MANAGEMENT OF IRRIGATION SYSTEMS TO COPE WITH DROUGHTS

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ABSTRACT

This paper aims at discussing several issues which can improve the management of irrigation systems to cope with droughts and water scarcity. The concept of drought is therefore analysed together with those on aridity, desertification and water shortage, so to better identify droughts among other water scarcity conditions. Main characteristics of droughts are then discussed, pointing out the needs for developing adequate monitoring and information systems. These include drought watch systems, which could follow the initiation, development and dissipation of droughts, and thus providing the information for decision makers and users. Such information systems are then analysed as a fundamental tool for supply management. Other aspects of supply management referred here in concern the enhancement of reservoir and conveyance capacities, the improvement of operation and management tools, the supply rules to be enforced during droughts, the training of managers, operators and farmers, and emergency planning. Finally, several aspects of demand management are discussed, including developments in irrigation scheduling and irrigation methods, as well as implications on farmers incomes resulting from adopting reduced demand strategies.

RÉSUMÉ

L'objectif de cet article est la discussion sur des approches à une meilleure gestion des systèmes d'irrigation pour mieux répondre aux contraintes de la sècheresse et des déficits en eau. Ainsi, le concept de sècheresse est discuté en rapport avec ceux d'aridité, de desertification et de pénurie en eau pour mieux identifier les spécificités des sècheresses parmi les autres régimes xériques. Les principales charactéristiques des sècheresses sont par la suite discutées, aussi bien que le besoin de développer des systèmes de monitorage et d'information, y inclus les systèmes de surveillance des sècheresses. Ces systèmes permettent le suivi de l'initiation, du développement et de la dissipation des sècheresses et produisent l'information nécessaire aux décideurs et aux utilisateurs.

Tels systèmes d'information sont aussi analysés comme des outils fondamentaux à la gestion des fournitures. Concernant celle-ci, d'autres aspects sont mentionnés tels que l'augmentation de la capacité des réservoirs et des systèmes de transport de l'eau, l'amélioration de leurs outils de gestion et d'opération, les règles de fourniture à être enforcées pendant les sècheresses, la formation des gestionnaires, des opérateurs et des agriculteurs, et les plans d'émergence.

Finalement, sont discutés divers aspects de la gestion de la demande, y inclus ceux relatifs à la conduite des arrosages, aux méthodes d'irrigation et les implications des stratégies de reduction de la demande sur le revenu des agriculteurs.

The sustainable use of water is not only a priority question for agriculture and for water scarce regions but for all sectors and regions. Imbalances between availability and demand, degradation of surface and groundwater quality, inter-sectorial competition, inter-regional and international conflicts, all bring the water issues to the foreground, particularly in drought-prone areas.

Because water is renewed in the course of the seasons it was viewed as a renewable and almost unlimited natural resource. Man progressively appropriated this resource and used it with too few restrictions, without enough care about conserving the resource, avoiding wastes and misuses, nor preserving its quality. Thus, nowadays, water is becoming scarce not only in arid and drought prone areas, but also in regions where rainfall is abundant.

The concept of water scarcity not only concerns the quantity of resource available, but also embraces the quality of water because degraded water resources become unavailable, or at least less available for human and nature uses. The perception that water is increasingly scarce gives to drought water management an increased relevancy.

Because irrigated agriculture is world-wide the sector with highest demand for water it is also largely affected by the scarcity of water resources. Irrigation is accused of misuse of water, of producing excessive water wastes, of degrading the water quality.

However, irrigated agriculture is supporting the living of an enormous part of the world rural population and is providing a large portion of world's food.

Recognisable efforts from innovation and practice, from funding agencies and managers, still are required to create appropriate issues for improving water management, to control negative impacts of irrigation, and increasing yields and farmers incomes.

There is also the need for a better understanding of the problems and issues related to water use in a world where water became a contentious issue for the next century. One promising issue is to consider the water not only as a natural renewable resource but as an environmental and economic good.

This paper intends to discuss how irrigation may contribute to mitigate the effects of droughts and, mainly, the issues in management required to improve the effectiveness of irrigation in mitigating such effects.

DROUGHT AND WATER SCARCITY CONCEPTS

Water scarcity, may be originated from one of the following xeric regimes: natural aridity and drought, or man-induced desertification and water shortage (see

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Vlachos and James, 1983; Pereira, 1990, 1997). Aridity is a nature produced permanent imbalance in the water availability consisting in low average annual precipitation, with high spatial and temporal variability, resulting in overall low moisture and low carrying capacity of the ecosystems.

Under such climatic conditions, water scarcity is permanent, ranging from extreme conditions in desert areas to mitigated situations in semi-arid regions. Irrigation plays a fundamental role in these areas to ensure food production and support living of rural communities.

Drought is a nature-produced but temporary imbalance of water availability affecting large areas, consisting of a persistent lower-than-average precipitation, of uncertain frequency, duration and severity, of unpredictable occurrence, resulting in diminished water resources availability and carrying capacity of the ecosystems. Droughts occur both in arid and humid areas. In semiarid and arid regions, drought aggravate water scarcity particularly when they last for more than one year, as it often happens. In humid areas, droughts of short duration may show evident impacts, much quicker but less persistent than in arid zones. Irrigation may help mitigating the effects of droughts when they are short and preparedness for droughts is effective.

It is important to recognise the unpredictable characteristics of droughts, regarding their initiation and termination as well as their severity. These characteristics make droughts to be both an hazard and a disaster. An hazard because it is a natural accident of unpredictable occurrence but of recognizable recurrence. A disaster, because a drought corresponds to the failure of the precipitation regime, causing the disruption of the water supply to the natural and agricultural ecosystems as well as to the human activities. Thus, while dealing with irrigation in water scarce situations resulting from aridity consists in establishing current, normal engineering and management measures, the management of irrigation under drought requires the enforcement of preparedness and emergency measures.

Desertification is a man-induced permanent imbalance in the availability of water which is combined with damaged soil, inappropriate land use, mining of groundwater, increased flash flooding, loss of riparian ecosystems and a deterioration of the carrying capacity of the ecosystems. However, the definition adopted in 1994 by the Commission for Combating Desertification is somewhat different, focusing on the land and not on the water availability: land degradation in arid, semiarid and dry sub-humid areas resulting from various factors, including climatic variations and human activities, where land means the terrestrial bio-productive system that comprises soil, vegetation, other biota, and the ecological and hydrological processes that operate within the system.

Desertification often occurs in semi-arid climates where the exploitation of natural resources due to human pressure overcomes the acceptable limits. Soil erosion and salinity are commonly associated with desertification. Water scarcity is therefore associated with misuse and abuse in the utilization of water, soil and other natural resources.

Drought strongly aggravates the process of desertification when increasing the pressure on the dimnished surface and groundwater resources. In areas prone to desertification, irrigation should give priority to re-establishing the environmental balance in the use of the natural resources and minimizing water wastes.

A water shortage is also man-induced but temporary water imbalance including groundwater over exploitation, reduced reservoir capacities, disturbed and reduced land use and altered carrying capacity of the ecosystems. Both the time and space scales of water shortages are smaller than those for desertification, but water shortages also contribute to initiate or to aggravate processes of desertification. Degraded water quality are often associated with water shortages and, like drought, aggravates related impacts. Irrigation management under water-shortage should also be aimed at restoring the environmental balances, and minimizing wastes and degradation of water.

The policies and practices of irrigation management under water scarcity situations must therefore focus on specific objectives according to the causes of water scarcity. The perception of the nature of problems is essential. Valuing the water as an economic, marketable good may be insufficient since water acts not only for producing but is also supporting and associated with other natural resources. A coupled environmental and economic approach is required in valuing the water, while an integrated technical and scientific approach is essential to develop and implement the management practices appropriate to deal with water scarcity and its causes.

DROUGHT CHARACTERIZATION, FORECASTING, MONITORING AND WARNING

The characterization of a drought, namely using indices, is controversial and several times contradictory. Agronomists often use the word drought to define a water stress condition affecting crop growth and yield. Meteorologists and hydrologists have developed indices which combine several hydrometeorological parameters or rely on probability functions (Cancellieri *et al.*, 1996; Hayes, 1996). Several examples are given by Yevjevich *et al.* (1983), Wilhite *et al.* (1987) and Agnew and Anderson (992). The adoption of the regional analysis is a significant improvement in characterizing droughts (G. Rossi, 1983; Rossi *et al.*, 1992).

The controversy in percepting droughts, and subsequently defining and characterizing them, does not help decision and policy makers to plan for droughts, to implement preparedness measures, neither to timely apply mitigation measures when a drought occurs, nor to adequately evaluate drought impacts. A first challenge thus is to improve a common understanding of drought phenomena and to adopt wide but explanatory definitions and sound characterization indices. This could facilitate the timeliness and appropriateness of the decision processes to cope with droughts.

A better understanding of droughts is essential to develop tools for prediction/forecasting of drought initiation and ending. This is essential to timely and appropriately enforce the measures to cope with droughts. Their pervasive impacts, slow initiation and undefined end make it difficult to select the opportunity of action. In case of a drought, the disaster elements only become evident much later, when the drought has already started, and the impacts last for long time after the drought has ended, particularly if the lack of measures and policies helped to turn the disaster into a catastrophe.

Difficulties on predicting the droughts are well known (Wilhite *et al.*, 1987; Easterling, 1989). Nevertheless, an adequate lead time, the period between the release of the prediction and the onset of the predicted hazard, is more important than the accuracy of the prediction (Easterling, 1989) because it makes possible that decision and policy makers prepare the policies and measures to be enforced to mitigate the effects of drought. In case of agriculture the lead time is essential to make it possible that farmers take the decisions required, altering crop and agricultural systems to cope with drought.

Difficulties in prediction lead some to develop early warning indices (Wilhite *et al.*, 1987; Palfai *et al.*, 1998; Cismaru *et al.*, 1998). These indices can be of meteorological or hydrological nature, combining actual and time series data, or they may result from stochastic treatment of reservoir volumes. Early warning can be supported by real-time agroclimatic networks or by the observation of the state of reservoirs.

The information on state meteorological and hydrological variables during the drought is essential to observe the development, maturation and dissipation of a drought. Surface and satellite based networks play a very important role, particularly when information models, including meteorological, hydrological, water supply, crop and irrigation models, can be applied and used. The development of drought watch systems could be of great importance not only for agriculture but for the overall management of water resources to cope with droughts.

Developments in instrumentation for data acquisition, storage, treatment and transmission are enormous. Improvements in software capabilities to create information for decision makers and users are also well developed. The main problem seems to be related to data management: institutions in charge of data collection tend to ensure all data treatment until the release of the final information, without fully using the skills of other institutions. This contradicts the essence of a network, which has to be considered not only as a combination of instruments but as a linkage of hardware and software skills and institutions, with common objectives and adopting an user-oriented perspective for the flow of information. The effective and efficient building of such networks constitutes an important challenge. Because droughts are transnational, the transboundary interdependence on the flux of information constitutes a further challenge. This identify the need to develop drought watch systems on an international basis.

SUPPLY MANAGEMENT

Information systems and networks

Careful, rigorous management of supplies to irrigation is required when water is scarce. Several aspects may be considered including planning, development of infrastructures, information and operation measures.

Water resources planning at basin scale, providing for water allocation, water use rules and water quality requirements, are still a basic aspect of supply management. Modern tools for water resources planning, including decision support systems and expert systems, make use of technical, environmental, economic and social criteria which may affect the management of irrigation. Main influences on operating irrigation relate to reservoirs operation, groundwater exploitation and diversion of surface water, which impact on the operation and management of conveyance and distribution systems.

To cope with drought, the water resources planning concerns preparedness measures for drought. One main aspect is then related to forecast and early warning of the drought on-set, as well as the forecast of drought severity and drought off-set. As referred above, this requires appropriate hydrometeorological and agrometeorological networks, interesting not only the institutions responsible for the acquisition of information, but also those representing the users, who should be able to timely implement the appropriate measures, including emergency measures. This area remains an area of concern, because more research is required, and because these information on weather and hydrologic variables is less and less available, with increased costs to users. Should agrometeorological information be free? How to price this information? These questions may deserve a wide discussion.

The competition for water is imposing restrictions to agriculture to divert good quality water. Thus, agriculture is increasing the use of low quality water in irrigated agriculture, including brackish, saline water, agriculture drainage water and municipal waste water. Such low quality supplies, which become more important when drought imbalances the current supplies, require an appropriate supply management and systems monitoring. Problems concern human health by direct or indirect exposure to contaminants, the pollution of surface and groundwaters through the irrigation return-flows, and the soil contamination and degradation due to salts applied with the irrigation water. Despite knowledge on impacts from using low quality water in irrigation is increasing, these impacts are not yet fully known, particularly on the long term. This justifies the implementation of appropriate monitoring systems and information networks in order to avoid that immediate solutions for water scarcity would favour land degradation and desertification.

Design and management of irrigation systems for operation under water scarcity conditions is another area of concern. However, it should be advisable to look carefully for the agricultural, farm production system and understand when it would be advantage to improve water application at farm level and, therefore, if targets for improving the institutional and operative conditions of the conveyance and distribution could include a better satisfaction of the on-farm demand. The need for innovative approaches in combining system and on-farm irrigation design and management is therefore evidenced.

This question also brings other aspects relative to supply management currently dealt, mainly the adoption of models to simulate and help decisions on water delivery, the use of improved structures for water control and regulation in conveyance and distribution systems, the utilization of improved hydraulic structures for turnouts and outlets, the strengthening of institutions and farmers participation for irrigation projects management, and the training of managers, field personnel and farmers. These aspects shall not be forgiven when supply management for drought situations is considered.

Enhancing reservoir and conveyance capacities

As pointed out in the definition above, a drought is characterized by diminished water resources and carrying capacity of the ecosystems. To a certain extend, the same applies to the other categories of xeric regime. The increase of available water resources through increased reservoir and conveyance capacities becomes one evident measure against drought impacts. However, these measures may often be very costly, both in economic and environmental terms. Among these measures are:

- Increased storage capacities, including large reservoirs with capacities for inter-annual regulation of water discharges, and small reservoirs, namely for supplemental irrigation and for enhancing the flexibility of irrigation scheduling at the farm.
- Improved irrigation conveyance and distribution systems, including compensating reservoirs for increasing the availability of water resources, and intermediate reservoirs for improving the flexibility of deliveries, avoiding system water losses during periods of low demand, and providing for reducing the impacts of excess demand during peak periods. In case of pressurized systems, the adoption of modifications in the irrigation network, like the linkage of pressurized distributors for reinforcing their capacity to respond to an increased demand, as well as the construction of small regulation reservoirs supplying selected distributors, are often appropriate solutions.
- The rehabilitation of irrigation systems is also as a main condition for effective implementation of drought operation and management rules, while good maintenance is another essential factor.
- The development of new sources of water supply to reinforce the systems supply is among measures relative to planning for droughts. These include: the construction and equipment of wells for conjunctive use of surface and groundwaters when regular supplies became scarce, the conjunctive use of fresh and wastewater, as well as the reuse of agricultural drainage water.

Supply management for droughts

This comprises the techniques, models and institutional measures that improve conditions for irrigation water supply when drought occurs, without modification of the carrying capacity of the systems. These measures, in general, are not drought specific and are often implemented when competition for water requires improved management conditions. They are of several nature and include:

- The development of hydrometeorological networks, data bases and information systems concerning the state variables required for real time operation of irrigation systems. These networks include ground and satellite based weather and hydrologic databases/GIS, which produce the information required to forecast water supply and demand in real time. Therefore, operation and management of the water infrastructures provide for the delivery schedules required during droughts. In combination with these data collection and processing networks, also agrometeorological irrigation information systems are required. These systems, often GIS, make full use of irrigation scheduling simulation models, providing information to managers and farmers, and supporting local or regional irrigation management programs, with evident benefices for drought irrigation management.
- Real time reservoir operation and management tools: these correspond to mechanistic and/or stochastic models, which use historical and real time hydrologic and weather data to forecast reservoir volumes and inflows as well as demand hydrographs, so to permit the real

time and remote control management of a reservoir. Releases may be optimized using linear or dynamic programming models and other decision support tools.

• Scenarios may be progressively updated and information provided to the users. The management of supplies should be combined with optimized demand control.

• Decision support systems may have a larger scope, serving not only to the reservoir operation and water system management, but to help users, farmers in particular, to select water use options, including crop patterns, irrigation scheduling and irrigation systems, to produce the demand which better responds to water constraints and economic and environmental factors.

• The appropriate regulation of irrigation reservoirs and conveyance and distribution systems require some kind of automation, either adopting local or remote control to provide for the required flexibility of deliveries. The latter is particularly important under drought conditions to take into consideration the time and spatial variability of the demand, so providing deliveries to match the demands with reduced system losses.

• Planning for droughts is an essential preparedness measure not only to establish allocation and delivery policies, but to enforce special operation and management rules during droughts. It should be also emphasized the importance of legislation for making the emergency measures operational in time.

Supply management during drought

Operation, maintenance and management (OM&M) of irrigation systems during drought is focused on improvement of supply conditions with limited available water. Two main issues are possible: to improve management of existing water supplies and to increase water supply sources.

The improved management of existing water supplies during drought includes:

• The revision of water allocation priorities, namely to give priority for domestic uses and for perennial crops, mainly orchards.

• The modification of delivery schedules, namely to enforce a rotation system or to change from on-demand into rotation of distribution sectors in irrigation pressurized systems. However, results may be contradictory, as analysed by Lamaddalena *et al.* (1995).

• The reduction of irrigation volumes, limiting the volumes allocated to each farm. This can be achieved by increasing the water prices for farmers using water above fixed volumes, imposing special delivery schedules, and enforcing penalties and incentives to farmers.

• Restricting the areas to be irrigated, namely using a planning methodology to help farmers to define the best crop pattern for the allowed acreage, cutting deliveries to land out of an approved irrigation plan.

• Changing crop patterns, decreasing the acreages for high water demanding crops, or leading the farmers to choose drought tolerant and drought resistant crops or selecting crops which use the land out of the peak irrigation season.

• Enforcing penalties for farmers wasting water and/or using water in crop land not approved to be irrigated.

• Finally, to enhance the maintenance of the water conveyance and distribution systems in order to ensure that operation and management can be performed at the best level of service.

The augmentation of water supply sources during drought include, as stated before, the conjunctive use of surface and groundwaters, the use of water pumped from reservoir dead storage, the reuse of irrigation return flows and agricultural drainage water and the conjunctive use of fresh water and brackish and wastewater.

To involve farmers in enforcing the supply management rules for drought, information, training, and framers participation are required. These include:

• the training of framers to choose the most adequate crop patterns and irrigation scheduling to withstand limited water supplies;

• the information of farmers on characteristics and limitations of the water supply systems;

• the assistance to farmers by the OM&M organization as a main tool to implement water conservation/water savings programs;

• the farmers participation in decisions relative to drought supply management, including the allocation of stored water volumes and the constraints for crop patterns.

The evaluation of plans, regulations and rules for supply management under drought should be a main preoccupation of supply managers, not only to update plans and decisions during drought, but also to help improving emergency plans to be applied in the future.

Emergency planning

These are preparedness plans referring to the emergency measures to be enforced when a drought occurs. Measures include grants to public agencies, and loans to water users associations aiming at to augment water supplies (construction and rehabilitation of wells, pipelines, pumping stations), to improve operation of water systems, to conduct studies for exploring new water supply sources and to assist users purchasing water rights (water banks). Credit lines for farmers are also among those measures, which should aim at help farmers to adopt water conservation practices.

These measures require the strong involvement of governmental agencies and users organizations. However, often they are only partially effective when decisions for emergency measures are taken too much late, or the institutional arrangements for utilization of loans and credits are not prepared and ready in time, or deadlines

for using funds are not realistic. Early warning of droughts is essential to make decisions in time.
Drought master plans or drought contingency plans are the emergency plans to be applied by system managers. These include the operation management and maintenance rules to be enforced under drought, as enounced before (Brown and Schild, 1990).

Demand management

When water is scarce several objectives may be enforced in on-farm water management: to maintain farmers incomes, to maximize the fraction of diverted water that is consumed in crop evapotranspiration, to minimize the irrigation system losses, or to minimize the fraction of diverted water that is not reusable (and, in many circonstances, that would be added to a saline watertable).
To maintain farmer incomes may be achieved targeting yields at the most economic return for the actual drought conditions. This depends on the structure of the production costs, including water prices and water application costs, in relation to product prices. This may be achieved by intensive cropping in a smaller area or by using the available water for reduced irrigation in a larger area.
When water is cheap there are not economic benefits or incentives for decreasing the fraction of water non consumed by the crops.
Thus, the objective of minimizing the non consumed fraction of diverted water, or minimizing the non reusable fraction, may be contradictory with the economic or yield objective of the farmers.
To enforce demand management policies may have several facets according to local conditions. When water scarcity results from a permanent water imbalance, demand management has to focus on making sustainable the use of water, so in keeping the farmers producing in a long term. When water scarcity results from a temporary imbalance, as under drought, temporarily reduced farm returns are acceptable. Targets could be implemented based on the knowledge of the crop water requirements and water-yield functions, of both physical and economic nature.
Normally, when water is scarce the environmental and economic value of the water should be high. Irrigation strategies should be designed and implemented as such, in order that the farmers optimize incomes and yields, as well as the consumptive use fraction of water diverted.
This implies that irrigation water be applied with high uniformity, with timeliness and in the amount due to satisfy the target consumptive use by the crops. A combined approach to improve the performances of the on-farm irrigation systems and to apply appropriate irrigation scheduling practices is then required.
Developments in areas relative to evapotranspiration and crop water requirements, models for irrigation scheduling, models for design of on-farm systems, tools to optimize crop patterns, and decision support systems are increasingly available. However, bringing these developments into the farming practice is slow and difficult. This calls for innovative institutional solutions to support farmers extension and training. Field evaluation of on-farm systems could play a major role in directly supporting farmers to implement improvements, and providing information for designers and other professionals. In drought-prone areas, these aspects should be included among the preparedness measures as they provide for reducing the demand and cope with droughts.
These aspects are particularly relevant when it is intended to reduce the fraction of applied water percolating below the root zone or running off from the irrigated fields. These waters are often degraded by solids in solution which are responsible for the contamination of groundwaters and surface waters by fertilizers, namely nitrates, and agrochemicals. These percolating waters are also one of the causes for the rising of saline watertables and waterlogging.
Appropriate water application and irrigation scheduling practices also provide to control negative impacts of irrigation.
The application of desired leaching fractions also requires that appropriate irrigation techniques be applied. The environmental perspective has then to be included in solutions for demand management under water scarcity conditions.

Conclusion

Irrigation management for drought and water scarcity situations is a complex question requiring the adoption of locally appropriate solutions.
Management should be seen within two main perspectives, supply and demand management. For both, many developments are available, as well as examples of success and failure.
However, adopting of such developments in practice is worldwide almost non-existent. In general, improvements require appropriate evaluation of local conditions and of performances of off-farm and on-farm systems which should help to identify problems, solutions and implementation measures.
Assigning an appropriate environmental and economic value to the water could also favour improvements in irrigation management under drought. ●

References were not published for lack of space. People who are interested in the complete bibliography may address either to the Author or to the Publisher.

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