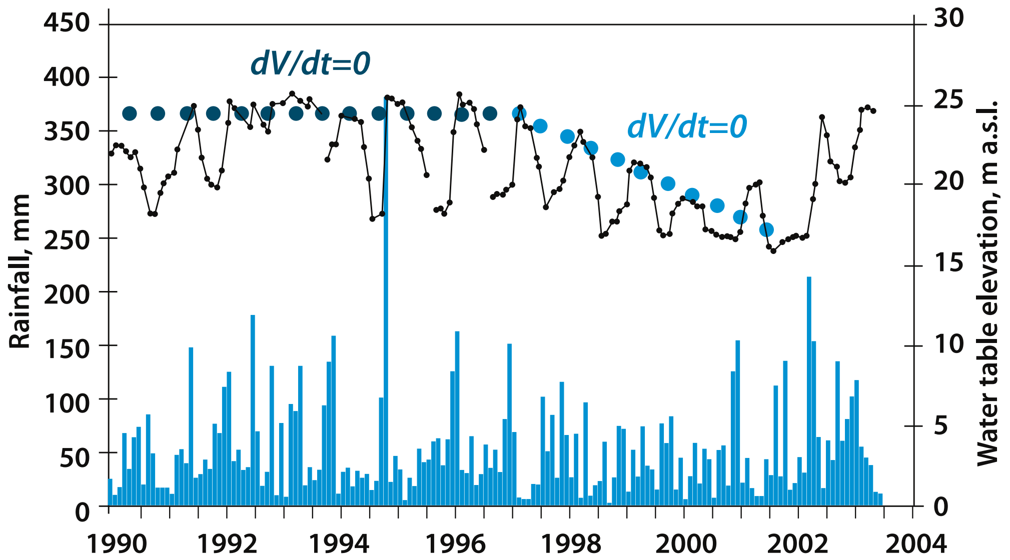

Figure 3. Local rainfall and hydraulic head evolution in a piezometer located in an unconfined aquifer. The period from 1990 to 1996 shows an annual recovery of the water table that allows assuming a nil loss from storage; that is, dV/dt=0. Contrarily, from 1997 to 2002, a water table decline due to rainfall scarcity indicate that pumpage affects stored water resources, and dV/dt<0. Checking for safety or sustainability also requires the evidence of hydrochemical information.

If $Q > \alpha$, ΔGW would be positive, indicating that $GW_{in} > GW_{out}$
If $Q < \alpha$, ΔGW would be negative, indicating that $GW_{in} < GW_{out}$
If $Q = \alpha$, then $GW_{in} = GW_{out}$

2) P-(ET+SR) < 0, meaning that Q-ΔGW is a negative magnitude, let us say β. As Q > 0, ΔGW must be a positive value, $\Delta GW = Q\text{-}\beta > Q$. This indicates a bigger contribution from ground water inflow ($GW_{in} > GW_{out}$).

3) P-(ET+SR) = 0, meaning that Q-ΔGW = 0. In this case, there is also a bigger contribution from ground water inflow, $GW_{in} > GW_{out}$ and ΔGW is equal to Q.

In summary, by evaluating P, ET, SR and Q, we are able to understand how water withdrawal influences the overall groundwater flow regime. Indeed, we can not know the magnitude of the GW terms, but we can predict which one will be larger and what will be the magnitude of the difference. In other words, it provides an approximation to the term named capture, as defined by Lohman (1972), and stated earlier by Theis (1940).

A last example

The water mass-balance, as described above, has been applied to the Selva Basin, Catalonia, NE Spain (see Figure 4; for details: Menció et al., 2010). It consists of a tectonic graben, formed during the Neogene. The main exploited aquifers are located in the sedimentary infilling of the basin area. This aquifer consists of a stratigraphic series of more than 200 m of layers of sand, loam and silt. The surrounding ranges are formed by igneous, metamorphic and sedimentary rocks. The geological contact between the ranges and the basin is defined by regional fault zones that have a significant role in the recharge of the basin's hydrogeological system. This range-and-basin area integrates two distinct hydrographic basins: the Onyar River basin draining to the north, and the Santa Coloma River Basin flowing towards the south (Menció, 2006; Folch, 2010). These drainage patterns reflect the recent tectonic evolution of the area. Both hydrographic basins cover an area of 565 km^2.

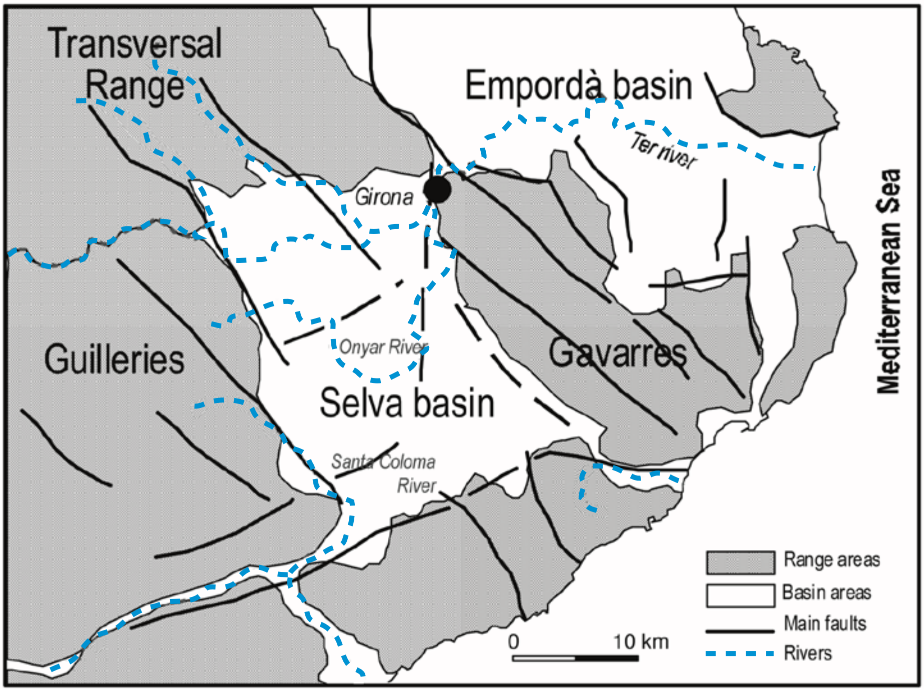

Figure 4. Geological scheme of the Selva Basin, showing its tectonic origin and the location of the main faults. These have an important role in the hydrogeological recharge of the aquifer layers within the sedimentary infilling of the basin.

Using averaged meteorological data during the last 30 years, annual rainfall is estimated in 398 hm^3; and the annual evapotranspiration, using Thornthwaite equation, is of 287 hm^3. The mean surface runoff recorded in this period at the gauging stations is 103 hm^3/year. Therefore, P-(ET+SR)=8 hm^3/year; consequently, $Q-\Delta GW > 0$. Since annual human groundwater exploitation, Q, is estimated in 27 hm^3, ΔGW=19 hm^3/year. This means that $GW_{in} > GW_{out}$.
Therefore, groundwater withdrawn forces an annual subsurface flow difference of 19 hm^3 from the neighbouring basins. Back to the capture concept, this result doesn't tell how much GW_{in} increases and GW_{out} decreases, but the difference between them. The accuracy of these magnitudes should be evaluated by numerical flow models, provided that there is appropriate hydrogeological information to build a model, and suitable tools by which to assess sustainability issues (Kalf and Wolley, 2005).

Conclusions

Water availability is a key issue to assess water sustainability. More importantly, river basin management plans must take into account the basin's own resources or inter-basin water transfers to assess the demand. Such water exchange between basins may go unnoticed when groundwater is the main resource. In this paper, the water balance equation has been reformulated to contrast the components of the natural hydrological cycle with human demand, emphasizing the contribution of groundwater from the surrounding basins as a captured resource by exploitation.
In agricultural basins where irrigation forms the biggest user of water, a proper approach to water management is based on a fair estimation of the crop needs, i.e. crop evapotranspiration, and a large-scale water balance to define water availability as a first step towards a sustainable use of water resources. Achieving sustainability implies a further analysis that must prove economic strength, ecological integrity and social equity of water uses (Flint, 2004).

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Earth Observation for Monitoring Water Use in Agricultural Systems

Guido D'Urso

The potential of Earth Observation techniques in supporting the management of land and water resources has nowadays been widely recognised. Twenty five years of observations with the multispectral Thematic Mapper on board of the Landsat satellites have shown that it is possible to detect land-use variations with great detail in many areas. Multi-temporal and multi-spectral classification techniques combined with ground reference data can be applied for detailed land use mapping and agricultural inventories. In more recent applications, vegetation and soil cover maps are considered as basic input for physically based models of land surface processes, i.e. models used for water management at basin scale, for evaluating the impact of irrigation in large areas on the aquifer regime or for the analysis of land-use in relation to run-off phenomena (Schultz et al., 2000).
As of today, it is possible to notice two main developments: a) the availability of new generations of sensors, with enhanced spectral and spatial resolution and angular viewing possibilities; b) a detailed knowledge of the land surface processes based on mathematical descriptions. These advancements have made a quantitative approach possible in the interpretation of data from remote sensing, that is a viable alternative to more traditional applications focused on qualitative and descriptive information, such as classification studies for land-use and land-cover mapping. Thanks to the improved observation techniques and the capacity to analyse the reflectance behaviour of complex vegetated surfaces, it is now possible to better characterize land surface processes by means of a more accurate analysis of relevant parameters.

In the spatial analysis of processes which are of particular interest for the management of water resources in agriculture, there are two main fields of interest in using Earth Observation data:

1) estimation of vegetation parameters, in particular the Leaf Area Index;
2) estimation of water balance parameters, with particular reference to evapotranspiration and soil water content.

In this paper, we briefly report on recent experiences regarding 1) and 2), carried out at the University of Naples, "Federico II", and their impact on the practical application of Earth Observation data.

Mapping vegetation parameters from Earth Observation data

The reflective properties of vegetation, as detected from a remote sensor, are dependent on canopy development, which can be measured using as parameters the fractional vegetation cover, the Leaf Area Index (LAI), surface albedo and the crop coefficient K_c. These parameters are needed as input data for modelling processes such as evapotranspiration (*ET*) and primary production (Glenn et al., 2008) and are directly related with the agricultural water use.

The potential rates of transpiration and soil evaporation and the amount of intercepted precipitation needed are determined by vegetation cover of the soil surface and by climatic parameters. The potential evapotranspiration ET_p (cm d^{-1}) from a canopy uniformly covering the soil surface may be estimated by using the well-known schematisation of Monteith, which requires the value of the LAI, surface albedo ρ, and the aerodynamic resistance $r_{a,H}$. Assuming that climatic parameters are constant over a certain area, *ETp* can be expressed as the product of a reference value ET_0, which only depends on climatic data, and of a vegetation-dependent parameter, which is a function of LAI, ρ and $r_{a,H}$:

$$ET_p=k(LAI, \rho, r_{a,H})\ ET_0 \tag{1}$$

The parameter *k* has the same practical meaning as the crop-coefficient K_c, widely used in irrigation, but it can be expressed as an explicit function of the cited canopy parameters (D'Urso and Menenti, 1995). For canopies not covering completely the soil surface, the potential soil evaporation can be estimated from ET_p as a function of LAI:

$$E_s=ET_p e^{-cLAI} \tag{2}$$

where *c* is an extinction coefficient. The potential transpiration rate is derived as:

$$T_p=ET_p-E_s=ET_p(1-e^{-cLAI}) \tag{3}$$

Also the amount of intercepted precipitation is related to *LAI*, and different empirical approaches can be found in literature (Liu, 1996).
Equations to represent the basic information for a rational utilisation of water resources in agriculture and they require knowing the value of standard meteorological variables i.e. air temperature and humidity, incoming solar radiation, wind speed, and the mentioned vegetation parameters. In large heterogeneous areas, it is needed to determine the spatial and temporal variability of such parameters; to this extent, various methodologies for the interpretation of Earth Observation data, ranging from empirical to more physically based algorithms, have been defined in recent years and validated in many different agricultural environments.
The canopy reflectance in the visible and near infrared ranges, results from the interaction of many different elements, such as the leaf area index, the leaf angle distribution, the spectral properties of leaves and of soil, the relative geometry of illumination and observation (Baret, 1991). Many efforts have been made in modelling the canopy reflectance behaviour either on a physical basis or approaching the problem in an empirical way. Due to the number of parameters required to define the canopy bi-directional reflectance functions, the inversion of physical models is practically an undetermined problem with the current high-resolution satellite sensors.
The simplest methods are usually based on the relationship between satellite-derived indices and the parameter of interest. The Normalized Difference Vegetation Index (NDVI) is the most widely used vegetation index (VI), and has been related to a variety of biophysical variables such as fractional vegetation cover (fCover) (Carlson & Ripley, 1997), fraction of absorbed photosynthetic active radiation (fAPAR) (Sellers et al., 1997), primary production (Monteith, 1990), leaf area index (LAI) (Gilabert et al., 1996) and crop coefficient (Kc). Even though a high number of alternative indices have been developed during the last decades, the NDVI remains the most well-known and acknowledged index applied for optical remote sensing data. In empirical methods, the canopy is in general assumed as a Lambertian surface, thus the canopy reflectance is constant with the angle of observation. Within the limitations of accuracy that this assumption implies, simplified models relating the canopy geometrical parameters to different types of vegetation indices can be developed.
On this approach, Clevers (1989) and Price (1992), among others, have suggested semi-empirical models for the retrieval of LAI from vegetation indices.
The simplified model CLAIR (Clevers, 1989) is based on the Weighted Difference Vegetation Index (WDVI), defined as follows:

$$WDVI=\rho_i-\rho_r\,\frac{\rho_{si}}{\rho_{sr}} \tag{4}$$

where ρ_r and ρ_i indicate the reflectance of observed canopy in the red and infrared bands respectively, while ρ_{sr} and ρ_{si} are the corresponding values for bare soil conditions. The LAI is related to $WDVI$ of the observed surface through the expression:

$$LAI=-\frac{1}{\alpha}\ln\left(1-\frac{WDVI}{WDVI_{\infty}}\right) \tag{5}$$

where α is an extinction coefficient to be determined from reference data; $WDVI_{\infty}$ is the asymptotical value of $WDVI$ for LAI_{∞}. A similar relationship was derived by Price (1992). The empirical parameters α and $WDVI\infty$ can be determined by means of on-site LAI measurements contemporary to satellite passes. Once calibrated, Equation can be used for mapping LAI from satellite-based WDVI images, also in different dates in order to monitor the canopy development (Fig.1).
Similar approaches and analyses can be found for estimating the aerodynamic roughness. Canopy aerodynamic properties are strictly linked to the crop height and to the Leaf Area Index and a correlation can be found between vegetation indices and the canopy roughness. Moran et al. (1991) tried out a purely empirical relationship linking the roughness length of alfa-alfa to the ratio of reflectance in near-infrared and red bands.
If satellite images are atmospherically corrected, the surface albedo values can be calculated as the weighted average of radiance over visible and near-medium infrared spectrum assuming as weighting parameter the percentage of solar radiance for each bandwidth (Menenti, 1984). In this case, the following relationship is applied:

$$r=\pi\int_0^{\infty}\frac{K^{\uparrow}(\lambda)}{K^{\downarrow}(\lambda)}d\lambda\simeq\pi\sum_{\lambda_l}^{\lambda_n}\frac{K_{\lambda}^{\uparrow}(d^0)^2}{E_{\lambda}^{0}\cos\vartheta^0} \tag{6}$$

In Equation (6) the spectral reflected radiance, $K^{\uparrow}_{\lambda}$ (W m^{-2}), and the extraterrestrial solar irradiance, E^0_{λ} (W m^{-2}), are integrated values over the width of each spectral band λ_i; ϑ^0 and d^0 are the solar zenith angle and the sun-earth distance in Astronomical Units. When using Thematic Mapper reflectance measurements r_{λ}, the albedo, can be calculated as:

$$r_p=\Sigma_{\lambda}w_{\lambda}r_{\lambda} \qquad \lambda=1,2,...,5,7 \tag{7}$$

where the weighting factors w_{λ} are given by:

$$w_{\lambda}=\frac{E_{\lambda}^{0}}{\Sigma_{\lambda}E_{\lambda}^{0}} \tag{8}$$

Figure 1. Raster map of Leaf Area Index derived from the processing of a Landsat TM image in an irrigation district in Southern Italy. The value of LAI, indicating the amount of foliage per unit area, is represented proportionally by gray tones.

Mapping water balance components

The models represented by the previous Equations are used in the planning phase of water resources management i.e. to evaluate the *maximum* water requirements of a given extension of cropped surface (Fig. 2). Diversely, the actual water balance is related to the soil water content, which is an extremely dynamic variable, depending on climate, vegetation and soil characteristics. One of the earliest and

still widely investigated applications of remote sensing in the evaluation of the water balance components is based on the estimation of *actual evapotranspiration ET* from the radiometric temperature of the surface T_s.
In these applications, the latent heat flux (λET) is usually derived as the residual term of the surface energy balance equation (Friedl, 2002):

$$\lambda ET=Q^*-G-H \tag{9}$$

where λ is the latent heat of vaporisation of water (J kg^{-1}), Q^* is the net radiation flux density (Wm^{-2}), G is the heat flux density into the soil (Wm^{-2}) and H is the sensible heat flux (Wm^{-2}). Q^* and G can be estimated from measured incoming radiation, surface albedo and LAI. This last term is usually expressed as follows:

$$H=\rho_a c_p \frac{T_s-T_a}{r_{a,H}} \tag{10}$$

with ρ_a expressing the air density (kg m^{-3}), c_p the air specific heat (J $kg^{-1}K^{-1}$), T_a is the air temperature (°C) and $r_{a,H}$ is the *aerodynamic resistance* for heat transport (sm^{-1}). In order to obtain reliable estimates of λET a correct estimation of $r_{a,H}$ is needed. Since the late '70s several studies have attempted to estimate daily values of λE from one-time-a-day measurements of radiometric temperature by using empirical relationships, which essentially combines Equations and in a unique relationship (Jackson et al.; 1977):

$$\lambda E=Q^*+A'-B'(T_0-T_a) \tag{11}$$

Approaches based on relationships similar to Equation have been applied for mapping λET from Landsat TM images (Moran et al., 1990; Sugita et al., 1992) and low-resolution satellite data for regional scale studies (Seguin et al., 1983; Taconet et al., 1986; Vidal et al., 1990).
Another crucial variable in the evaluation of a water balance is the soil water content, since it influences the exchange of water and energy fluxes through the soil surface and it determines the partition of surface runoff and soil infiltration. In-situ measurements techniques of *soil water content* become impractical when dense spatial and temporal resolutions are required. As an alternative, passive and active microwave imaging techniques from aircrafts and satellites may provide information on the spatial distribution of surface soil water content. The possibilities and limitations of passive and active microwave sensors for monitoring soil water content have been evidenced in many recent studies; a review of the current status of research in these fields can be found in Engman et al. (1995) and Petty et al. (1996). Due to the complexity of microwave backscattering of vegetated sur-

Figure 2. Vector map of potential evapotranspiration ETc of irrigated parcels derived from the LAI map of Figure 1 and ground-based meteorological data.

faces, the limited penetration depth in the soil and the technical characteristics of instruments available today and in the near future, there are serious limitations in the use of microwave space-borne sensors in the field of agricultural water management.

The remote sensing techniques described above, aimed at detecting terms of soil water balance, have produced a better understanding of land surface-atmosphere processes and their parameterisation (Bastiaanssen, 1995; Feddes, 1995; Wood, 1995). However, their support to the operational problems in the management of water resources is limited to the calibration and validation of hydrological models.

On-Farm irrigation managements

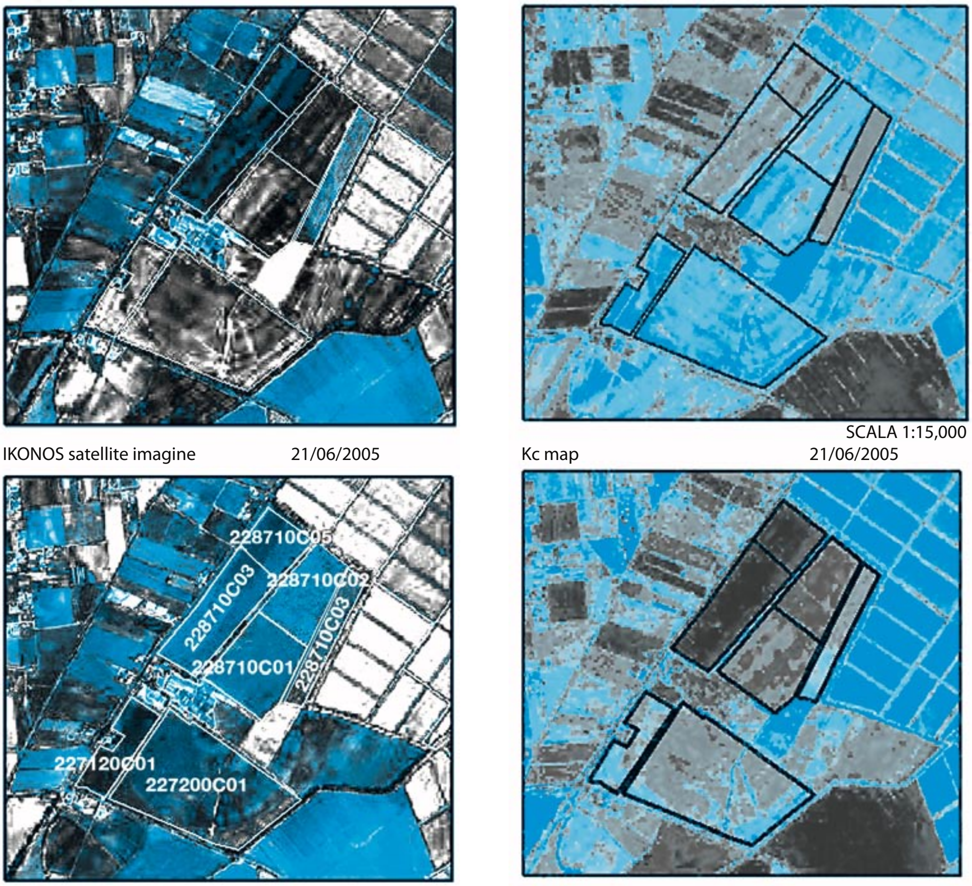
Ariespace

from 27/06 to 03/07/2005

IKONOS satellite imagine 03/07/2005 | Kc map 03/07/2005

SCALA 1:15,000

IKONOS satellite imagine 21/06/2005 | Kc map 21/06/2005



Crop coefficient -Kc

0 0.3 0.7 1.0 1.4

CWR: (ETo X Kc - rain) x area

Weekly Crop Water Requirements (cubic meter)

ID Field	Ha	CWR
227120C01	2.64	928
227200C01	11.94	4071
228710C04	2.49	379
228710C01	5.08	1633
228710C02	3.84	1118
228710C05	2.35	4.28
228710C03	5.25	980

Weekly Reference Evapotranspiration

ET_0 (27/06 - 03/07) = 36.10 mm

ET_0 (20/06 - 26/06) = 43.77 mm

Daily Reference Evapotranspiration

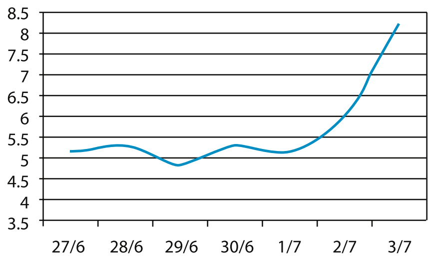


Figure 3. Example of information distributed to farmers via MMS (mobile phones) and e-mail. Colour composite derived from high resolution satellite images and Kc map for a period of 4-7 days.

From research to application in irrigation management

Current Earth Observation (E.O.) platforms have greatly enlarged both the quality and the revisit time in the visible and near infrared ranges. The spatial resolution of 10 m or smaller is of great value for all precision-agriculture practices. A similar process has not occurred for observation in the thermal range, in spite of the great progresses made in understanding the energy balance of vegetated surfaces.

As such, the analysis of E.O. data in the visible and near infrared ranges for vegetation characterisation appears to be the most promising E.O. technique, readily transferable for application in water resource management. There are examples of "Decision Support" tools in irrigation management based on the integration between remote sensing, GIS and Information and Communication Technologies (I.C.T.). An example of irrigation advisory service supported by Earth Observation techniques has been developed in the Campania region (www.consulenzairrigua.it) (Fig. 3).

In the near future, thanks to improvements in the spatial and radiometric accuracy of new sensors, a more accurate estimation of this type of applications can be achieved. Thanks to the development of fast-access to Web resources, the time lag between satellite image acquisition and access of data by the final user has significantly been decreased.

Earth Observation data provide an effective and objective evaluation of agricultural water demand, at different spatial scale (from basin level to individual farms). When planning the allocation of water resources among different users, the adoption of E.O. techniques significantly reduces the uncertainty of water requirements assessment for the agricultural sector. This allows for a participatory approach in using scarce water resources, thus avoiding potential conflicts.

At the level of individual farms, the knowledge of the maximum amount of water to be applied may impact the production costs, not only with regard to water consumption, but also to the energy for pumping and the maximum yield in presence of poor drainage. The integration of E.O. data in personalised information for the final users, as in the example of mentioned advisory service, represents an easy-to-use tool to support irrigation operations. The experiences carried out in the Campania region have demonstrated that in most cases farmers tend to apply a 30-40% surplus water reduction, on the basis of their personal perception.

From these considerations, it is clear that there is a "cost-benefit" effectiveness in using E.O. data in operational irrigation contexts, with tangible benefits for a better management of water resources.

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Water, Economy and Sustainable Agriculture

Laura Riesgo

Water economics is today in a stage of "maturity" in Southern European countries. This situation is characterized by the combination of the following circumstances (Randall, 1981):

- High and growing water demand
- Inelastic long-term water supply
- Growing competition between water uses
- Negative externalities associated to water use
- High social costs due to a growing use of water
- Storage and distribution water infrastructures are obsolete

This "maturity" has motivated a debate on irrigation water use efficiency, especially in Southern European countries where irrigation is responsible for over 70%-80% of water uses. The apparently inadequate management of water in irrigated areas (water losses in distribution systems and application to crops with low profitability) was an issue to support the implementation of new water policies. Within water demand policies it is possible to distinguish different domains: the public reallocation of water resources, water pricing, the promotion of efficiency in water infrastructure development and the implementation of water markets (Chakravorty and Zilberman, 2000; Dinar et al., 1997; Easter and Hearne, 1995; Sumpsi et al., 1998).

This paper focuses on water pricing as a policy instrument to manage water demands assigning water a fixed price. This price allows its reallocation among potential users in order to increase the recovery of water supply costs (Lee and Jouravlev, 1998; Sumpsi et al., 1998). Water pricing is an interesting issue in Southern European countries, where new water demands are required for agriculture and crops with low profitability. These requirements are inefficient from an economic perspective, since water is supplied at highly subsidized prices (below the real supply cost).

In the following sections, the legislation on water pricing at European Union (EU) and national level are presented. Spain was selected as an example to see how the European law regulation was implemented in national legislation. In the last section, trade-offs between efficiency and equity in water pricing are analysed.

• Legislation on irrigation water pricing

The analysis of the implementation of irrigation water pricing is introduced by describing the legal framework that determines how it should be applied. Rules for irrigation water pricing in Spain are developed according to both the European normative level, through the Water Framework Directive, and the national level, through the Water Act.

Water pricing and the Water Framework Directive

On December 22, 2000, the Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy, or in short, the Water Framework Directive (WFD) was adopted. The implementation of this Directive involved an important change in the European legislation on water resources, including the agricultural sector.

The WFD aims to prevent further deterioration, to enhance the "good status" of aquatic ecosystems and to promote sustainable water use. These objectives shall be pursued at river basin district level, as the main unit for management of river basins in each Member State, through the development of river basin management plans. These plans should be based on the analysis and evaluation of human activity impacts (human pressures and impacts) on the status of water resources. Thus, specific measures at river basin shall be defined and implemented for the achievement of "good status" of water resources. In order to design the river basin management plan, Member States have to specify the geographical coverage of river basin districts, provide a list of competent authorities for each district (responsible for the design and implementation of the management plan) as well as ensure public participation during the planning process.

The implementation of the WFD demands important changes in water management policy. The adaptation to the WFD requirements may have a greater im-

pact in Southern European countries, characterized by uneven distribution of water resources, water scarcity, drought as well as extreme flood episodes. Also, in these countries the agricultural sector is responsible for at least the 70% of all water uses.
The WFD shall take into account Economics as a key discipline to achieve the “good status” of water resources. This is an important novelty brought by this Directive, as the economic principles and instruments are to be taken into account in water policy as tools to support water management decision making, to achieve an integrated water resources management system and a sustainable use of water resources.
Finally, the WFD also requires an adequate implementation of the principle of “full cost recovery” of water, including at least industrial, domestic and agricultural uses. Moreover, the WFD fully takes into account the ‘polluter pays principle’. In short, this Directive gives a key role to water pricing in order to achieve a sustainable water policy.

Legislation in Spain

The WFD was transposed to the Spanish legislation by the Article 129 of Law 62/2003 of 30 December 2003 (Accompaniment law of the State general budget for 2004). The way to transpose the WFD into Spanish legislation was hurried due to the short transposition timescale foreseen by the European directive, but also because of the lack of foresight of Spanish lawmakers. In any case, it is worth noticing that the Accompaniment law of the State general budget transposed, in a literal way, those issues relevant for being considered as a law. Important amendments were included in the rewritten text of the Water Law. These changes affected the Title III on development of river basin management plans. Among others, the main important issues included were: (a) a new definition for river basin districts; (b) changes in public water management, setting up Water Councils in each district and appropriate Competent Authorities; (c) new environmental objectives, to be added in river basin management plans; (d) the mandatory design and implementation of programmes of measures to fulfil those objectives, and (e) the principle of water uses’ cost recovery (Gómez-Limón and Riesgo, 2010).
As mentioned above, to complete the WFD transposition some subsequent regulations were necessary. First, Laws 125 and 126/2007 of 2 February 2007 were implemented. Law 125/2007 sets the location of river basin districts following the previous river basin configuration. These river basin districts (including surface and groundwater) are considered the geographical units for planning.
The planning process also requires a committee including representatives from those authorities with competence on water management. This committee, or competent authority, shall promote participation and cooperation to achieve an

effective implementation of water management policy in each river basin district. To fulfil this objective Law 126/2007 was approved in order to regulate the committee's membership, the application of rules and the competences of Competent Authorities Committees within each of its river basin districts.
The Regulation on River Basin Management Planning (RRBMP), approved by Law 907/2007 of 6 July 2007, completes the legal framework on water management planning required by the WFD. The RRBMP sets up the mandatory contents of new river basin management plan as well as the development and endorsement procedures. However, due to technical difficulties on the development of water management plans (plenty of interdependent issues and measurements) an Instruction on River Basin Management Planning was approved by the Ministerial Order ARM/2656/2008 of 10 September 2008. The aim of this instruction is to present technical criteria to homogenise and systematise river basin management plans for each river basin district following the RRBMP.

• Efficiency versus equity

Efficiency in water use

Water pricing and efficiency

Although water pricing is an environmentalist demand, the reason on which this instrument is based is purely economic. In this sense farmers, according to economic theory, would respond to the introduction of (or an increase in) water prices by reducing their consumption, in accordance with a negatively sloped demand curve (see Figure 1). Water savings would be reallocated amongst other uses with higher productivity (industrial use) or with environmental purposes (ecological flows), according to social preferences. Such reallocation of water resources would improve the water use efficiency.
In the short term, efficiency improvement occurs when the benefit provided by the last unit of water (marginal value product) is the same in all its possible uses (industrial, domestic, agriculture, recreational and ecological) and to the marginal cost of water supply. Regarding this criterion of efficiency, the main alternative is to set water prices according to marginal cost. If this condition is fulfilled use/allocative efficiency is achieved and total economic welfare is maximised (Coase, 1980).
The main advantage of this water pricing system is the achievement of an efficient allocation of resources from an economic perspective. However, several disadvantages can also be outlined. In particular, it is rather difficult to identify and quantify all costs and benefits from water use and, therefore, reflect them in water prices. Following this economic principle, the presence of high variability of water

users' locations or a difference in water quality leads to different marginal costs of water supply and, therefore, to different water prices.
Water scarcity is another factor that complicates water pricing. Thus, the marginal cost (including opportunity costs) of water ranges form a virtual zero in the rainy season to a high cost in summer. For instance, taking into account that marginal cost of water supply should equal its real price, consequently water price should increase during drought periods. In this sense, water prices should vary between seasons, crops, irrigated areas, neighbourhoods or users. In practice, this system is very complex to implement both by the administration and the final users.
Indeed, if the aim of water pricing is to achieve efficiency, the most suitable economic instrument is the implementation of water markets. The interaction of water supply and demand will determine the marginal value and cost of water (market price at equilibrium).

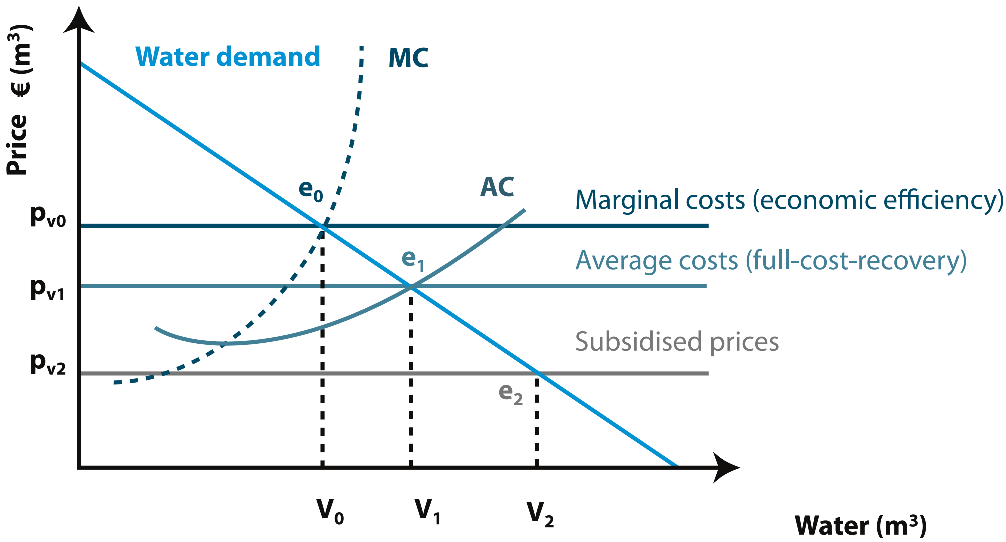

Figure 1. Water pricing options (MC: Marginal Costs; AC: Average Costs).

Due to problems to put into practice water prices based on marginal costs of water supply, an alternative is to equal prices to average costs (see Figure 1). This water pricing system aims to recover all costs of water supply (operating costs, management costs, depreciation and maintenance of water infrastructure, externality costs (or benefits) and environmental costs). The main advantage of this system is the proportional distribution of water costs amongst users, making its implementation easier. However use/allocative efficiency is not achieved by this water pricing system since water price is equal for all users and water resources are not reallocated to higher-value uses.

Water pricing and cost recovery

Besides achieving economic efficiency, another water pricing aim is to recover water supply costs (total revenues equal total costs). To cope with this, the capacity to recover all costs should be analysed first. Figure 2 shows the revenue and demand curves.

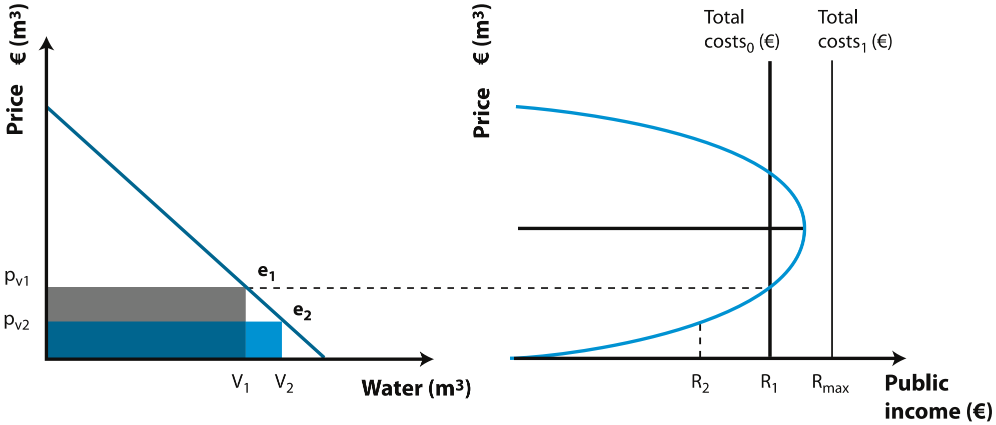

Figure 2. Cost recovery.

Public revenues collected by water tariffs have a maximum value (Rmax), achievable for the water price associated to a unit-elastic demand point. This maximum tariff collection shows the capacity of the system to recover water supply costs.

Irrigation water pricing in Spain is implemented by subsidised tariffs based more on equity than efficiency criteria. This tariff system results in a low recovery of the cost of water supply. For instance, in Spain it is possible to distinguish a highly productive agricultural system, such as the greenhouse farming located in the Mediterranean coast. This agriculture is very competitive and may afford higher water prices than those currently paid ("Total costs$_0$" in Figure 2), covering almost all water supply costs. In this situation, water tariffs equal to average water cost results in the recovery of the costs of water supply. However, there are other agricultural systems unable to recover the costs of water supply ("Total costs$_1$" in Figure 2): those systems characterised by low productivity and oversized hydraulic infrastructures. The presence of latter agricultural systems makes it difficult to achieve the full cost recovery in the short run, because of costs associated with water infrastructures.

Efficiency and water demand

Since the demand curve slopes down, irrigation water pricing causes a decrease in the consumer (farmer) surplus (see Figure 3). This loss in consumer surplus can be split up into two parts:

- Transfers from consumers to the administration by water tariffs
- Losses from water savings (change the crop mix)

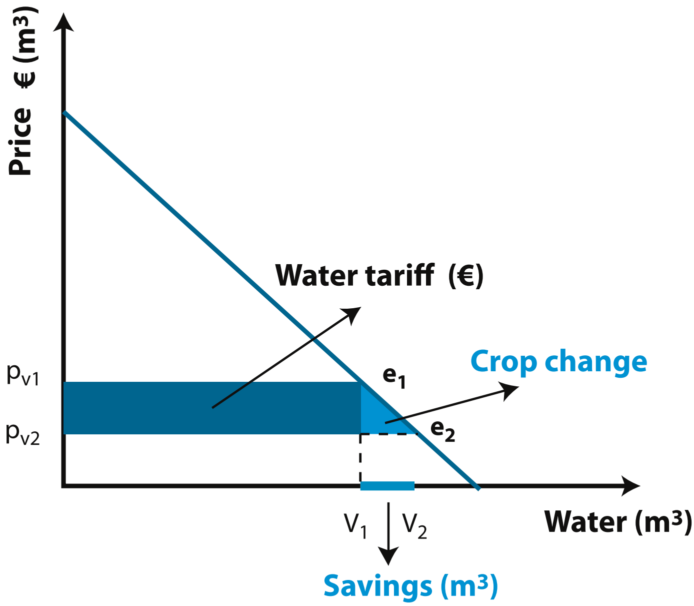

Figure 3. Water pricing and irrigation water demand.

Water tariffs do not cause any social welfare loss since they do not mean any efficiency loss or gain, but an income transfer from agriculture to the administration. However, water pricing causes a welfare loss for farmers resulting from changes in their crop diversity. At aggregate level, water savings from this change in crop diversity may be reallocated to more highly productive uses (domestic water, industrial water or recreational uses). By contrast, if water savings are not allocated to uses with higher added value for the whole society, water pricing would result in an allocative inefficiency.

It is worth mentioning the effects of the slope of water demand on potential efficiency gain (or loss). Efficiency gains would be potentially larger if water tariffs are applied in elastic demands, whereas these gains would be minimal if water tariffs are applied in inelastic demands. For instance, if water tariffs are applied in perfectly inelastic water demand curves, the efficiency gains would be zero. The price elasticity of demand depends on the water productivity in different uses. In highly productive water uses (i.e. greenhouse farming) water demand tends to be more inelastic and farmers might afford higher water prices. By contrast, low productive water uses (i.e. extensive agriculture) show an elastic water demand curve. As mentioned above, improving allocative efficiency for water resources by water pricing is only achievable for latter uses.

Equity in water allocation

Equity in water resources allocation should be linked to rural development policies, since irrigation is a way to improve farmers' income and welfare in rural areas. There is often a trade-off between efficiency and equity. Efficiency means that water resources are allocated to highly productive users, whereas low productive users would have a welfare loss. Usually in agriculture these low productive users are economically disadvantaged and the implementation of water pricing systems based only on an efficiency criterion will result in a significant income loss, and in some cases might lead to the abandonment of the agricultural activity.

In case equity would be the criterion followed by the administration, there are two ways to allocate water amongst users.

First, tariffs based on a percentage of net profits due to irrigation water availability. In practice this system can be implemented by a tax on net profits, i.e. those farmers with higher incomes pay more taxes. By using this pricing system, it is possible to achieve an equitable distribution of income: highly productive farmers would pay more taxes and the public sector would redistribute tax revenues amongst low productive farmers. However, this pricing system has an important drawback since it is disconnected from water use and water supply costs. Another disadvantage of this system comes from the difficulty of estimating the net profits of irrigation water availability.

Secondly, water tariffs can be implemented by the administration according to users' income. The implementation of subsidised water tariffs would mean a subsidy to economically disadvantaged irrigation users in order to increase their income. This is the case in Spain, where equity takes priority over efficiency in the water tariff system. This water pricing system based on subsidised tariffs is more equitable since there is a redistribution of income towards the poorest sector of agriculture, but it also results in some drawbacks since it does not give any incentive for water savings.

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Abstracts and Authors

PUBLISHED PAPERS

Michela Miletto - UNESCO, World Water Assessment Programme

Foreward

Eriberto Eulisse, Melike Hemmami and Esther Koopmanschap

waVE Water Civilizations International Centre (Italy), Doga Dernegi (Turkey), Wageningen UR Centre for Development Innovation (the Netherlands)

Preface

Shaminder Puri - International Association of Hydrogeologists

Introduction. Why Worry about Transboundary Aquifers in Promoting Sustainable Agriculture?

Almost 2 billion people on earth rely entirely on ground water for their water needs, including drinking and irrigation. Almost 40% of the worlds population (3Bn) lives in one or another transboundary water system; almost 60% of all water flows cross one international boundary or another. In considering how to make agriculture sustainable, do we need to include the consideration of transboundary management in our battery of tools? While the individual farmer can have little influence on the outcome of policy decisions, poorly structured decisions could have significant impact on small farming communities. How then can we take agricultural water needs into account in formulating national and regional transboundary water policy decisions? Further, how has the globalisation of economies affected transboundary water use? Does the current economic crises give the policy developer an opportunity or is it a threat?

Claudio Gandolfi - University of Milano (Italy)

Modelling Tools to Support the Harmonization of Water Framework Directive and Common Agricultural Policy

After a few years from the delivery of the EU Water Framework Directive (WFD) the need to link agriculture and WFD has emerged as one of the highest priorities; therefore, it is important to discuss on how the EU Common Agricultural Policy (CAP) can contribute to the achievements of the WFD objectives. The work presented in the seminar has got some innovative aspects: not only does it couple an economical model and a spatially distributed hydrologic model, but also embodies the two models in a wider procedure aiming at supporting the process of water resources planning at basin scale, based on the IWRM (Integrated Water Resources Management) paradigm. In practice, the economical model defines different land use scenarios deriving from the effects of the CAP on the farmers' productive choices; the hydrological model assesses the crop water requirements and determines the consequent variations of irrigation water demand at the basin scale; finally, the modified pattern of irrigation demand of each land use scenario is incorporated into a multi-objective optimisation procedure, which generates a set of efficient water management policies. This paper illustrates the results of the application of these tools to a pilot study basin in Northern Italy, the 6,500 km2 wide Adda river basin.

Bernard T. Nolan - US Geological Survey (USA)

Determining Groundwater Vulnerability to Nitrate Contamination from Agricultural Sources

Logistic regression and nonlinear regression are useful methods for predicting aquifer vulnerability at large spatial scales. The LR and NLR models summarized here are parsimonious and were calibrated to observed chemical concentrations. Whereas LR predicted the probability of exceeding a specified nitrate concentration, the nonlinear GWAVA model predicted nitrate concentration based on network averages of nitrate and explanatory variables. The GWAVA model structure is more physically based than LR because it segregated nitrogen sources from physical factors that control nitrate transport and fate in groundwater. CART has fewer statistical assumptions than LR and MLR and is useful for exploring large data sets with many variables. CART analysis indicated that the interaction between redox variables and N from farm fertilizer was key to explaining nitrate occurrence in shallow groundwater.

Bruna Gumiero, Bruno Boz and Paolo Cornelio

University of Bologna (Italy), University of Padova (Italy), Acque Risorgive Drainage Authority (Italy)

River Restoration and Sustainable Agriculture in the Venice Lagoon Basin: the Nicolas Project

The Venice Lagoon is a wide, shallow coastal basin extending for about 50 km along the north-western coast of the Adriatic Sea. A large portion of the catchment of the Venice lagoon is within one of the main Italian reclaimed areas for agriculture. The lagoon has been substantially modified by human activities over the last century through the artificial control of the hydraulic dynamics of the lagoon. Moreover, the land use of its catchment is mainly agricultural (67%). As a consequence, over the past decades, nutrient loads delivered to the Venice Lagoon have attracted considerable concern. The Regional Authority established a series of targets to reduce the level of nitrogen and phosphorous entering the Lagoon to prevent eutrophication. The Drainage Authority (Consortium) Dese Sile in the last decade has been active in a number of activities, among which the Nicolas project, aimed at developing a catchment strategy to reduce nutrient loads entering the Venice Lagoon from its rivers.

Luís S. Pereira - **Universidade do Lisboa (Portugal)**

Irrigation Water Use, Conservation and Saving. Issues to Support a New Paradigm and the Sustainability of Water Uses

Concepts and performance related to water use are useful in analysing water conservation and saving aimed at an efficient water use and coping with water scarcity. In this paper, new indicators are proposed to include the consideration of water reuse and assist in identifying beneficial and non-beneficial water uses. Former indicators do not refer to the consumptive and non-consumptive water use, do not make a distinction between beneficial and non-beneficial water uses, and assume that irrigation efficiency is the most important factor to deal with; moreover, former indicators are not well related to production objectives of farmers and water users. An analysis of water productivity concepts, including economic water productivity, useful in irrigation and for other uses, is presented to complement the proposed indicators. These concepts are discussed with the purpose of developing new approaches and a common understanding of issues for efficient water use. **Key-words**: beneficial water use, water wastages and losses, water productivity.

Josep Mas Pla - Universitat de Girona (Spain)

Estimating Water Balances in Agricultural Basins. Impacts of Water Withdrawal on Existing Resources and Water Quality Related Problems

Agricultural demand stands for the largest of the human water uses; therefore, water efficiency in irrigation is a challenge for water managers. Rational use of water in agriculture intends avoiding aquifer overexploitation as well as a deterioration of ground water quality because of the leaching of fertilizers and pesticides.
Estimating the water needs is a task that depends on meteorological variables, the hydrological characteristics of the soil, and the type of crop. Those values can be easily calculated. Nevertheless, allocation of regional water resources to agriculture has to consider the overall water balance in the basin. In this way, water functions as supplying human demand for domestic or industrial uses and providing a sufficient amount of stream discharge for the ecological processes.
This contribution reviews the water budget approach as way to estimate the magnitude of all the components of the water cycle under a development state; that is, when water is pumped off the aquifer to supply human demand. Moreover, the water balance is herein presented as a tool to define when a safe or a sustainable water management has been reached. Both concepts –safe and sustainable yield- would be discussed as fundamental concepts to achieve an appropriate use of water resources.

Guido D’Urso - Università Federico II di Napoli (Italy)

Earth Observation for Monitoring Water Use in Agricultural Systems

During recent years there has been much progress in understanding land surface-atmosphere processes and their parameterisation in the management of water resources in agriculture. Earth Observations techniques in different regions of the electromagnetic spectrum have been used for about three decades to monitor and analyse land surface. Nowadays, these techniques are available for practical application in the field of land and water engineering. At the same time, technological developments leading to a new generation of remote sensors - with improved spatial and/or temporal resolution - provide the opportunity for new observational and modelling perspectives. In this paper, a brief overview of current techniques and recent developments for the utilisation of Earth Observation data for the management of land and water resources will be given, with particular emphasis on the researches carried out at the University of Naples “Federico II”. These researches have been focused on the estimation of vegetation parameters, i.e. fractional cover and Leaf Area Index. These data are used as input in agro-hydrological models for evaluating the water balance of agricultural systems, with special concern to irrigation planning. New techniques in the acquisition and processing of Earth Observation data may improve the accuracy of evaluation models, with great benefits for the management of agricultural water use.

Laura Riesgo - **Universidad de Sevilla (Spain)**

Water, Economy and Sustainable Agriculture

It was no coincidence that behind the origin of the first human civilizations (Mesopotamia, Egypt, etc.) was hidden the same driving force: irrigation farming. Indeed, when humans learned how to properly combine labour, land and water, then they were able to generate the food surpluses to allow labour and trade specialization. These specializations were sine qua non conditions for the emergence of the first cities and empires. Irrigation farming development is basically due to its higher productivity (increase in crop yields) as well as to the possibility of growing new crops in arid climates (summer and permanent crops, such as fruit trees). Both factors cause that since ancient times irrigation is considered a core activity for human survival and for social and economic development. Taking into account these advantages, we can see that since then the irrigated area in the world is still increasing. Nowadays the total surface of irrigation farming reaches 280 million hectares (FAO, 2007), which shows that irrigation is a key sector to achieve food security in the world (UN, 2003). However, the development of irrigation farming in developed countries seems to be depleted at present. Thus, the increasing scarcity of water resources as well as the new requirements for sustainable rural development will introduce new constraints in the irrigation expansion. It is also worth to point out that Europe, and especially the Mediterranean area, is faced with a "mature" water economy (Randall, 1981). This period is characterized by a high and growing water demand, a rigid long-term water supply, obsolescence of most of water infrastructure, a strong competition between different uses and the presence of negative environmental externalities. This situation has caused an intense debate on efficient water use in agriculture. Thus, the apparent mismanagement of irrigated water (water "losses" and its application to low profitability and low labour-demanding crops) has provided a strong argument to justify a policy review about water use and irrigation farming. Facing this situation, countries try to implement water policies focused on the demand management. Thus, it is possible to distinguish four economic instruments that help to increase water use efficiency such as reallocation of water resources, improvement of water infrastructures, water pricing and the introduction of water markets.

UNPUBLISHED PAPERS

Andrea Merla - World Bank

Balancing Overuse and Conflicting Uses of Water Resources in Surface and Groundwater Basins

Overuse and conflicting uses of water resources in surface and groundwater basins, particularly agriculture related ones, result in significant ecological and economic damage, reduced livelihoods for the poor, and increased political tensions among upstream and downstream communities and/or states. With increased climate variability and more frequent droughts and floods, the conflicts and water scarcity increase dramatically. Additionally, shallow groundwater over-extraction and saline intrusion along coasts are becoming major global threats to human development and environmental sustainability.
Use of Integrated Water Resources Management (IWRM) policies has been identified as the answer to balancing competing and conflicting uses of water resources to inform and consider tradeoffs being made in socio-economic development objectives and ecosystem protection. These hydrologic unit-based IWRM approaches provide a framework for practical considerations in tradeoffs among water resource uses with participation of stakeholders and support the incorporation of benefits across boundaries into decision-making. Targets related to IWRM were adopted at the Johannesburg Summit. Links between IWRM in basins and ICM at downstream coasts are of pivotal importance as cooperation contributes to securing not only local waters uses but also global public goods that benefit all stakeholders. The presentation will examine selected examples of transboundary basins and aquifers distributed across various climatic and socio-economic conditions

Marco Acutis - University of Milano (Italy)

Characterizing Groundwater Pollution due to Agricultural Activities

The world is facing a new difficult period, where agricultural lands are reducing, and population is increasing. So there is a specific need to increase agricultural yields in more favorable areas. This objective can be pursued only with intensive cropping systems, using improved agronomy and genetics, but using also large amount of fertilizers and pesticides. As a consequence there is a risk for environmental quality, in particular for groundwater, where one of the main problem is to preserve their quality for potable use. Groundwater quality is an issue common to developed and developing countries, and is only partially due to agricultural activities. Not all the pesticides are needed because of the need to control weeds and biotic adversities in cropped fields, also roads, ballast and industrial areas weeding play an important role. In the same way not all the nitrate in groundwater comes from agricultural activities: industrial discharges, sewage plants poorly made, the mineralization of the organic matter are also important. Nevertheless, the definition and the employment of cropping systems (a cropping system is a sequence of crops in time and space, each one with their own management of fertilization, irrigation, crop protection, tillage etc.) is a precise responsibility of agronomy and farmers, which have the role of developing systems characterized by a low level of environmental impact, high sustainability and high yields. There is a need to consider cropping systems as agro-ecosystems, due to the complexity of the interactions among the different system's components and the driving forces (e.g. climate, social condition etc.) acting on the system itself. The most important points to obtain high yields are the nitrogen fertilization and the crop protection: without nitrogen fertilizer and protection a yield of 10% of the actual one is expected in developed agricultures. In previous historical periods, where price of fertilizers was low, particularly if compared with the value of the products, there was a strong tendency to overfertilization. Another sources of risk is typical from the areas where livestock (cows and pigs) are very intensively grown, as in Po Valley (northern Italy), UK, Denmark, Belgium. In this cases, the problem is the over availability of manure and slurry.

Considering that the cropping system is the base unit to study nitrogen and pesticide dynamics, two main ways to assess their risk for groundwater quality are available, the first based on indicators (Bockstaller et al., 2009), the second on the use of mathematical models simulating the cropping system behavior. From the bio-physics point of view, cropping system models are
the main instruments for the scientific analysis of their fate, as well as the instrument to test a priori different management alternatives. An example of a model specifically conceived to manage an agroecosystem is CropSyst (Stockle et al, 2003). A detailed description of an agro-ecosystem from the point of view of pesticides dynamics is available from the Pearl Model (Leistra et al., 2001). Main biophysics concepts of carbon and nitrogen models are summarized in Gabrielle (2003).

The lecture explores the framework of controlling groundwater pollution through the correct management of cropping systems, explaining the dynamics of pollution risk from agricultural practices and the main instrument to study, measure, control and design agro-ecosystems, with a specific reference to cropping system models.

Nunzio Romano - **Università Federico II di Napoli (Italy)**

Ecohydrology: an Integrated and Sustainable Approach for Water Resources Management in Rural Areas

Because of pressures generated by an increasing exploitation of natural resources (like soil, water, and vegetation), the entire scientific community is now aware and concerned of the scarcity of these resources and the tight interrelation between technological progress, environmental quality, sustained equity and quality of life. Integrated resource management and sustainable use of resources are important for sustained socio-economic development as a careful trade-off between economic growth and the resulting negative impacts of resource exploitation to fund this growth. Whilst a consensus has emerged that the principle of sustainability should prevail in the management of water resources, there is less agreement about the selection of the appropriate tools to facilitate this sustainable use. The search for appropriate and practical answers to meet these needs no longer relies solely on detailed studies of fundamental hydrological processes, but also requires an assessment of the effects exerted by the space-time evolution of these processes on distribution and functionality of terrestrial ecosystems, i.e. eco-hydrology rather than simply hydrology.

Soil and water provide the media for eco-hydrologic processes and mathematical models of different complexity have been developed for describing these processes. Progress has been achieved in advancing scientific knowledge on the soil-plant-atmosphere continuum (SPAC) as well as in developing improved monitoring and modeling techniques, but difficulties still exist in exploiting these results by decision makers and stakeholders that should plan suitable and effective interventions to protect the ecosystems. Major reasons for that are at least twofold and involve both experimental and modeling issues. Fairly good description of the basic hydrologic processes has been aided at the local experimental level by the availability of accurate measuring techniques and devices. On the other hand, reliable model predictions on the evolution of hydrologic processes are still difficult to achieve, particularly at the space scales of interest for environmental planning.

This talk would review and provide a critical account of quantitative analyses of the processes underlying the soil-vegetation-atmosphere (SVA) dynamics. In addressing an issue as complex as prediction of soil-water-vegetation interactions under a specific climate, with its diversity of drivers and processes, it is important an in-depth understanding of the effects of hydrological processes on the structure and dynamics of ecosystems. Water dynamics in the ecosystems is controlled by several nonlinear and interacting processes, which are also characterized by a relatively large spatial and temporal variability. Laboratory and field experiments will be thus reviewed as they represent a valuable basis to throw ourselves toward challenging questions in vadose zone hydrology, such as the "scale-transfer" and model over-parameterization problems, with related problems of parameter non-uniqueness and uncertainty of the simulation. Laboratory experiments on soil cores and columns provide confirmation of theories and enable soil hydraulic characteristics to be identified more accurately. Investigations carried out at plot, transect, and catchment scales provide insights into the hydraulic response of field soils and help in understanding to what extent small-scale measurements provide information about larger scale water flow and solute transport processes. Hydrologic models will be presented and discussed in terms of their parameterization and with a view to their effectiveness with respect to the specific problem being solved.

Anna Romani - Universitat de Girona (Spain)

Nutrients in Surface Waters

Natural and human-made aquatic ecosystems are continuously exposed to new and varying loads of nutrients, pesticides, acidifying compounds and pathogens. These inputs are derived from local (urban and industrial sewage) and diffuse (mostly agricultural) sources. Nutrient excess may cause eutrophication, stimulating primary production up to unsustainable limits for the aquatic ecosystems. Nitrogen and phosphorus from the river water are used by bacteria and primary producers. As a consequence, nutrient declines downstream (a self-depuration process) under non-saturation conditions. As a direct result, algae (biofilms) may increase their biomass and produce large accumulations when favorable light and nutrient conditions are prevalent. Nutrient ratios are also relevant. Low ratios of nitrogen to phosphorus (N:P) and variation in total P or total N have been related to noxious and sometimes toxic cyanobacteria blooms. Relationships between biomass (mostly expressed as chlorophyll) and nutrient supply rate can be described by empirical models, designed to predict nuisance levels of algal biomass. Even though most of the models are linear (developed through the application of linear regression), some incorporate curvilinear terms, indicating that asymptotic relationships are possible.
The control of nutrient arrival and their effects on aquatic ecosystems requires of adequate planning in agricultural landscapes. Maintaining well-preserved riparian vegetation can effectively buffer the arrival and derived effects of nutrients on aquatic ecosystems. Restoration of aquatic ecosystems needs to be addressed at a landscape level to effectively ameliorate these effects.

Elena Floria Garcia - Agència Catalana de l'Aigua (Spain)

Fertilizers (Nitrate) in Groundwater

Abstract: Presence of nitrogen compounds (especially nitrates) is the main problem concerning groundwater diffuse contamination in Catalonia. This has been well established during the works fulfilling articles 5, 6 and 7 of the Water Framework Directive (2000/60/EC) (http://mediambient.gencat.net/aca/ca/planificacio/directiva/inici.jsp, the "IMPRESS" Document). The most important sources of nitrogen in groundwater are manure spreading and mineral fertilisers. This pollution primarily affects catchments of drinking water for the public supply.
The Council Directive 91/676/CEE concerning the protection of water against pollution caused by nitrates from agricultural sources was adopted on December 1991. Since then, the Catalonian Government has been established a considerable range of administrative rules and management programs, with the aim to reduce the environmental impact of agricultural nutrients on ground and surface water quality. The Decrees 283/1998 and 476/2004, which designate the nitrate vulnerable zones (NVZs), and the programs of agriculture beneficial management practices (BMPs) are the most significant regulations on nitrate management.
The talk aims to show the temporal evolution and general trends of nitrate pollution from 2000, with special emphasis on implications for water supply management. A critical revision of the measures and particular actions carried out by the Catalan Water Agency are made and the new measures recently included in the Catalan River Basin District Management are also presented.

Avner Vengosh - Duke University (USA)

Domestic Sewage Effluents and Agriculture Development

Abstract: In water-scare areas of the world, treated sewage effluent is becoming an important water source that substitute the diminishing or contaminated freshwater resources. In some Mediterranean countries it is expected that future utilization of treated domestic sewage will become the major source for irrigation water. In addition to biological and organic contamination, one of the important constraints for the utilization of wastewater is the inorganic chemical composition, particularly the content of salts such as sodium, chloride, and boron.
Recycling of nutrients and nitrification process also affects water resources associated with wastewater contamination. This presentation highlights the impact

of naturally occurring (geogenic) and man-made (anthropogenic) salinization on the quality of water resources and agriculture development.
The lecture introduces the geochemical and isotopic tracers that provide the identification tool for delineating the salinity sources in water resources, particularly in arid areas. That includes major chemistry, minor and trace metals, and the isotopic systematics of dissolved constituents in water (boron, strontium, nitrogen, sulfur, radium).
Examples will be provided from case studies of research conducted in the Mediterranean coastal aquifer of Israel and the Gaza Strip as well as other stressed aquifers in arid zones (e.g., the Jordan River, California, Jordan, Negev). The overall objective of this presentation is to illustrate the relationships between scientifically-based evaluation of water-quality deterioration processes and adequate policy strategies for sustainable development of water resources.

Kamel Zouari - Ecole Nationale Superieure des Ingenieurs de SFAX (Tunisia)

Impact of Agricultural Practices on the Quality and Quantity of Water in the Region of Cap Bon (North East of Tunisia)

Understanding water budgets and water quality is a fundamental requirement for the assessment and successful long-term management of ground-water resources. In all arid and semi-arid countries, such as in Tunisia, agriculture remains the main water consumers and water pollutants. Multidisciplinary approaches are used to assess the interaction between agriculture practices and groundwater availability. Isotopes and geochemical tracing are simultaneously used with hydrodynamical studies to assess water fluxes between surface water, subsurface water in the first level of soils and groundwater.
Four case studies will be presented:
- Quality degradation of a shallow aquifer due to agriculture fertilizers in North-Eastern Tunisia
- Marine intrusion in a coastal aquifer due to intensive agriculture exploitation in South-Eastern Tunisia
- Artificial recharge of a multilayered aquifer using regulated dam water releases in Central Tunisia
- Irrigation return flow and groundwater contamination in South-Western Tunisia

Jan Olof Lundqvist - **SIWI Stockholm International Water Institute (Sweden)**

How to Meet Increasing Food Demand with Less Water and an Increasingly Erratic Rainfall?

In many of the presentations made at the World Water Week in Stockholm, August 16 - 22, it was argued that the increase in demand for food will make it necessary to increase production by about 50% between 2000 to 2050. As a result of changes in the diet composition, the pressure on water resources will be proportionally higher. At the same time, the demand for water will increase from other sectors, notably in urban areas. The demand for water from other sectors is associated with an ability to pay for water services, e.g. the industrial and service sectors. The provision to households is, generally, given the highest priority. Hence the argument that there is likely to be less water available for agriculture and especially for food production. At the same time, increasing traditional storage of surface water is increasingly costly and difficult for various reasons (environmental, protests from downstream communities..). The new situation is compounded by the pronounced variation in rainfall, which is likely to be more erratic in years to come as a result of climate change. A certain drop in rainfall means a higher drop in run-off.

Under these circumstances, it is a huge challenge to make “reasonably sure” that enough food is being produced. But increased production is not the panancea. It is revealing to look at recent figures from FAO about the food production in the world. It is shown that world cereal production increased by 7% between 2007/08 and it has never been higher. One would believe that this fortunate development should result in an improved food security in the world. However, in the same period, the number of undernourished in the world increased by about 150 million. The figures just quoted seem to suggest that information about food production and supply (at the market) cannot be used to interpret what is the develoipment effect.

Enrico Brugnoli - **Institute of Agro-environmental and Forest Biology (Italy)**

Water-Use by Land Vegetation: Linking Carbon and Hydrological Cycle

The availability and quality of water in many regions of the world are threatened by overuse, misuse and pollution, and it is increasingly recognized that both are strongly influenced by terrestrial ecosystems, especially crops and forests. Agriculture is the largest water consumer and, with increasing global population, agricultural production also increases, causing an increasing demand of water for irrigation and for urban uses. On the other hand, forests are recognised to be major players in regulating the hydrological cycle and, especially, the water flow through the terrestrial biosphere. In addition, global change is altering the biosphere-atmosphere exchange and, consequently, water flows, therefore influencing the availability of water resources. As a consequence of global warming, large area of the world is becoming more prone to drought and the risk of desertification will inevitably increase. Hence, the relationship between terrestrial ecosystems and water is a critical issue and deserve increasing attention. One of the main questions is how to increase food (and forest) production with limited water and land resources. Several factors may contribute to save water in agricultural and forest ecosystems. One of the main determinants to decrease the water-use by crops is the increase of water-use efficiency (WUE), defined as the ratio of dry matter production to water consumed, which is a relevant parameter in determining plant and crop productivity, at least in water-limited environments. In turn, WUE is dependent on the photosynthesis and transpiration rates. Hence, improving WUE may be relevant to increase productivity and/or decreasing the water consumption. Stable isotopes analysis in plants is very useful to study productivity and WUE. Carbon isotope fractionation during photosynthesis is negatively correlated with WUE through two independent relationships with the ratio of leaf intercellular and atmospheric partial pressures of CO_2, i.e., the balance between photosynthetic capacity and stomatal conductance. Hence, studying the stable C isotope composition of plants allows to compare water-use efficiency in crop species. On the other hand, the ^{18}O isotopic enrichment in leaves is strongly dependent on the transpiration rate and, hence, it is largely determined by stomatal conductance and by the evaporative demand of the atmosphere. Therefore, combining the study of ^{13}C and ^{18}O in plants and crops it is possible to separate biochemical and diffusional limitations to photosynthesis and to identify strategies to improve crop water-use efficiency.

Sabri Sener - **University of Ankara (Turkey)**

Effective Use of Irrigation Water and its Effect on Transboundary Water Management. A Case Study: the Euphrates and Tigris Rivers

Despite cordial relations between Turkey, Syria and Iraq the issue of water allocation has continued to cause some friction between the governments since late1980s. The aim of this study is to show that if transboundary water resources are cooperatively and effectively managed, it can make a significant contribution to regional peace, stability and sustainable economic growth. There are mainly two big transboundary rivers in the Middle East, Euphrates and Tigris rising from Turkey and flowing through Syria and Iraq. Both rivers are fed by snowpack and rainfall in eastern Turkey and in northwest Iran. The flow of the rivers varies considerably every year. In years of low flow make irrigation and agriculture difficult. Turkey started a very big integrated project called GAP (acronym for Southestern Anatolian Project) for the economic and social development of the region. The project covers the lower parts of the Euphrates and Tigris rivers and 9 provinces in the region. A total of 6.47 million people live in these provinces. Syria and Iraq have similar storage and irrigation projects on these rivers. These projects will be complementary for each other and help the sustainable use of existing water resources.

Research results carried out on irrigated agricultural crops comparing different irrigation systems in Euphrates and Tigris Rivers' Basin in Turkey, showed that, 700-900 mm irrigation water per season is sufficient for optimum yields for the most of the summer crops, provided that modern irrigation technologies are used in irrigation.

The total long term average discharge of Euphrates and Tigris Rivers is about 82 bm^3/year. When total irigable area is considered in the region (Euphrates and Tigris Rivers` Basin), total irrigation water need is approximately 58 bm^3/year, which is 70.7 percent of the existing capacity of these two major rivers. If these three countries could increase the application of water and energy saving irrigation methods in agriculture, they will be able to mitigate the possible effects of climate change and drought in the future. This makes it urgent for them to take necessary measures to support the small and medium size farmers who have limited financial resources to shift from surface irrigation to water and energy saving irrigation technologies.

DVD contents (audio files and power point presentations)

Monday 5 October

Michela Miletto - UNESCO WWAP
The World Water Assessment Programme
Andrea Merla - World Bank
Balancing overuse and conflicting uses of water resources in surface and groundwater basins
Marco Acutis - Università degli Studi di Milano (Italy)
Characterizing ground water pollution due to agricultural activities
Nunzio Romano - Università Federico II di Napoli (Italy)
Ecohydrology: an integrated and sustainable approach for water resources management in rural areas
Josep Mas Pla - Universidad de Girona (Spain)
Estimating water balances in agricultural basins. Impacts of water withdrawal on existing resources and water quality related problems

Tuesday 6 October

Anna Romani - Universidad de Girona (Spain)
Nutrients in surface waters
Elena Florìa Garcìa - Catalan Water Agency (Spain)
Fertilizers (nitrate) in ground water: Àrea de Planificació per l'Ús Sostenible de l'Aigua
Avner Vengosh - Duke University (USA)
Domestic sewage effluents and agriculture development
Luis Santos Pereira - University of Lisboa (Portugal)
Irrigation water use, conservation and saving. issues to support a new paradigm and the sustainability of water uses

Wednesday 7 October

Field trip to Quarto d'Altino (Venice). Pumping Areas of Carmason: the Nicolas Project
Bruna Gumiero (Università di Bologna) and Paolo Cornelio (Acque Risorgive Authority)

Thursday 8 October

Kamel Zouari - Ècole Nationale Superieure des Ingenieurs de Sfax (Tunisia)
Impact of agricultural practices on the quality and quantity of water in the region of Cap Bon (North East of Tunisia)
Jan Olof Lundqvist - Stockholm International Water Institute (Sweden)
How to meet increasing food demand with less water and an increasingly erratic rainfall?
Enrico Brugnoli - Istituto di Biologia Agroambientale e Forestale (Italy)
Water-use by land vegetation: linking carbon and hydrological cycle
Thomas Nolan - US Geological Survey (USA)
Determining ground water vulnerability from agricultural pressures
Claudio Gandolfi - Università degli Studi di Milano (Italy)
Modelling tools to support the harmonization of Water Framework Directive and Common Agricultural Policy
Guido D'Urso - Università Federico II di Napoli (Italy)
Teledetection techniques for sustainable agricultural development
Shaminder Puri - UNESCO
Why worry about transboundary aquifers in promoting sustainable agriculture?

Friday 9 October

Sabri Sener - University of Ankara (Turkey)
Effective use of irrigation water and its effect on transboundry water management. Case study: Euphrates and Tigris Rivers
Laura Riesgo - Universidad de Sevilla (Spain)
Agriculture, water and economy

The Venice University of Ca' Foscari has a consolidated management expertise in organizing research and training events and activities. Its Department of Environmental Science has a well-known reputation for transnational exchanges and comparative research.
The Department offers its students a wide range of exchange programs like the Erasmus-Socrates, as well as specific programs in cooperation with other Universities.
The Department manages a number of mobility projects among which an ALFA project in water coastal management, funded by the European Commission, and the Internationalization Policy Project, which backs mobility of Ph.D, post-Docs and upgraduated students from Latin America and other Mediterranean countries to Venice.
Another international project is RIM, aimed to create a Mediterranean doctoral programme of studies on sustainable development, in particular on "Man, society and environment in the Mediterranean" (project co-funded by the Italian Ministry of University and Research, MIUR, and implemented in partnership with the Autonomous University of Barcelona, the University of Tunis El Manar, and the University Mohammed V, Agdal, Tunisia).

Water is a key issue of Civilization. Today, however, water has been reduced to a mere 'commodity' and has lost the cultural dimensions that have characterized many past Civilizations.
The Water Civilization International Centre (waVE) is a Non Profit Organisation established in Venice, aimed to change unsustainable behaviours and practices in water use and management. waVE's objective is to restore a positive relationship between Man and Water.
The Centre manages projects and disseminates research findings aimed to seek for sustainable solutions to global water crisis.
waVE promotes the recovery of both the material and non-material heritage of water, and the use of local/traditional knowledge of past societies that have elaborated original and innovative practices to face threats such as water scarcity, draughts, and desertification.
The Centre was established in 1996 and is supported by different institutional partners, among which the Venice University of Ca' Foscari, the Provinces of Venice, Belluno and Trento, the Benetton Research Foundation, the Acque Risorgive and the Piave Drainage Authorities, the water agencies of Veritas, Alto Trevigiano Servizi and AATO of Venice Lagoon, the Municipality of Fontanafredda (Pordenone) and B&M Engineering (Treviso).