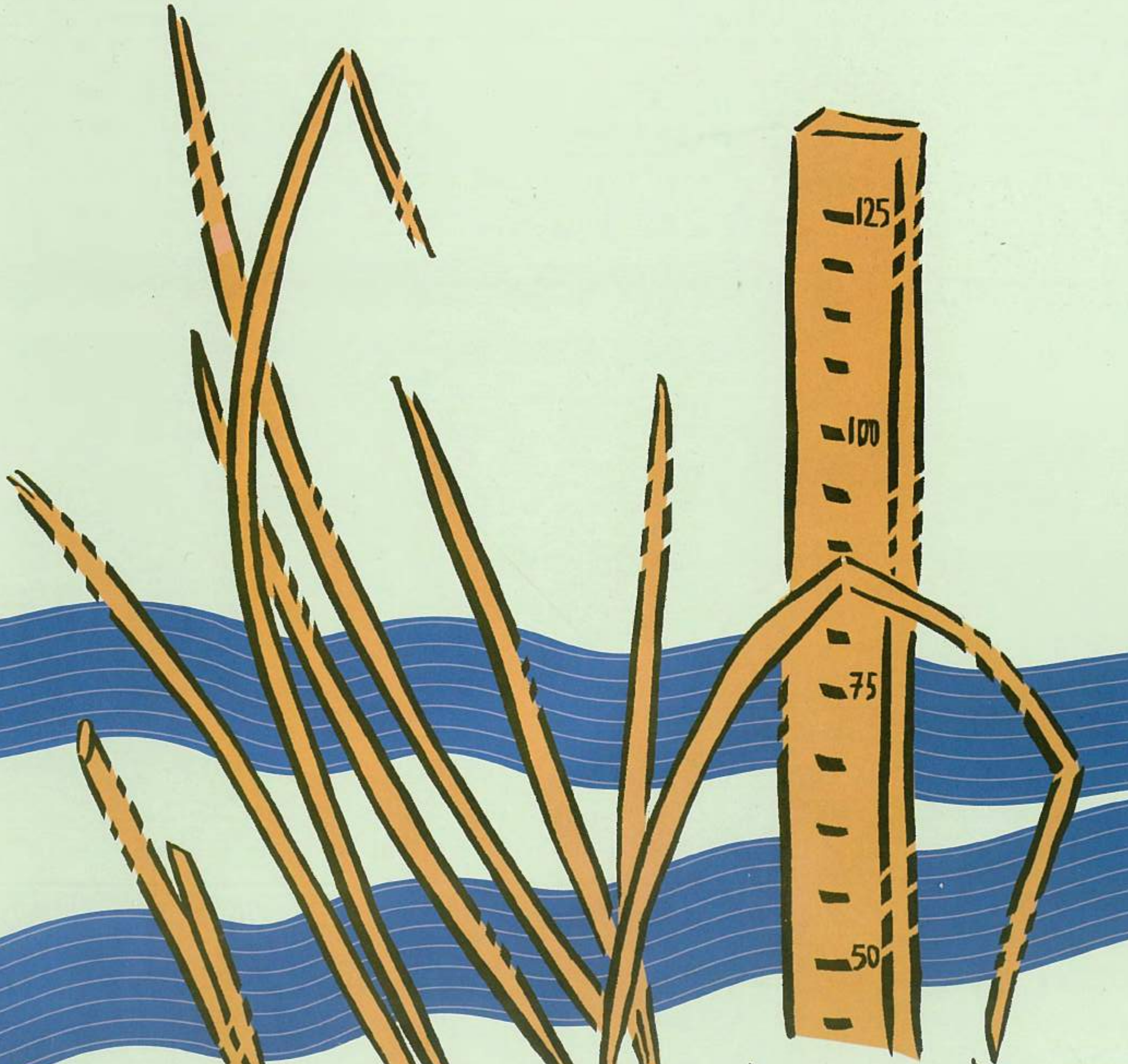
TOUR DU VALAT

MedWet

Conservation of Mediterranean Wetlands

Wetlands and hydrology

M. Acreman



MedWet

The MedWet initiative

The Mediterranean basin is rich in wetlands of great ecological, social and economic value. Yet these important natural assets have been considerably degraded or destroyed, mainly during the 20th century. MedWet is a concerted long-term collaborative action, launched in Grado, Italy in 1991, to stop and reverse this loss and to ensure the wise use of wetlands throughout the Mediterranean.

The MedWet initiative is guided by the Mediterranean Wetlands Committee (MedCom), under the umbrella of the Ramsar Convention on Wetlands, which brings together 25 governments from the region, the European Commission, the Barcelona and Bern Conventions and international NGOs. It seeks partners and funds for implementing the Mediterranean Wetland Strategy, which includes conservation actions in wetlands of major importance in the region (especially Ramsar sites) and the promotion of national wetland policies, which take account of wetland values during the planning process. MedWet also provides a forum for regional exchange of experience at a technical level and publishes a range of wetland management tools with financial support from the European Union.

The concept of MedWet and its importance for promoting wise use of Mediterranean wetlands has been unanimously endorsed by the Contracting Parties to the Ramsar Convention on Wetlands.

The MedWet publication series

Wetlands are complex ecosystems, which increasingly require to be managed in order to maintain their wide range of functions and values. The central aim of the MedWet publication series is to improve the understanding of Mediterranean wetlands and the policy issues that surround them, and to make sound scientific and technical information available to those involved in their management.

Mike Acreman
Wetlands and Hydrology
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Titles of the collection:

1. Characteristics of Mediterranean Wetlands
2. Functions and Values of Mediterranean Wetlands
3. Aquaculture in Lagoon and Marine Environments
4. Management of nest sites for Colonial Waterbirds
5. Wetlands and Water resources
6. Aquatic emergent Vegetation, Ecology and Management
7. Conservation of Freshwater Fish
8. Vegetation of temporary Marshes, Ecology and Management
9. Salinas and Nature Conservation
10. Wetlands and Hydrology

Introduction

Water is essential to all life, but either too much or too little can have serious consequences for humans.

Water is essential to all life, but either too much or too little can have serious consequences for humans. Indeed, floods* and droughts kill many millions of people each year. Floods also damage property and cut communication lines, whilst shortage of water reduces crop yields and creates supply restrictions for agriculture, industry and households. Consequently, mankind has sought to control the hydrological cycle, to even-out the natural variations in water availability, in time (by storing water during wet periods for use during dry periods) and space (transferring water from areas of surplus to areas of deficit), thus reducing flood risk and supply shortages. Engineers have played a crucial role in water management, defining solutions to benefit mankind.

Kakado National Park, Australia.

* *Refer to glossary, page 101.*

As early as 6000 BC, the Egyptians manipulated water to irrigate crops and built the Sadd el-Kafar ("dam of the Pagans") around 2800 BC. Dams can store water during the wet season and release it during the dry season or when needed for irrigation or hydro-power generation. The Romans are noted for the huge aqueducts that they constructed (between 50 BC and 100 AD) to distribute water, such as the Pont du Gard, that supplied Nîmes (in southern France). These projects, including the Alicante dam (41 metres high), built in 1594, were considered as a miracle of modern engineering, reducing floods, improving agriculture and securing water supplies. More recent mega-hydrological projects include the pumping of water from wells 450 metres deep in the remote southern Libyan desert and piping it 1000 km to the coast to grow crops.

During the 18th century, the River Guadalquivir in Southwest Spain was straightened, reducing its length by 50 km (7.4%) to reduce flood risk. In the 19th century widespread floodplain* reclamation began to improve agriculture, involving the construction of embankments along major rivers, such as the Rhône, to prevent flooding. Intensification of agriculture and industrial and urban development continued during the 20th century as the population increased and engineering techniques improved, culminating in the 1950s and 1960s with the construction of major dams. This led to the belief that man could control the environment totally.

Through the past few decades, there has been an increasing realisation that the "hard" engineering approach to water management has had its costs as well as its benefits. Installation of powerful pumps, whilst

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Dams have been an important part of human development for thousands of years.

Rivers have been channelised and embankments constructed to protect riparian land from flooding.

producing short-term economic benefits, has led to over-exploitation of groundwater in many parts of the Mediterranean, such as in the La Mancha region of Spain[1]. In the search for ever-greater control over the environment, many of the natural control mechanisms have been inadvertently destroyed. For instance, the draining of farmland, the straightening of river channels and their separation from their floodplains by embankments has increased flood risk downstream. For example, serious flooding of cities in Germany and the Netherlands along the River Rhine during 1994 were made worse by the presence of embankments upstream. These had separated the river from the floodplain wetland, protecting agricultural land, but preventing access by the river to natural floodwater storage. In response to these floods, during 1995 two large flood storage wetlands were created on the German bank of the Rhine as part of a programme to reduce flood damage downstream and restore degraded floodplains. This type of environmental engineering marks a significant change in approach. Instead of fighting against nature, to working with it.

Wetlands in particular have suffered during past water management schemes due to misunderstanding of their role in the hydrological cycle. They were considered just to evaporate vast quantities of valuable water and harbour diseases.

In it's 1970 report, the United Nations Food and Agriculture Organisation (FAO) recommended drainage of the "wastelands" of the Messara valley on the Greek island of Crete as part of water management for agricultural improvement.

1 - Acreman (2000)

In contrast, however, recent studies have highlighted some important functions that wetlands can play ; removing pollutants, reducing floods, recharging groundwater and regulating the flow of water[1], thus performing for free the processes which engineers have spent large sums of money creating technologically. Indeed, because of these significant hydrological functions, wetlands are now described as "the kidneys of the landscape"[2]. In addition, wetlands provide numerous valuable products, such as fish and reeds for thatching, plus habitats for wildlife, which may provide the basis for tourism. Furthermore, the traditional way of life on many wetlands is part of the cultural heritage of local communities. Because of these functions, products and attributes, wetland conservation is becoming an integral part of integrated water management. The water allocation required to maintain wetlands is often more than repaid by the products and services they provide.

The purpose of this booklet is to explore the relationship between wetlands and the hydrological cycle. It gives details of the hydrological components of wetlands, the extent to which different wetlands can regulate floods, sustain flows during dry periods and recharge groundwater. It indicates how these ecosystem functions can be interrupted or eliminated by human interference in the hydrology of wetlands. It concludes that sustainable water management is best achieved through judicious utilisation of the natural functions of wetlands in conjunction with new technologies for controlling the hydrological cycle.

Reedbeds, like these, in Canada, are now used to threat sewage.

1 - Skinner & Zalewski (1995)
2 - Mitch & Gosselink (1993)

Introduction

Nobody wants to wipe away centuries of human achievement in flood prevention and water management, yet there is a growing recognition that there may be more benefits to be had through judicious use of natural functions of ecosystems that are useful to man whilst continuing to use the best and most appropriate technology for a high quality of life.

Hydrology and wetlands

Glaciers in the Alps,
an important source of water.

The endless water cycle

Water is the lifeblood of our planet. It is fundamental to the biochemistry of all living organisms.

People need water to drink, wash, cook, grow crops, generate power and run industries. Water provides a permanent habitat for many organisms, including some 8,500 species of fish, and a breeding ground or temporary home for others, such as most of the world's 4,200 species of amphibians and reptiles. Water is also a universal solvent and is the major pathway for the flow of sediment, nutrients and pollutants.

Through erosion, transportation and deposition by rivers, glaciers and ice-sheets, water shapes the landscape and through evaporation* and condensation it drives the energy exchange between land and the atmosphere, thus controlling the Earth's climate.

The total amount of water on Earth is 1.4 billion km^3, but only around 41,000 km^3 circulates through the hydrological cycle, falling as rain or snow, infiltrating into the soil and rocks, flowing as rivers, through wetlands to the sea and evaporating. The remaining water is stored for long periods in the oceans, ice caps and aquifers*.

Furthermore, the renewal rate provided by rainfall varies around the world. In the Atacama desert, on the Chile-Peru border, it almost never rains, whilst 6,000 mm of rain per year is not uncommon in parts of New Zealand.

In any one place rainfall also varies from year to year. In the early 1980s the world witnessed tragic scenes of drought and starvation in the Sahel, but by August 1988 floods ravaged the same region.

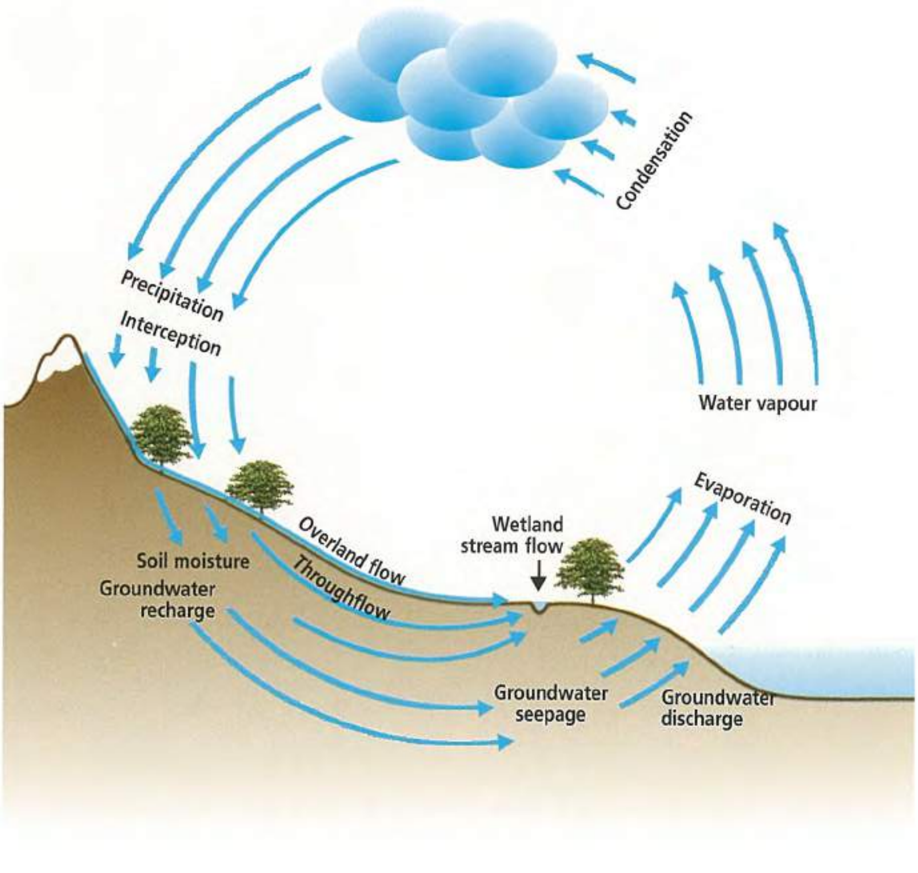
Water availability also varies over a longer time scale. Some 10,000-20,000 years ago, during glacial phases in high latitudes, rainfall over the current Sahara desert and Middle East was much higher and percolation of water to underlying rocks led to the build up of substantial groundwater resources[1]. However, the recent drier climate in these regions means that recharge is much reduced and groundwater exploited is not being replaced at the same rate, if at all.

Superimposed upon natural climate cycles are man-induced global changes. The consensus is that during the next century global temperatures will rise by about 0.2°C per decade[2], with some areas exceeding this rate and some areas cooling. Changes in climate will affect the hydrological cycle in various ways. Evaporation is likely to

1 - Goudie (1977)
2 - Houghton et al (1996)

rise and rainfall may become less reliable, thus it is feared that many areas will become drier and that floods and droughts may become more frequent and more extreme.

All these factors are important in assessing the storage, diversion and use of available water and provide the backdrop to important planning decisions that may have implications for the next 100 years or more.



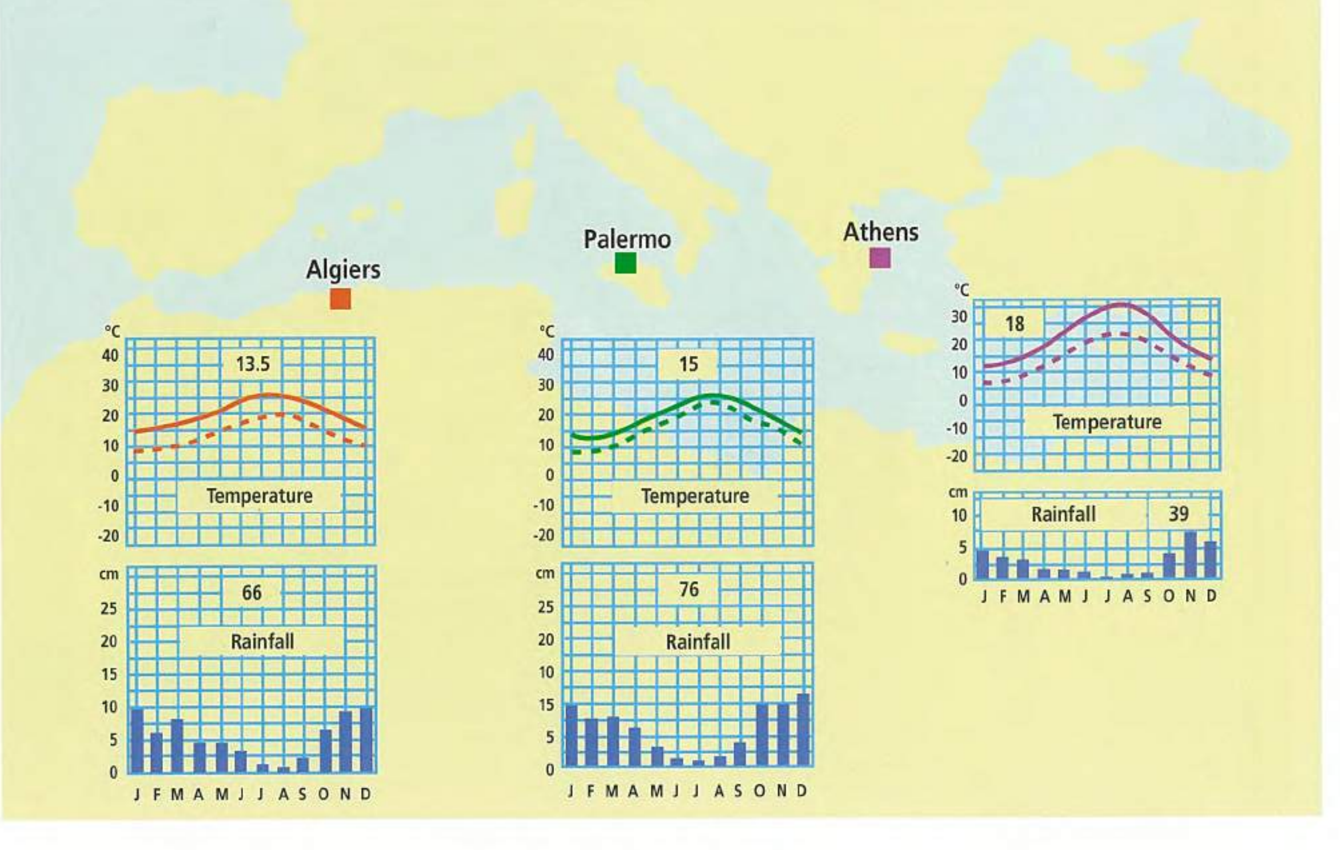
The hydrological cycle.

Managing an unpredictable resource

The climate of the Mediterranean is characterised by hot dry summers and mild wet winters.

The coasts of Algeria and Libya normally have seven dry months, receive only around 200 mm of rain in an average year and have typical July temperatures of 30°C. Partly due to wind direction and the location of mountain chains, a prominent feature of the region is the difference between west and east coasts. Durres, on the coast of Albania receives around 1,100 mm per year, whilst Bari in Italy (on the opposite side of the Adriatic Sea) has only 560 mm. Likewise, the east coasts of Greece have about half as much rain as the west. Another important characteristic is the inter-annual variability in rainfall and the sporadic occurrence of extreme events. For example, Spain experienced five years of drought in the early 1990s, whereas in 1997 and 1998 it received above average rainfall. This needs to be taken into account when designing river engineering projects such as dams, and bridges, since average figures mask this high variability.

Temperature and rainfall variations across the Mediterranean.



When rain does fall, it tends to arrive as heavy storms. Rainfall of over 125 mm in a day, often with thunder, is common in the Mediterranean and records for individual sites include even more severe storms, such as Tripoli (130 mm), Haifa (183 mm) and Malta (295 mm). Thus some areas may receive their total annual rainfall in just a few days.

Water demand in the Mediterranean rises sharply in the summer, when crops require irrigation and tourists arrive, particularly along the coast. Large numbers of dams have been built throughout the region to store winter rain for summer use: Spain alone has 847 large dams. These

Sediment movement

Heavy storms often trigger landslides and river-bank erosion, carrying sediment into reservoirs. In a study of sediment carried by rivers throughout the world[1], much of the Mediterranean (specifically the northwest of Africa, Italy, the Balkans, including Greece and Turkey) has been classified in the highest category, with more than 500 tons km^2 yr^{-1}.

The proportion of eroded material that reaches a river is called the sediment delivery ratio*. On large catchments much eroded material remains on the slopes, whereas in small catchments it tends to find its way to the river.

This relationship between the sediment delivery ratio and catchment size is demonstrated by data for Tunisia. Perhaps more significantly, these data show the expected life of a dam in Tunisia is less than 100 years.

In an extreme case in 1997, a recently completed small reservoir in Tunisia became completely filled with sediment within 10 minutes following a severe storm. It had been designed using average figures for the rates of sediment transport in the area, not taking account of extreme events.

Sediment in reservoirs in Tunisia[2].

Reservoir	Catchment area (km^2)	Erosion ($t\text{-}km^2\text{-}year^1$)	Sediment concentration in river (kg/m^{-3})	Reservoir volume (million m^3)	% filled each year	Year of operation
Mellégue	10.300	695	38	268	0.8	21.3
Nebaana	855	2300	47.5	86.4	1.5	10
Lakhmess	131	5070	86	8.0	2.69	9.3
Kasseb	101	2865	53	81.9	0.5	7.5
Bézirk	84	2430	45.6	6.5	1.76	14.8
Chiba	64	4220	72.5	7.9	2.81	12
Masri	40	6050	85	6.8	2.58	7.5

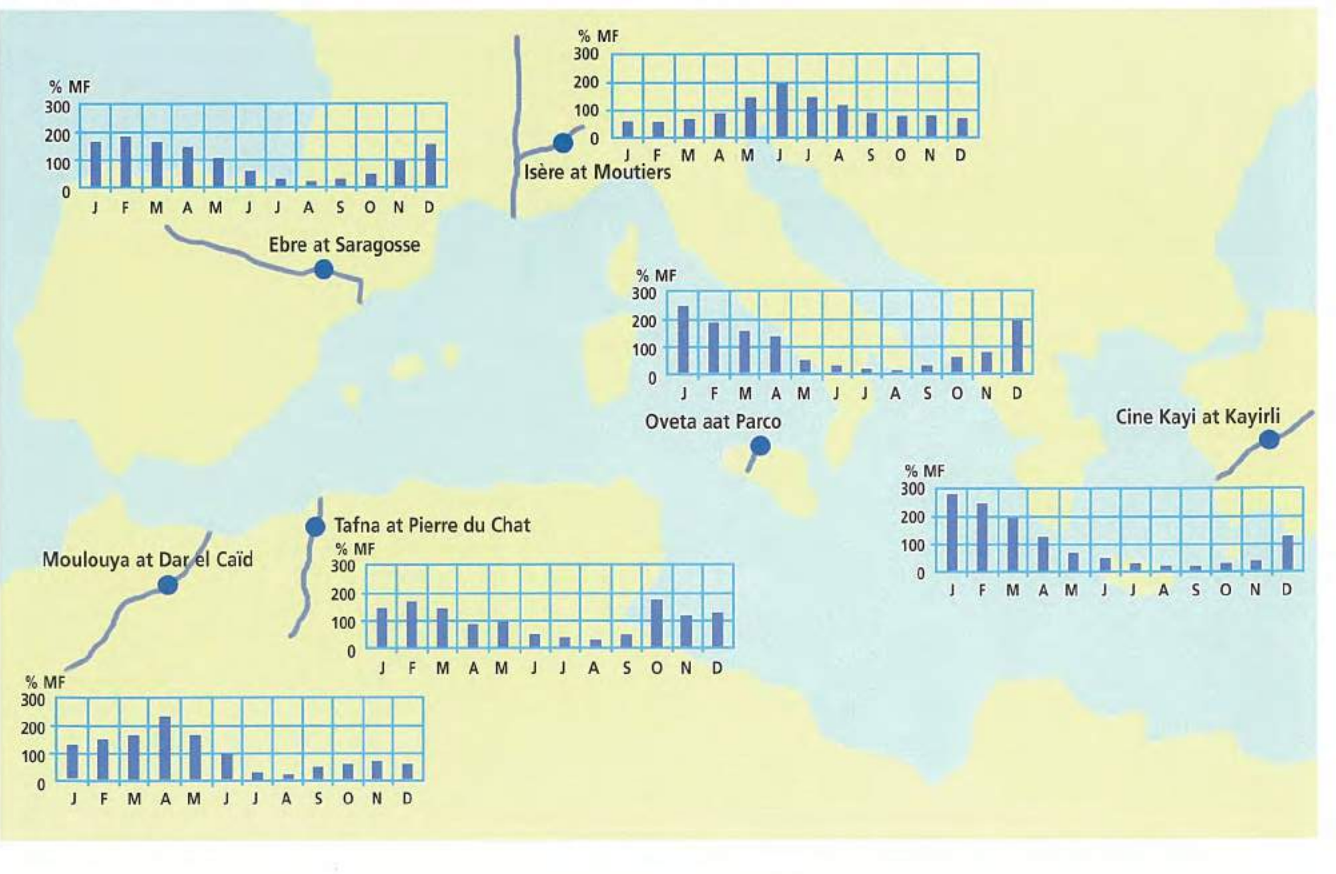
1 - Walling & Webb (1987)
2 - After Ghorbel (1980)

Varying flow regimes in the Mediterranean.
Maximum river flows occur in winter and minimum flows (which often means a dry river bed) occur in late summer. This is demonstrated in the flow records from Spain, Turkey and Italy. It is noteworthy that flows on the Tafna at Pierre du Chat in Algeria are less consistent due to high inter-annual variability. High mountain ranges in the region, including the Atlas (Morocco), Sierra Nevada (Spain) and the Alps (Italy, France) receive significant snowfalls which augment river flows during the Spring melt. This can clearly been seen on the graph of flows recorded on the Isère at Moutiers (France) fed by snow-melt from the Alps and to a lesser extend by records from the Moulouya at Dar el Caid (Morocco) where flows in April-June are derived from snow-melt from the Atlas mountains. Because of high evaporative loss and percolation to groundwater, surface runoff is only some 20-40% of rainfall[1].

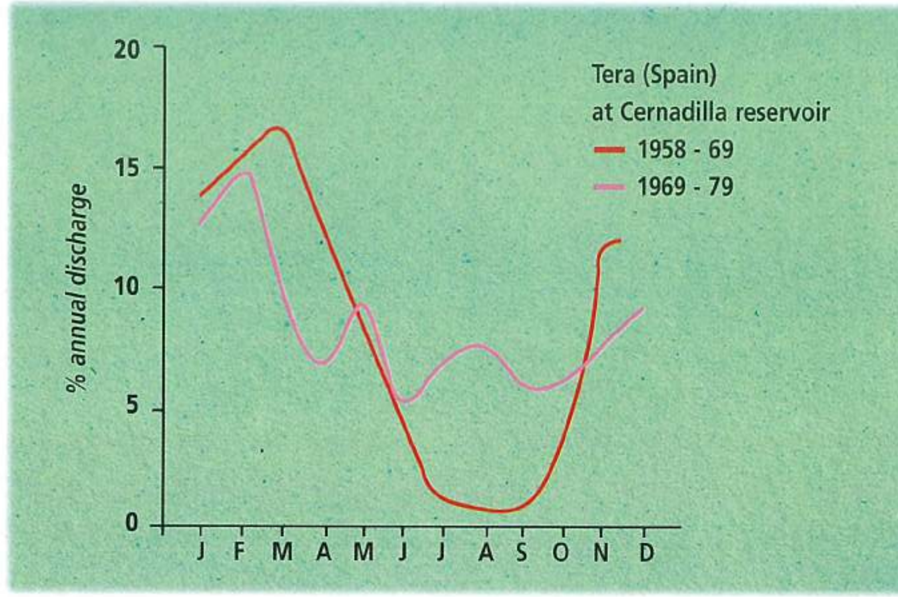
dams can have a significant impact on the hydrological regime of rivers downstream.

Other river engineering schemes involve the transfer of water to the driest regions from areas of relative surplus, such as the diversion of water from the Acheloos river in Greece to irrigate the Plain of Thessaly. However, there has been growing awareness of the negative ecological impacts of this scheme on the Messolongi wetlands at the mouth of the river. Similar large water transfers have been proposed in other areas, such as in Spain, where water flowing north and west into the Atlantic would be pumped into the headwaters of the River Ebro for subsequent re-abstraction downstream in the Mediterranean basin.

Much of the Mediterranean area is underlain by highly permeable rocks, such as limestone, and aquifers provide important water resources. In Greece, groundwater provides 29% of water resources, compared to 23% in Italy[2], most of which is used for irrigated agriculture. However, agricultural intensification (often sponsored in Europe by subsidies from the European Union) has led to over-pumping of aquifers leading to a decline in groundwater levels of up to 50 metres during the past 10-20 year in many aquifers throughout the Mediterranean. In Spain, 51 aquifer units have pumping rates

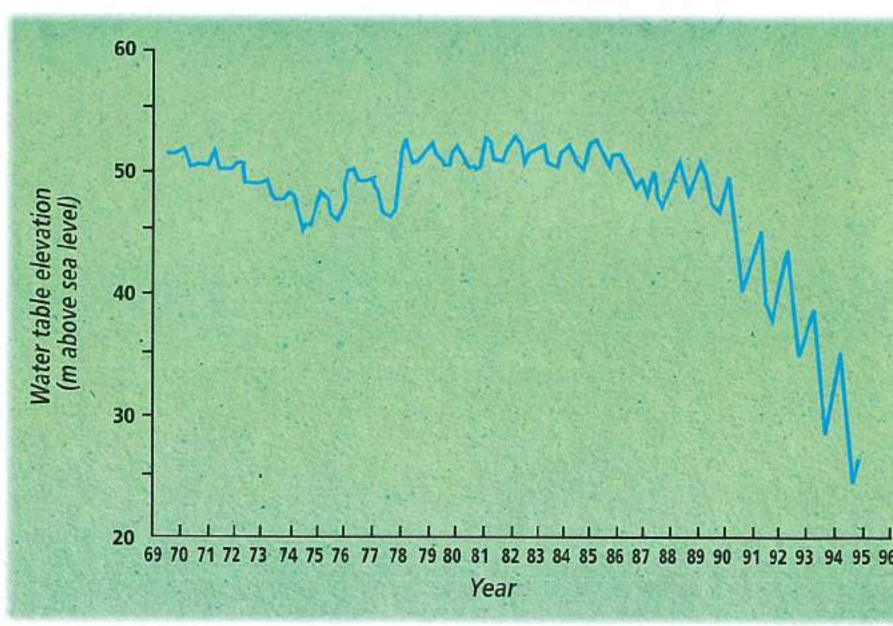


1 - Friend-Amby (1997)
2 - EEA/UNEP (1997)



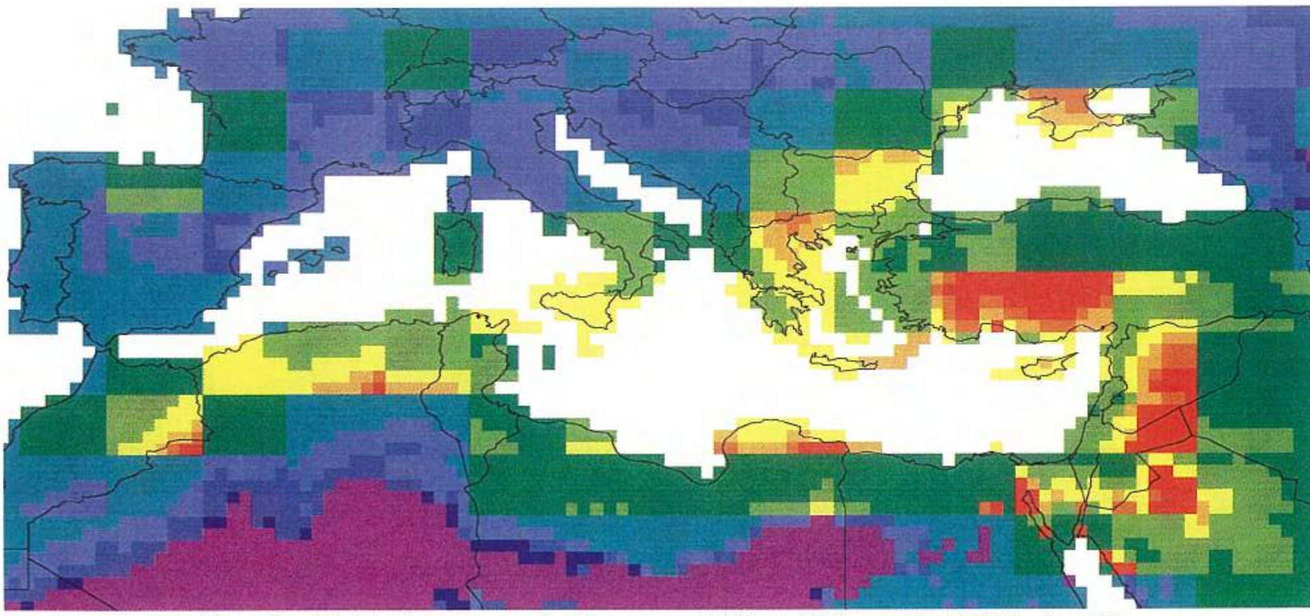
Impact of Cernadilla Reservoir on the flow regime of the Tera River, Spain. The solid line shows the typical Mediterranean river of the Tera River. The natural regime follows a pattern of high flows in the Spring following winter rainfall and low flows* in the summer when rainfall is low and evaporation high. The pink line shows the impact of the reservoir, smoothing out these seasonal variations in flow[1].

greater than recharge rates and 15 have been declared over-exploited. In Libya, where groundwater has already been over-exploited, causing salt-water to invade the aquifers, the Great Man-Made River Project was devised to transfer water from aquifers in Libya's remote southern desert to the Mediterranean coast.



Decline in groundwater level in a borehole in the Messara valley, Greece. This is typical of the fall in level in heavily exploited aquifers throughout the Mediterranean[2].

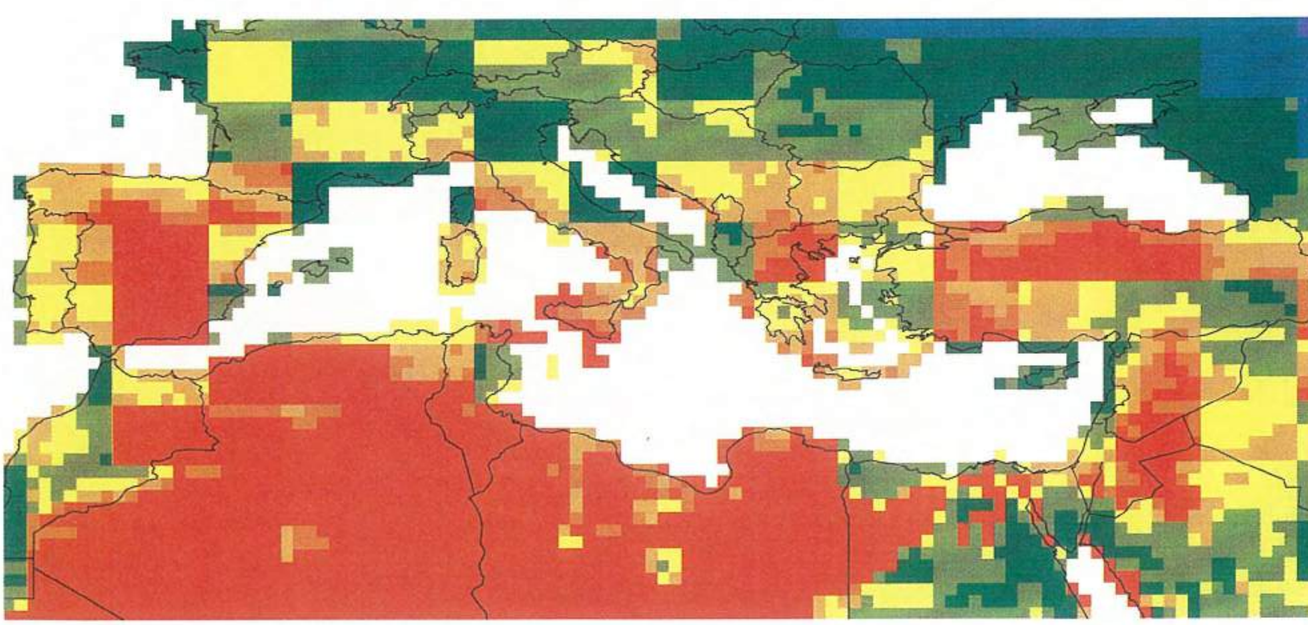
1 - Estrela et al (1996)
2 - Acreman et al (2000)



Change in rainfall for the wet season (october to march) (%) - HadCM2 scenario - GHGX for the 2050s

< -25 | - 25 to -20 | -20 to -15 | -15 to -10 | -10 to -5 | -5 to 0 | 0 to 5 | 5 to 10 | 10 to 15 | 15 to 20 | 20 to 25 | > 25

Climate change scenarios* for 2050 for the Mediterranean.
The baseline climatology 1961-1990 was provided
by the Climate Research Unity, University of East Anglia, UK[1].



Change in rainfall for the dry season (april to september) (%) - HadCM2 scenario - GHGX for the 2050s

< -25 | - 25 to -20 | -20 to -15 | -15 to -10 | -10 to -5 | -5 to 0 | 0 to 5 | 5 to 10 | 10 to 15 | 15 to 20 | 20 to 25 | > 25

1 - New et al (1999)

Climate change : an uncertain future

In the future, the hydrology of the Mediterranean may become even more variable as man exerts a greater influence on the environment, changing the climate through burning of fossil fuels.

Scenarios run for the year 2050 for the Mediterranean, using the UK Hadley Centre's global climate model, suggest that winter rainfall (October-March) could increase in central and eastern Spain, southern France, northern Italy and the Alps by up to 15%.

This could be beneficial if it falls as low intensity rain that increases groundwater recharge*. However, climate change may increase the frequency of storm events and more violent thunderstorms could lead to increased risk of floods and landslides.

In contrast, in other parts of the Mediterranean, winter rainfall is expected to fall, with the decrease exceeding 10% in Sicily, the Greek islands, southern Turkey and northern Libya.

Throughout the summer (April-September), rainfall is likely to decrease over much of the Mediterranean, particularly in Spain, northern Turkey and north Africa, where the decrease may exceed 25%.

However, it should be noted that summer rainfall in these areas is currently low, so a large percentage reduction does not equate to a large decrease in millimetres of rain. It is estimated that the 1.5-2.0°C rise in temperature and 10% reduction in rainfall, that could occur by 2050 (suggested by IPCC, the Intergovernmental Panel on Climate Change), could lead to a 40 to 70% reduction in renewable water resources[1]

Successful management of the hydrological cycle will thus require new strategies, including use of natural ecosystem processes, such as the water regulation functions performed by wetlands.

1 - Estrela et al (1996)

Hydrology and ecosystems

The Bruntland Report, "Our Common Future"[1], "Caring for the Earth"[2] and Agenda 21 from the UNCED Conference in Rio in 1992 marked a turning point in our thinking about water and ecosystems.

A central principle that emerged was that the lives of people and the environment are profoundly inter-linked and that ecological processes keep the planet fit for life providing our food, air to breathe, medicines and much of what we call "quality of life". The sustainable development of water was the focus of the International Conference on Water and the Environment (ICWE) which took place in Dublin in 1991 (a preparatory meeting for UNCED). Participants concluded that "since water sustains all life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems"[3]. For example, upstream ecosystems need to be conserved if their vital role in regulating the hydrological cycle is to be maintained. Well-managed headwater grasslands and forests reduce runoff during wet periods, increase infiltration to the soil and aquifers and reduce soil erosion. Downstream ecosystems including coastal lagoons provide valuable resources, such as fish nurseries, floodplain forests or pasture, but these must be provided with freshwater and seen as a legitimate water user.

At the UNCED Conference itself, it was agreed that "in developing and using water resources priority has to be given to the satisfaction of basic needs and the safeguarding of ecosystems" (Agenda 21 chapter 18, 18.8). Thus whilst people need access to water directly to drink, irrigate crops or supply industry, providing water to the environment means using water indirectly for people[4]. This concept is so basic that it has permeated all aspects of water resource management, such as the new water law of South Africa, Principle 9 of the law states that: "the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems". This provides a sound example for other middle income countries since South Africa is a semi-arid country with water resource problems similar to those experienced in the Mediterranean.

Vegetation is particularly important in the hydrological cycle. A rain forest tree can release 11,000 m^3 of water into the atmosphere during its lifetime[5], but much of this is recycled and not lost from the forest.

1 - WCED (1987)
2 - IUCN/UNEP/WWF (1991)
3 - ICWE (1992)
4 - Acreman (1998)
5 - Gash et al (1996)

In the Amazon rainforest, 50% of rainfall is derived from local evaporation. After forest cover is removed an area can become hotter and drier because water is no longer cycled between plants and the atmosphere. This can lead to a positive feedback cycle of desertification*, with increasing loss of water resources in that area.

Results of simulations using a global circulation model, in which the Amazon tropical forest and savannah was replaced by pasture land, predicted a weakened hydrological cycle with less precipitation* and evaporation and an increase in surface temperate[1] due to changes in albedo* and roughness. Rainfall was reduced by 26% for the year as a whole[2]. Similarly, modelling the removal of natural vegetation in the

Concepts of the river system

Engineers and ecologists tend to look at rivers in different ways. Engineers see the practical, physical uses of rivers, such as evacuating floods, navigation and water supply. In contrast, ecologists consider a river as a living system, rather than simply as an inanimate resource waiting to be exploited.

Two concepts are particularly important to the ecological view.

First is the "river continuum concept*" that encompasses the linkages upstream and downstream from a river's source to the coastal zone, which may include delta or lagoon systems. This includes the gradual natural changes in river flows, water quality and species, that occur along the river's length. In general, nutrients and sediment are generated in the headwaters and are are recycled downstream to drive plant growth. One of the most obvious characteristics of the river continuum concept is the migration of fish from the sea to spawning grounds in the headwaters. River engineering projects, such as dams and barrages, break this continuum causing radical changes in flows, water quality and stopping the movement of species.

The second concept is one of "flood pulse concept*". This is based on the importance of lateral connectivity between rivers and their floodplains and sees the inundation of floodplains as the main driving force behind river life, not a problem that needs eradicating. Rivers provide the floodplain with nutrients and sediment, whilst the floodplain provides a breeding ground for river species and improves water quality through settlement of sediment and absorption of nutrients and pollutants.

By embracing some of the ecologists' views of a river, working with nature rather than against it, engineers can achieve more sustainable river management by integrating these natural "living" characteristics of rivers into development options.

1 - Lean & Warrilow (1989)
2 - Shukla et al (1990)

Sahelian region of Africa suggests that rainfall has been reduced by 22% during the period June-August and the rainy season has been delayed by two weeks[1]. Therefore these ecosystems function as water cycling systems between the earth and the atmosphere and in return for the water they use, they provide the service of regulating both global and local climate and maintaining local water resources.

Experience from South Africa has shown that clearing a catchment of exotic trees from Australia that evaporate more water than the native "fynbos" can increase total runoff by 6%. As a result, the ministry of water resources has adopted a widespread "Working for Water" programme with cost-effective benefits for water supply and for employment.

Land use change and climate in the Mediterranean

Within the European Commission funded EFEDA[2] project, detailed meteorological measurements were made in La Mancha region of central Spain.

The resulting data were input to atmospheric models. These models have subsequently been used to investigate the impact of changing the land surface vegetation on the climate of the region (in particular soil moisture and rainfall).

These simulations show that gross changes of the vegetation, i.e. changing forests to dryland agriculture across the Iberian Peninsula, does reduce the summer rainfall regime, both within the Iberian region and in adjacent areas. Additional simulations are currently taking place as part of the Climate and Land Degradation programme, with simulations based on historical vegetation changes.

1 - Xue & Shukla (1993)
2 - Bromley et al (1996)

Hydrological management and wetland degradation

The movement of water through wetlands can be a very important part of the hydrological cycle.

Wetlands can store large quantities of water, thus acting as natural regulators, reducing flood runoff and providing a water source during the dry season. Wetland plants collect sediment, remove many pollutants and recycle nutrients, thus water leaving a wetland is often of better quality than the incoming water.

The natural process of accumulating sediment and vegetation means that many wetlands become gradually drier and eventually turn into terrestrial ecosystems. Direct and indirect hydrological management has considerably altered the rate of change of wetlands. To some degree, new artificial wetlands have been created by building reservoirs, canals, flood storage areas and reedbeds to treat sewage effluent or mine-water. However, the loss of wetlands has far outstripped the gains.

The view that wetlands are wastelands, resulting from ignorance or misunderstanding of the valuable role in the hydrological cycle, has led to their conversion to intensive agricultural, industrial or residential uses. Individual desires of farmers or developers have been supported by government policy and subsidies.

In addition to direct action on the land, river engineering schemes have diverted water away from wetlands as it has been believed that this water is wasted in the wetland or at least has a lower value than its use for agriculture upstream. Some organisations still look upon wetlands only in terms of their potential to provide farm land to feed an ever expanding population, which normally requires alteration of the natural system. Wetlands may also be lost by pollution, waste disposal, mining and groundwater abstraction.

Wetland loss in Mediterranean Europe[1].

Countries	Period	% loss of wetlands
France	1900 -1993	67
Spain	1948-1990	60
Italy	1938-1984	66
Greece	1920-1991	62

1 - CEC (1995)

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The water balance of wetlands

Measuring water level in Diawling National Park wetland, Mauritania.

Balancing inputs and outputs

The amount of water on Earth is more or less fixed. Some water is converted in bio-chemical processes, such as respiration and photosynthesis, though these tend to balance each other out.

The majority of water is neither created nor destroyed, it only moves from place to place and changes in form (ice, liquid or water vapour) and quality (eg. salinity, pollutant load). This conservation of mass is a fundamental principle in hydrology. The cycling of water between the oceans, the atmosphere and the various stores and flows of water on the land, including wetlands, is a continuous process of loss and renewal – called the hydrological cycle. Water falls as rain or snow, infiltrates into the soil and rocks, flows as rivers to the sea and evaporates back to the atmosphere. This natural hydrological circulation is inextricably intertwined with the social, economic and political structures that organise societies' use of natural resources.

On a smaller scale the concept of conservation of water mass can be applied to wetlands, or any other ecosystem, in the form of a water balance* or water budget. The latter term comes from the similarity with financial accounting; the amount of money you have in the bank is equal to the inputs (the amount you pay in) minus the outputs (the amount you take out to pay bills).

River flow measurement station on River Logone, Cameroon.

The water balance of wetlands

In a similar manner, the quantity of water stored within a wetland is equal to the inputs (rainfall, inflow from rivers or springs) minus the outputs (stream outflow, recharge to the ground and evaporation).

The water balance of a wetland can be summarised by a simple equation as follows:

$$dV = P + Qi + Gi - Ei - Qo - Go \pm T \pm H$$

where:

dV is the change in volume of water within the wetland
P is precipitation (rainfall, snow, dew etc) directly on the wetland
Qi is river and other surface water inputs to the wetland
Gi is spring flow and other groundwater inputs to the wetland
Ei is evapotranspiration from the water surface, vegetation and soils of the wetland
Qo is surface outflow from the wetland
Go is groundwater recharge from the wetland
T is tidal movement which may be an input (+) to the wetland or an outputs (-) from the wetland
H is the human influence which may be an input (+) to the wetland (e.g. effluent discharge), or an output (-) from the wetland (e.g. abstraction for irrigation)

The measurement of the above components of the wetland water balance is described in Annex A.

Quantification of the water balance of a wetland provides information on its hydrological functions, including flood control and groundwater recharge. It indicates the potential water resource available within the wetland for human use and the habitat available to aquatic species. When the water balance is used as the basis of a hydrological model* the impacts of management, such as dam construction, can be predicted.

Automatic weather station provides data to determine rainfall and evaporation.

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Hydrological modelling

A model is a simplified representation of the key processes in a system.

Models of wetlands vary according to their purpose. Conceptual models attempt to find simple relationships between components of the hydrological cycle. The water balance equation provides the basis for a conceptual model of wetland hydrology. In contrast, deterministic models try to represent the actual physical, chemical and biological processes at work. These would include the physics of water movement through the soil or hydraulics of flowing water over a floodplain, defined by complex differential mathematical equations.

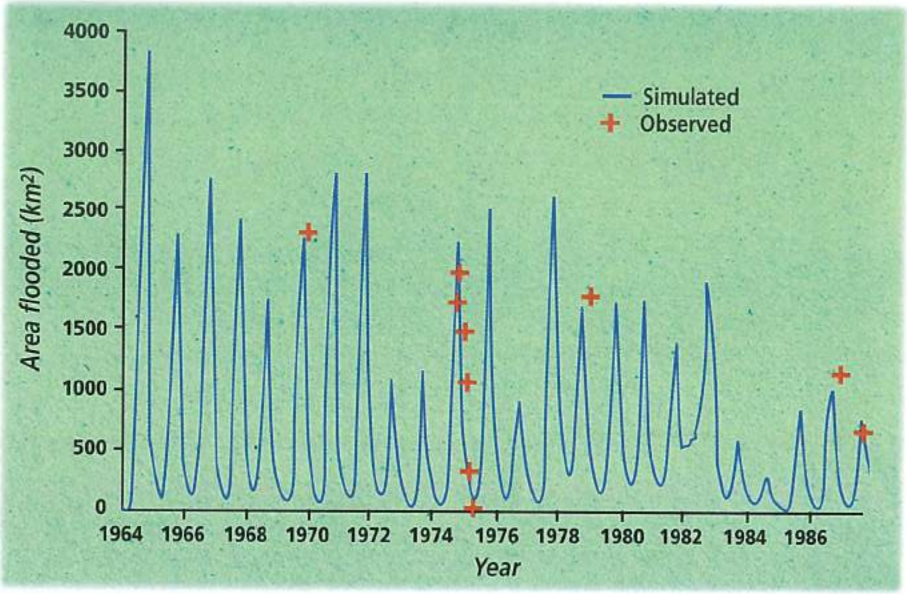
A computer spreadsheet was used to construct a conceptual model of the Hadejia-Nguru wetlands in Nigeria using measurements of the various components of the water balance[1]. The total outputs (evapotranspiration, groundwater recharge and river outflow) are generally higher than the inputs (river inflow and direct rainfall) because storage in the wetland has been depleted during the period. Evaporation is equal to around 64% of the river inflow. Recharge to groundwater is volumetrically less important than evapotranspiration, but more important in most years than river outflow. Overall river outflow is some 24% of river inflow.

Based on the same concept, a monthly model was also constructed. In this model, the storage of water within the wetland was converted into a prediction of the areal extent of flooding using field measurement of depth. To test the model's performance, these predictions were compared with recorded observations of flood extent made from satellite images and aerial surveys. The observed flooded areas were well predicted by the model.

The importance of a good model is that it can be used to estimate the hydrological response of the wetland, such as the extent of flooding in years when no measurements were made. In addition, models predict the response of the system to external or internal changes. Thus if rainfall or evapotranspiration rates alter due to climate change, or river inflows change due to abstraction upstream, the impacts on wetland hydrology and on outflows can be estimated.

1 - Hollis & Thompson (1993)

The water balance of wetlands



Areas of flood extent in the Hadejia-Nguru wetlands simulated by a hydrological model, compared with observed flood extent[1].

Floodplain inundation.

Part of the annual water balance of the Hadejia-Nguru wetlands[1].

Year	River inflow (million m³)	Rainfall (million m³)	Evapotranspiration (million m³)	Groundwater recharge (million m³)	River outflow (million m³)	Change in storage
1964	7,940	1,524	4,762	2,165	2,424	+ 113
1965	5,185	858	3,864	1,691	1,448	- 960
1966	6,603	759	4,165	1,842	1,664	- 309
1967	5,104	776	3,486	1,825	1,257	- 688
1968	4,710	542	2,990	1,544	1,323	- 605
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
1985	2,485	275	1,690	750	599	- 279
1986	2,657	153	1,477	614	1,290	- 571
1987	2,504	161	1,337	621	683	+ 24

1 - Hollis (1986)

Wetland management using hydrological models

There are various ways in which the hydrological cycle can be managed. Management may be intentional, such as the construction of dams to regulate river flows by storing water during the wet season and releasing it during the dry season or when required for hydropower generation. Management may also be unintentional. For example, global warming due to the build-up of greenhouse gases, such as carbon dioxide, alters the patterns of rainfall and evapotranspiration.

For wetlands, hydrological management may have positive or negative impacts. In some cases hydrological management may be required to meet certain wetland management objectives. For example, the creation of reed beds is a high priority in many western European countries, both to attract rare bird species, such as bittern, and to generate income through the sale of reeds for thatching. Maintenance of optimal water levels for the reeds and associated wildlife over the year is crucial. This may involve pumping water into or out of the wetland, or allowing water to flow between different compartments within the wetland. The quantity of water required is complicated by the conflicting needs to flood out terrestrial plant species such as willow, grasses and weeds, to secure relatively low water levels at the reed planting stage early in the growing season, and to raise water levels progressively as the reed shoots grow. Clearly, a detailed understanding of the water balance is required, including the evaporation rates of reeds during different stages of growth.

Hydrological management in the catchment feeding the wetland may have negative impacts on the wetland itself. For example, the water balance of the Ichkeul wetland in Tunisia has been impacted by the construction of six dams within the catchment and a sluice blocking interaction between the wetland and the sea[1]. Before 1984, the winter water balance inputs (surface inflows and rainfall) were dominant and water levels rose to flood the margins of the wetland. In the summer, rainfall is low and evaporation high, so the water surface fell to such a low level that sea water flowed in. The balance was thus dominated by evaporation and tidal flows. Diversions of water and abstraction for irrigation were predicted to reduce inflows by 180 million m^3. A further 70 million m^3 would be lost by evaporation from the dams' reservoirs. In addition, the input from the sea would be zero (also affecting the salinity).

1 - Hollis (1986)

The water balance of wetlands

From the water balance data, other hydrological factors can be determined. For example, the time taken for the entire volume to be changed can be calculated – this is called the turnover rate*. The residence time* is effectively the same thing, but is expressed as the length of time water stays within the wetland.

Turnover rate is a measure of the degree of flushing that takes place and will be important for many aspects, such as water quality, particularly at Ichkeul where the water becomes saline in the summer, but fresh in the winter. In Ichkeul, where the average volume of water is 90 million m^3, the natural turnover rate is 3-4 times per year resulting in rapid flushing of sediment, nutrients, salt and any pollutants. When all the dams are completed, the wetland will turnover once every five years. This will lead to accumulation of sediment and salt and possibly eutrophication* by trapping of nutrients.

The economic value of the fisheries and grazing of Ichkeul, sustained by the natural hydrological regime, far exceeds the benefits of using the water for intensive irrigation, for which the dams are being built[1]. The fisheries alone is valued at US$ 650,000 per year, whilst the sewage treatment function was valued at US$ 170,000.

Hydrological management of the catchment through dam construction is not always negative for wetlands. Several reservoirs in the UK, including Gladhouse Reservoir in Scotland and Rutland Water in England, are artificial wetlands created for public water supply but due to their important ecological character have been designated as Ramsar sites* and Special Protection Areas* (under EC Directive 79/409).

Water balance of Lake Ichkeul[2].

	Inputs (million m^3)		Outputs (million m^3)		Turnover time (outflow/volume)
Natural hydrological conditions in the Ichkeul wetland (up to 1984)	River inflow	300	Outflow	330	3.6 time per year
	Rainfall	50	Evaporation	80	
	Seawater inflow	60	Total	410	
	Total	410			
Predicted hydrological conditions in the Ichkeul wetland after construction of six dams (after 2000)	Residual river inflow to wetland*	50	Outflow	20	0.2 times per year
	Rainfall	50	Evaporation	80	
	Seawater inflow	0	Total	100	
	Total	100			

* residual river flow calculation
River flow : 250 Diversion and Irrigation : 180 Reservoir evaporation : 70

1 - Thomas & Hollis (1991)
2 - Hollis (1986)

Lake Kariba, in southern Africa, created by the construction of Kariba dam, supports an important inland fishery and the whole shoreline has been declared a "recreational park" as the availability of water during the dry season attracts large herds of buffalo, eland and other species. However, the dam has also had negative effects on the ecology downstream and on the health of local people as disease vectors, such as snails, have proliferated.

In most wetland management decisions, evapotranspiration is only considered as a negative function of wetlands and described simply as a "loss" in water resource assessments. However, transpiration is part of the natural process of plant growth, whether in crops or wild species. It has been suggested that much inland rainfall actually derives from locally evaporated water and not from moist air from the oceans[1]. This idea has been explored in the Sahel where it is postulated that evaporation from wetlands creates rainfall nearby[2].

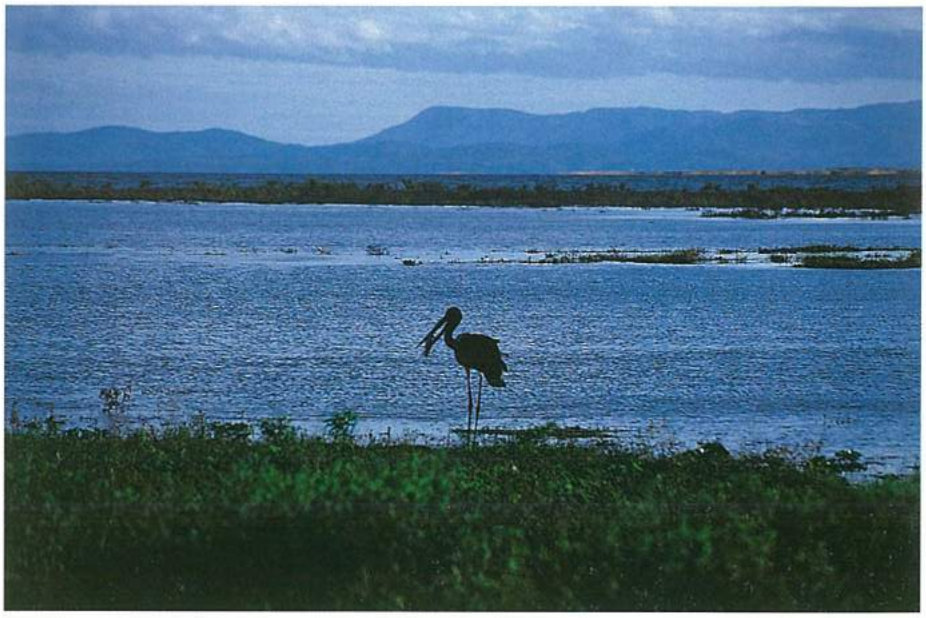
However, in some wetlands water is recycled internally which stabilises micro-climatic conditions. In the valleys of south-west Uganda, local concern for the effect of wetland loss on the local micro-climate was an important factor in the 1986 ban on wetland drainage. This has important implications for wetland management. For example, there is anecdotal information that evaporation from the Sudd wetlands in southern Sudan (around 16,000 million m^3 $year^{-1}$) supplies rainfall in the Ethiopian Highlands. If this is the case, construction of the Jonglei canal, which aimed at by-passing the wetlands and thus reducing evaporation by 4,700 million m^3 $year^{-1}$, would reduce rainfall in Ethiopia.

M. Bureau / Bios

Lake Kariba in Zimbabwe is a reservoir with high biodiversity that attracts thousands of tourists from around the world.

1 - Hare (1985)
2 - Savenije & Hall (1993)

The water balance of wetlands



Lake Kariba

M. Acreman

Wetlands and floods

Floods are truly the Jekyll and Hyde of environmental processes. Frequent newspaper headlines remind us that floods can be very destructive, taking many lives and causing extensive damage to property. Less widely appreciated is the important creative role that floods play in natural irrigation, shaping the landscape, maintaining biodiversity and fertilising floodplain soils.

Human activities in catchment areas, here in Nepal, are an important factor for floading downstream.

Most people consider only the negative aspects of floods. This is not surprising as floods in China alone in 1998 killed 3,000 people and

J. Roché

River Loire, France.

caused $20 billion worth of damage and affected one-fifth of the country's population. Calculations for the middle reaches of the River Loire in France suggest that the annual cost of flood damage is around 400 million Francs[1]. Considerable time and funds have consequently

What is a flood?

A flood is normally defined as "inundation of land that is normally dry". A typical example is when a river rises above the level of its banks and water flows over riparian land. A critical point is clearly when water inundates agricultural land, roads and railways or flows into houses or factories. However, a precise definition is more difficult for three reasons.

First, the term "normally dry" is rather ambiguous because some riparian areas may be inundated every year, some every few years and some very rarely.

Second, variations in the height of the river banks mean that a high river level causing overbank inundation at one point may be contained within the banks at another point.

Third, many river banks are gently sloping or contain a series of steps rather than a single unambiguous break between channel and floodplain.

Hydrologists take a different perspective and define a flood as any significant rise in river level, regardless of whether water remains in the channel or flows or bank. The flood hydrograph provides the basic tool of analysis.

1 - Torterotot (1998)

been invested worldwide in controlling floods so that riparian areas can be exploited for agriculture, industry or residential building.

Those responsible for flood protection have traditionally been engineers who are trained to seek structural solutions to flooding problems, for example by building dams and embankments, or straightening river channels. This approach has often created many problems. For example, the separation of the floodplain from the river by embankments, whilst providing local protection, eliminates natural flood storage, and may increase flood risk downstream. In addition, when the embankment is over-topped it prevents floodwater returning to the river prolonging and intensifying the flooding. These problems were highlighted during the Mississippi floods of 1993, after which the US government agreed to review the entire basis of its flood defence strategy. This has prompted consideration of alternative solutions, such as restricting building close to the river or exploiting the natural processes in the catchment, including wetland storage, that can play a role in regulating flood flows.

Flooding is a natural process that fertilises the floodplain soils. It is mankind's occupation of the floodplain that has created the notion of flooding as a problem.

In contrast to the negative view, the flood-pulse concept sees the flood waters as the life blood of the river, its associated ecosystems and dependent rural communities. As a result of periodic inundation, the floodplains of the major rivers of the world including the Amazon, Zambezi, Nile, Mekong and Ganges support wetland ecosystems of exceptional productivity. In many cases this is in sharp contrast to the surrounding arid and semi-arid rangelands where the dry season is long and very arid.

Floods: risk or benefit?

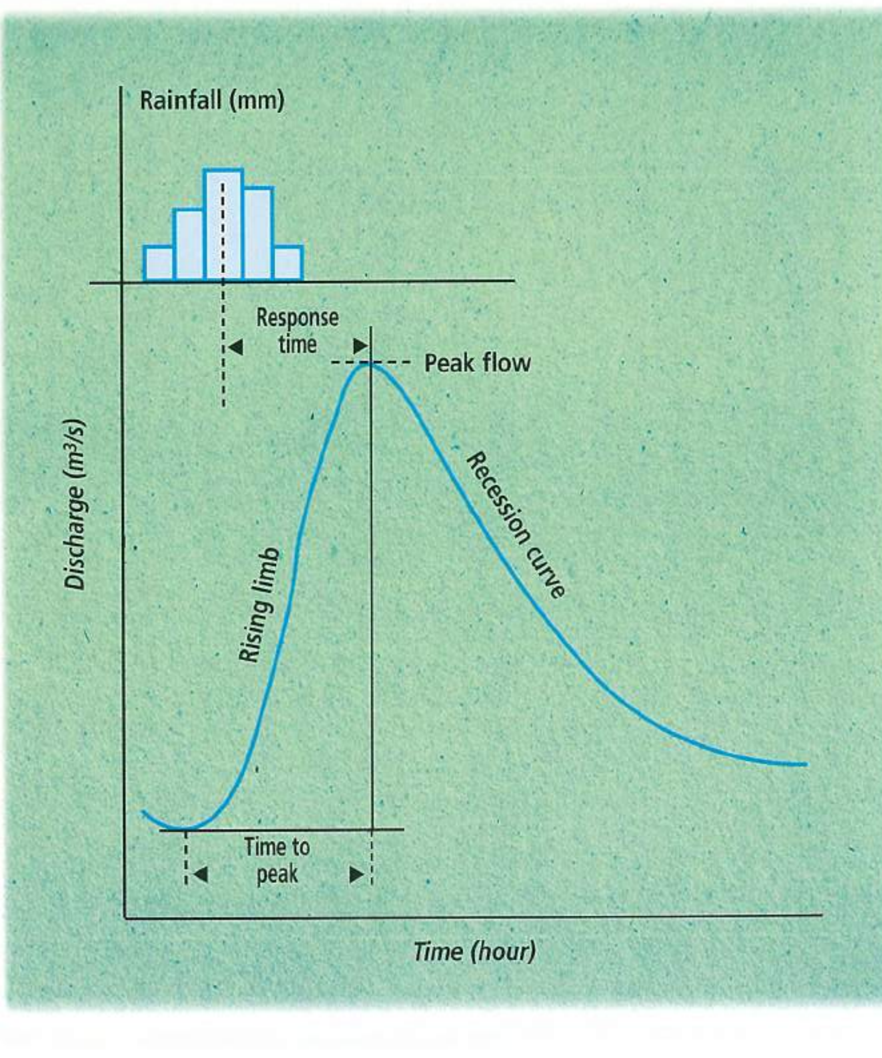
Floods are a reality, but assessing their potential impact depends on two factors.

The first factor, hazard, relates to the physical hydrology of the catchment and hydraulics of the river channel and its floodplain. These determine how often riparian land will be flooded, to what depth and for how long.

The second factor, vulnerability, represents the sensitivity of the land to flooding in economic and social terms and relates to land use and social perception of flooding.

This socio-economic factor can be positive if the flood water provides natural irrigation, fish habitat or soil fertility, in which case floods are beneficial. In contrast, it can be negative if industrial or residential property is damaged or destroyed. If there is an incompatibility between physical factors (the hazard) and socio-economic factors (vulnerability) flooding is a risk.

For centuries, these floodplains have played a central role in the rural economy of the region, providing fertile agricultural land that supports a large human population. The flood-waters bring essential moisture and nutrients to the soil and provide a breeding ground for large numbers of fish. Water that soaks through the floodplain recharges the underground reservoirs, which supply water to wells beyond the floodplain. As the flood-waters recede arable crops are grown, but some soil moisture persists to the dry season and provides essential grazing for migrant herds of cattle and wildlife.



The flood hydrograph.

What causes flooding?

Flooding is a natural process. River channels are naturally adjusted to contain average-sized flows.

Therefore it is expected that every few years higher flows will occur that exceed the channel capacity, thus water will flow over the banks and inundate the adjacent land. Flooding should not be viewed as some cataclysm, but simply part of natural variation in hydrological processes. It is only because mankind has settled on land that naturally floods, that a conflict has arisen between people and high river flows.

Floods are generally a response to heavy rainfall or melting snow (or a combination of both). Although isolated floods may result from other factors, such as breaking of natural or man-made dams. In broad terms, large catchments respond to long duration rainfall (over weeks or months) whereas flooding on small catchments is normally caused by brief intense rainfall, such as thunderstorms. The size of the flood is also determined by the proportion of rainfall that reaches the river and the speed of runoff. Trees and other dense vegetation help to absorb water and encourage infiltration of water into the soil; this both reduces the runoff volume and increases the time taken for water to reach the river. Deforestation or overgrazing of grasslands can thus increase flood risk. Urban developments (with their large areas of roofs, roads, car parks etc) and soils that are frozen or compacted by cattle or agricultural machinery, tend to be impermeable, so a high proportion of the rainfall runs off rapidly into rivers creating a high flood risk.

C. Ruoso / Bios

Deforestation in the Himalayas has been linked with increased flooding downstream on the Ganges and Brahmaputra in Bengladesh[1].

1 - Agarwal & Chak (1991)

Flood frequency

In the same way that rainfall varies from storm to storm, so floods range in magnitude from minor increases in river flows, which occur very frequently, to major rare events, where large areas of land are inundated.

Flood magnitude is recorded in terms of river flow (normally m^3s^{-1}) or flood level (m). Flood rarity is given in terms of its probability, or chance, of occurring.

A "one hundred year flood" is a flood that only has 1 in 100 chance of occurring in any year (and thus will only occur once, on average, every 100 years).

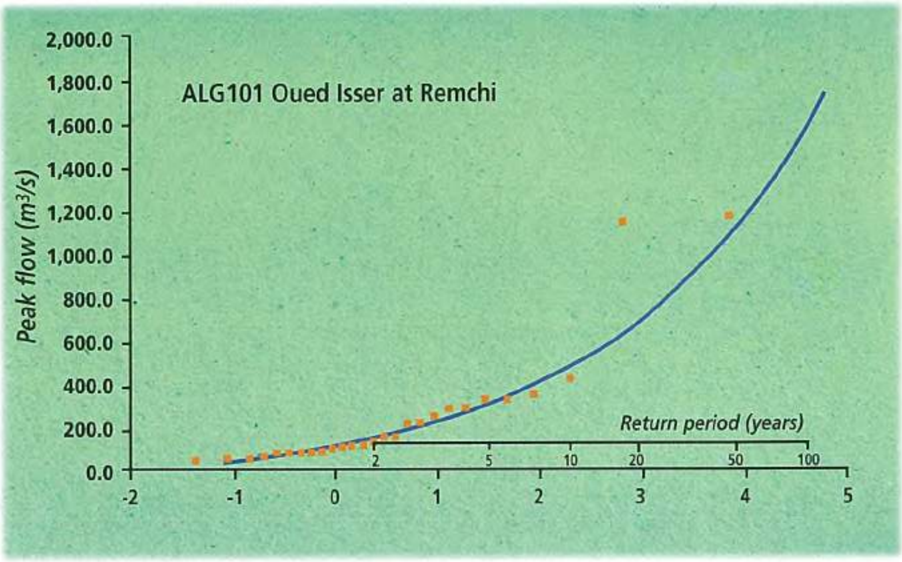
The relationship between flood magnitude and rarity, is called the flood frequency curve*. This is used by hydrologists as a design tool.

In general, the more strongly a structure is built, the more it costs, so bridges and embankments are designed to a standard such that allows them to withstand a given severity of flood.

A typical example would be to build flood embankments to a 100-year flood standard. Thus they would be over-topped only once, on average every 100 years.

Dams are normally built to more stringent specifications, as the damage caused by a dam break is more catastrophic. Consequently, dams are designed to withstand a 1 in 10 000 year flood or greater.

The flood frequency curve* for the Oued Isser River, Algeria. It is noteworthy that two floods are much larger than all the others, which are of similar size, demonstrating the great variability in floods in the Mediterranean. It also shows the danger of relying on short records for design purposes. If this river had only been monitored for a short period with only the smaller frequent floods recorded and the rarer, much larger, flood events missed the curve would look quite different. The 100 year flood would be much lower and flood embankments or bridges would be under-designed [1].



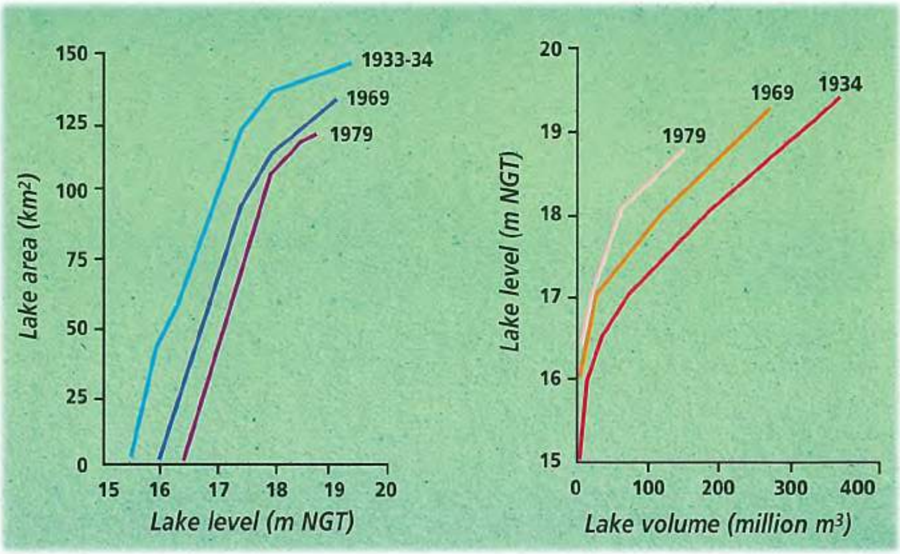
1 - Meigh & Farquharson (1985)

Wetlands and floods

A great deal of evidence, both anecdotal and quantitative, exists to suggest that wetlands play an important role in controlling the size and timing of floods.

For example, during the wet season, the Pantanal wetland in central South America absorbs flood water from the Parana River, thus reducing flood risk downstream[1]. Similarly, when the River Mekong in South-East Asia rises, water flows into the Tonlé Sap wetland, which can store around 46,000 million m^3 of water[2]. This significantly reduces flood risk in the Cambodian capital of Phnom Penh.

In the Mediterranean, some wetlands also help to reduce flood risk downstream. Lake Fetzara, a shallow 13,700 hectare depression in the floodplain of the Oued Seybouse in Algeria, provides an excellent example. The importance of the lake for flood regulation only became apparent after it was completely drained in the 1930s. In the 1980s, floods caused substantial damage downstream since the lake no longer stored the flood-water. Since then, the sluice gate at the outlet has been closed in the winter to retain flood-water, which is released steadily during the spring and summer. Effectively, the natural processes of the wetland have been recreated artificially. Sebkhet Kelbia in Tunisia used to perform a similar flood storage function reducing flood risk in downstream. Its capacity has been reduced by two-thirds since 1933 due to sedimentation caused by serious soil erosion in the catchment upstream. Storage became insufficient to mitigate the major floods in the late 1960s and early 1970s, which



Hypsometric curve* for Sebkhet Kelbia, Tunisia, defining the relationship between water level and volume [3].

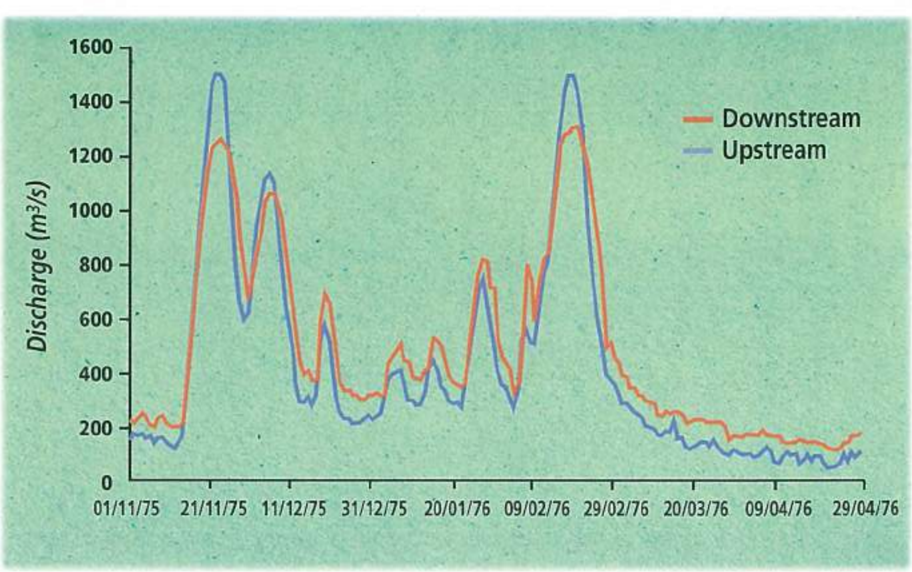
1 - Bucher et al (1993)
2 - Van der Linden (1990)
3 - Hollis (1992)

Flood reduction by wetlands

The River Saône in France, which joins the Rhône before entering the Mediterranean, is very suitable to demonstrate the flood reduction effect of wetlands. Instruments in the river at Mâcon and Couzon-au-Mont-d'Or record the flow. Between 1 November 1975 and 29 April 1976, there were two large floods and several events of smaller magnitudes. Along the river reach between the flow measurement stations, there are several floodplains. During low flows* and small flood events (less than about 900 m^3s^{-1}) the downstream flow is greater than the upstream flow, as a result of water joining the River Saône from various tributaries between the measurement stations. In contrast, during large floods (greater than about 900 m^3s^{-1}) downstream flows are less than upstream flows because flood-water is stored on the floodplain. These wetlands hence play a crucial role in reducing flood peaks and so give important flood protection to the cities, such as Lyon, downstream.

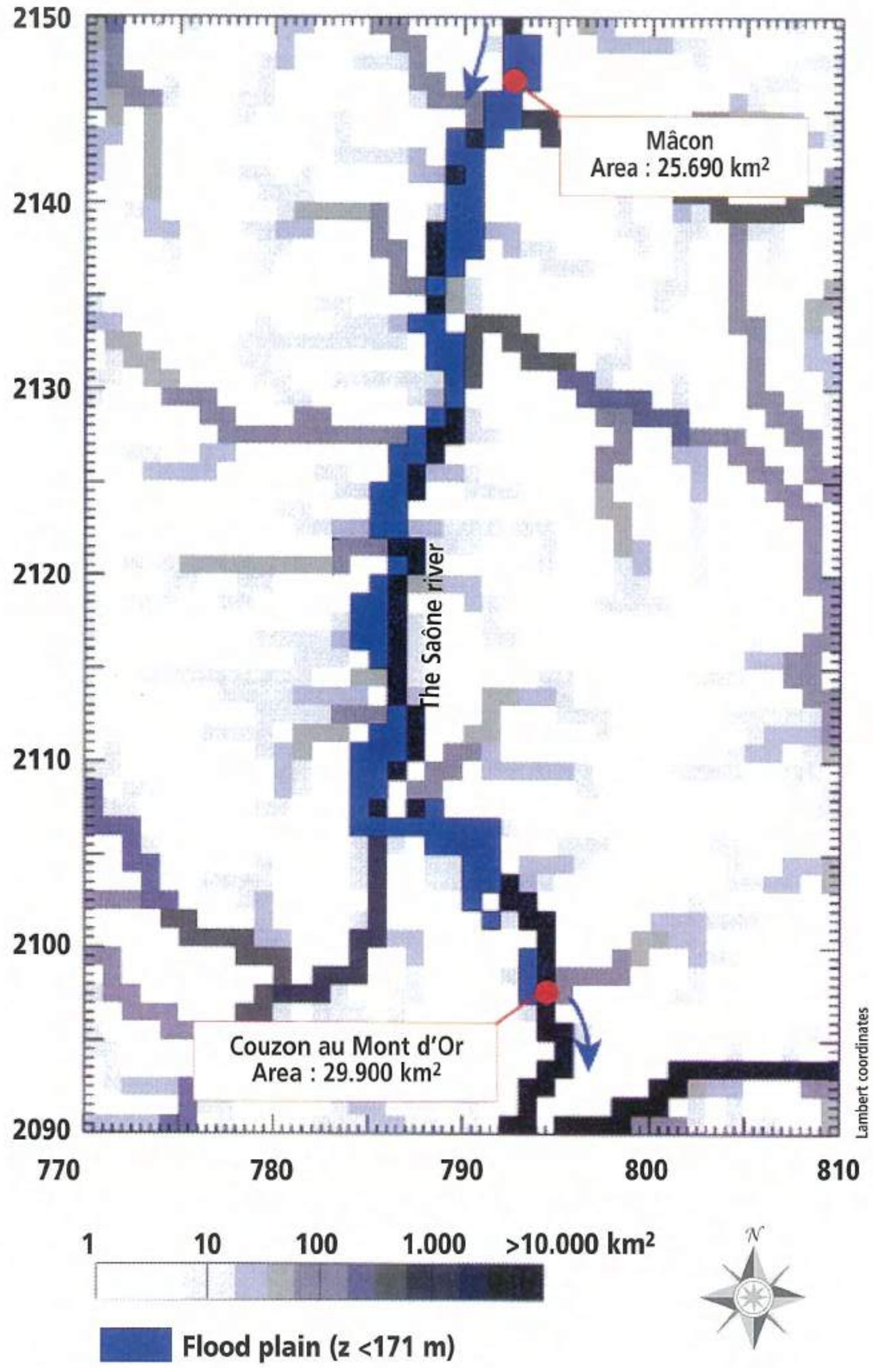
J. Roché

Flooded wheat field in the Saône plain.



Flow record for the River Saône, 1 November 1975 and 29 April 1976 at two flow measurement stations (blue upstream, red downstream) showing the flood reduction effect of floodplains[1].

1. Leblois & Sauquet (1997)



Map of the Saône valley from a Geographical Information System* showing floodplain areas[1].

1 - Sauquet, pers. comm.

killed many people and cut the main north-south roads, railways and telephone lines.

Hydraulic engineers and hydrologists have studied the movement of water along river channels and floodplains for many years. As water flows downstream, friction between the moving water and the channel bed reduces the flow speed and hence the river level. This has two effects, the peak flow during a flood will decline as the flood wave travels downstream (unless a major tributary joins) and the duration of the flood hydrograph will increase. When water flows over the floodplain adjacent to the river during a flood, these effects are amplified because the water has a greater area over which to spread-out. If the floodplain is highly permeable, as found, for instance, on sandy soils in India[1], infiltration of water will increase the impact and reduce flood peaks further.

This important "flood reduction" function of wetlands has clear direct value. As an example, in Massachusetts USA, 3,800 hectares of wetlands along the main stream of the Charles River provide natural valley storage of flood-water. It is estimated that if these wetlands had been destroyed by reclamation, the increased flood damage would have cost US$ 17 million each year[2]. Conservation of wetlands was found to be the most economic option for flood protection.

In most cases, a floodplain becomes flooded as a result of over bank flow. However, this is not true of all floodplains. The floodplain of the central Amazon becomes flooded as a result of the water table rising and reaching the surface. In this case, the floodplain contributes to the flood rather than reducing it[3].

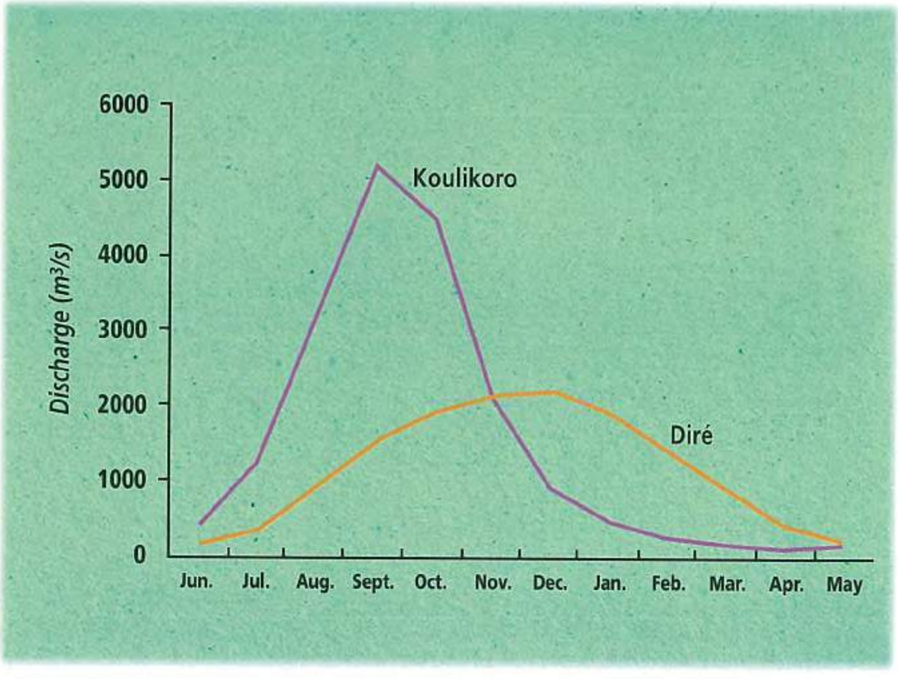
1 - Nielsen et al (1991)
2 - US Corps of Engineers (1972)
3 - Hodnett et al (1997)

Flood desynchronisation*

As described above, the process that reduces flood peaks, also delays the timing of the peak flow.

Where floods may cause damage, this provides more time for evacuating people and livestock or protecting property. Where floods are beneficial, such as in the interior delta of the River Niger in Mali, farmers have exploited the time between rainfall and flooding created by the Niger delta wetland. The Niger rises in the Fouta Djalon mountains of Guinea, only 200 km from the Atlantic Ocean and where the annual rainfall exceeds 2,000 mm per annum. At its northern extremity, on the fringe of the Sahara desert in Mali, the annual rainfall is only around 200 mm per annum[1]. The flood peak flowing into the delta (at Koulikoro) can be as high as 8,000 m^3s^{-1}, but is normally around 6,000 m^3s^{-1}. The average outflow peak (at Diré) is around 2,300 m^3s^{-1}. This is a classic example of flow through a delta with the peak being reduced and the outflow being of longer duration than the inflow.

For the delta area the wet season is from May to October, with most rain in the period from June to September. The flood hydrograph upstream of the delta corresponds closely to the rainy season, with perhaps a month or so delay, the peak actually occurring towards the end of the rainy season. On the other hand the flood hydrograph downstream of the wetland is much more extended and flatter than



Average inflow to the Inner Niger delta, Mali (at Koulikoro) and outflow (at Diré) hydrographs for the period 1979 to 1987, which included two very severe drought years.

1 - Chene & Ehrlich (1985)

the inflow and also it is a further two or three months delayed. This is not only true at Diré but also further downstream for a length of 600 to 700 kilometres to Niamey and on to Koulikoro on the Benin frontier.

Farmers in this very arid area have taken advantage of the flattening and extension of the hydrograph in their agricultural practises. Rice is planted towards the end of the rainy season in July. The delay between rainfall and flooding gives time for the seeds to germinate and get established. The young plants then grow rapidly as the flood-water advances. The crop is harvested in December as the flood waters recede. As the flood recedes it leaves behind it a band of saturated land. Dry-season crops are planted in this band a month or two before the rainy season starts. There is sufficient moisture available for the crops to start growing and establish their root systems. The arrival of the rainy season enables them to continue growing until harvest. The phasing of rainfall and flooding in this region allows the farmers to grow several crops during the year. This is important not just for its intrinsic economic value but also because it allows a number of different cropping options to be carried on simultaneously which, given the variability of the climate and consequent variability in yields, increases the chances of getting sufficient food.

M. Acreman

Farms take advantage of desynchronisation of rainfall and flooding to grow crops in the inner Niger delta, Mali.

Traditional approaches to flood protection

Throughout human history, industrialisation, residential expansion and intensification of agriculture have gone hand in hand with increased management of water. Examples include the elaborate irrigation canals of the Andes and the groundwater exploitation canals (kareses) of Pakistan.

Some systems, such as water meadows, developed in Europe since the Middle Ages maintained flooding to enhance hay and crop production, but in a more controlled manner.

However, rapid advances in technology, particularly during the 20th century, have led to the belief that man can control nature and eliminate natural hazards, such as floods. Engineers were given responsibility for flood protection and sought structural solutions through construction of flood embankments and dams, or widening and straightening river channels to protect riparian areas. Whilst partial success has been achieved, this approach has a number of disadvantages.

First, increasing the channel size or constructing embankments on a reach of river does not reduce the flow of water, it prevents flood water spreading over the floodplain and eliminates natural flood storage and attenuation. Thus, whilst the embankments offer flood protection immediately behind the defences themselves, that flood water must go somewhere. In practice, embankments merely transfer the problem downstream, where they actually increase the flood peaks, exacerbating flood damage and bank erosion. This was the case along the River Rhine in 1994. Serious flooding of cities along the lower reaches of the river was made worse by the presence of embankments upstream, which separated the river from the floodplain, protecting agricultural land, but preventing access by the river to natural floodwater storage. In 1995, two large flood storage areas were created on the German bank of the Rhine by removing the embankments to reconnect the river to its floodplain as part of a programme to reduce flood damage downstream.

The second disadvantage is that flood defences often build a false sense of security leading to intensive development of land behind them. They can only be built to give a certain level of protection. If a flood occurs that is more severe than the design, the embankment is over-topped and flood damage is often worse that if the embankment was not present. This has been shown to be the case in Bangladesh, where intensive agriculture and housing has developed behind flood embankments and large floods have exceeded the design and caused catastrophic damage and loss of life.

The third disadvantage arises because water that over-tops the embankment is prevented from re-entering the river. These problems were highlighted during the Mississippi floods of 1993 that caused $12-16 billion of damage and took 38 lives, when water remained on farmland, in houses and across roads long after the river itself subsided. This prompted the US government to reconsider its structural approach to flood defence. The Assistant Director of the US Corps of Engineers, concluded "it's unlikely you'll see more reservoirs or more levees on the biggest river system in the US".

The fourth problem is that dams and embankments prevent the natural renewal processes, such as soil fertility on riparian agricultural land that is maintained by periodic deposition of silt on the floodplain during floods. In addition, whilst upstream dams may assist with flood protection, they act as sediment traps and water below the dam is virtually silt-free. This reduces the beneficial effects of floods and makes river water more erosive causing increased erosion of banks and bed.

C.H. Smith / P. Arnold Inc. / Bios

Tow and barge on the Mississippi river.

The changing paradigm

The concepts that flooding is a natural process that can have many benefits and that flood-risk is man-made, by people living and building in the floodplain, are becoming more widely appreciated.

Three key concepts run through the new paradigm: holistic, integrated and management.

- Holistic, through considering the whole catchment, so that developments in one part are not adversely affecting other parts of the catchment. This includes the linkages, upstream and downstream, through a river system ("river continuum concept") and the inter-relationship between rivers and their floodplains (the "flood pulse concept").
- Integrated, through collaboration between stakeholders (i.e. different organisations and institutions responsible for or interested in water).
- Management, as opposed to control, by letting floodplains play their natural role whilst protecting vulnerable areas, discouraging new floodplain development and providing incentives to move some activities to higher ground.

In the past there has been a conflict of interest between flood engineers whose goal is to evacuate flood water as quickly as

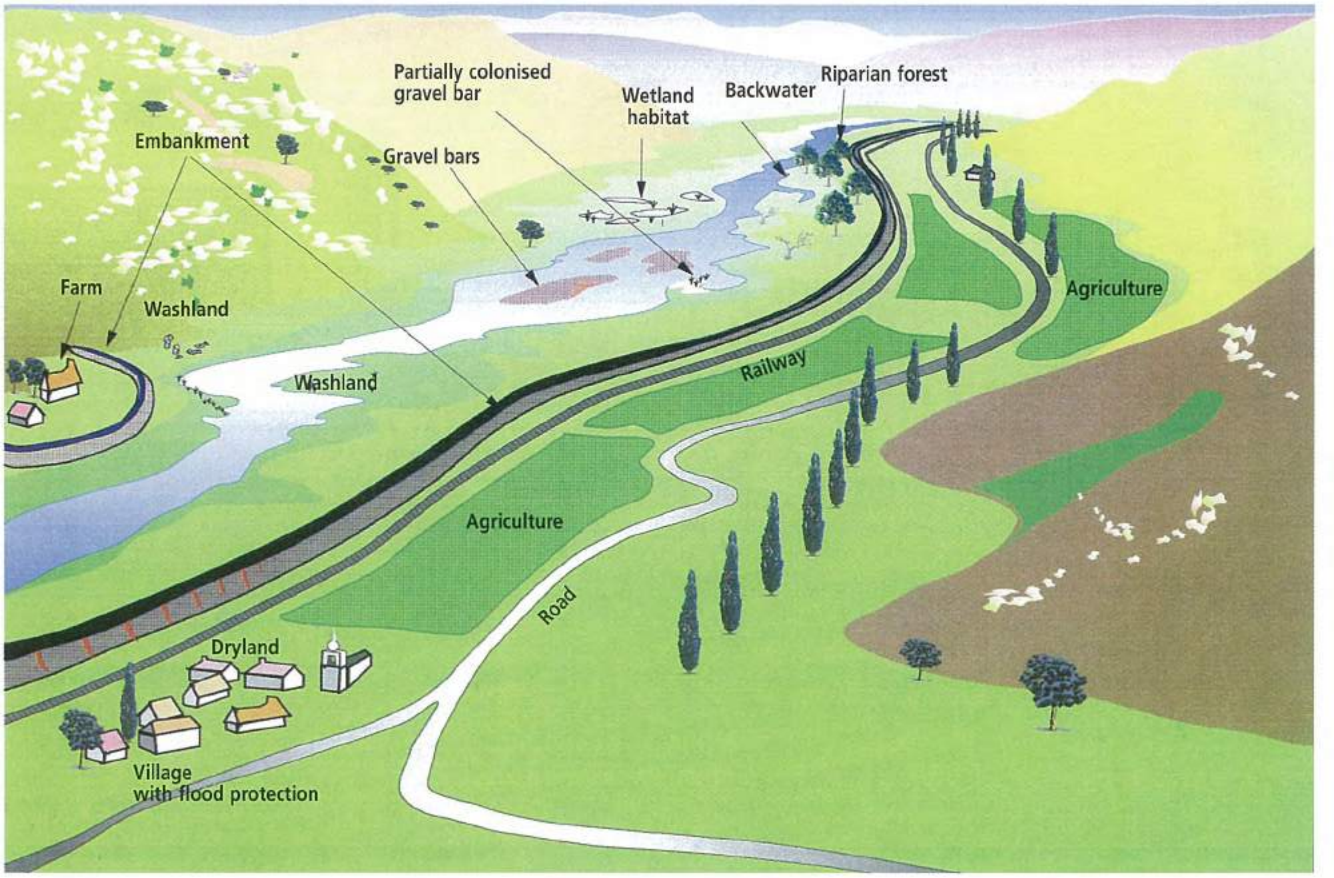
J. Roché

Intensive housing has been developped behind embankments.

possible, water resource managers who are faced with water supply shortages during dry periods and conservationists who are trying to conserve river and wetland biodiversity. This has prompted consideration of alternative solutions, which manage floods, rather than trying to stop them, working with natural hydrological processes rather than against them, resulting in a "win-win" situation. The World Wide Fund for Nature, for example, has established the "Living Rivers" campaign which promotes the consideration of rivers as functioning ecosystems and not just as conduits to evacuate flood water.

An obvious solution is to reduce the flood risk, not by reducing the flood peak*, but by restricting development on the floodplain. In the USA, a cost effective approach is to buy land close to the river within the "floodway" (defined by the extent of the 100 year flood) and to use this land for recreational parks or wetland reserves uses which do not suffer, and may benefit, when inundated. Clearly, in very densely populated countries, it may not be possible. However, some measures are always possible. The most important parts of the floodplain, containing arable land, housing, roads and industry can be protected, whilst other areas can be designated as wash-lands, where natural

Reaching a compromise between flood protection of critical areas and conserving the natural processes of the river.



Many natural rivers divide into several channels.

M. Acreman

processes of flooding and channel adjustment can continue. This avoids expensive river engineering works that would be needed if the river was to be totally controlled, produces natural flood storage areas to reduce the risk of flooding downstream and conserves wildlife habitats. In some countries, housing developments on floodplains have no living accommodation on the ground floor; this is used for storage of easily replaceable items. It is then accepted that these areas may flood occasionally without great economic losses.

Degraded catchment headwaters, formerly with forests and grasslands, can be restored. This helps increase infiltration of water into the soils and rocks. Not only does this reduce flood risk downstream, but also reduces soil erosion and recharges aquifers which increases water resource availability. Such restoration is being attempted in west Pakistan where floods cause severe soil erosion and damage to property and groundwater levels are falling partly due to reduced recharge.

Restoration and re-connection of wetlands to water courses by removing embankments is a further example. First, flood risk downstream is reduced and second, storage of water on the floodplain deposits silt that fertilises the soil, recharges the groundwater and improves the habitat for a wide of range of wetland species. Following recent floods along the Rhine proposals are in place to re-connect the river with floodplains upstream of major cities as the most economic and environmentally friendly flood management measure. Similarly, a major project has recently started in the Napa Valley in California, USA, to remove flood embankments to reduce flood risk. A method for zoning the floodplain has been produced by combining the risk (chance of inundation to a certain depth for a certain duration) and vulnerability (the socio-economic costs of inundation)[1]. This allows identification of the areas that need greatest protection and those that can be best used for flood storage.

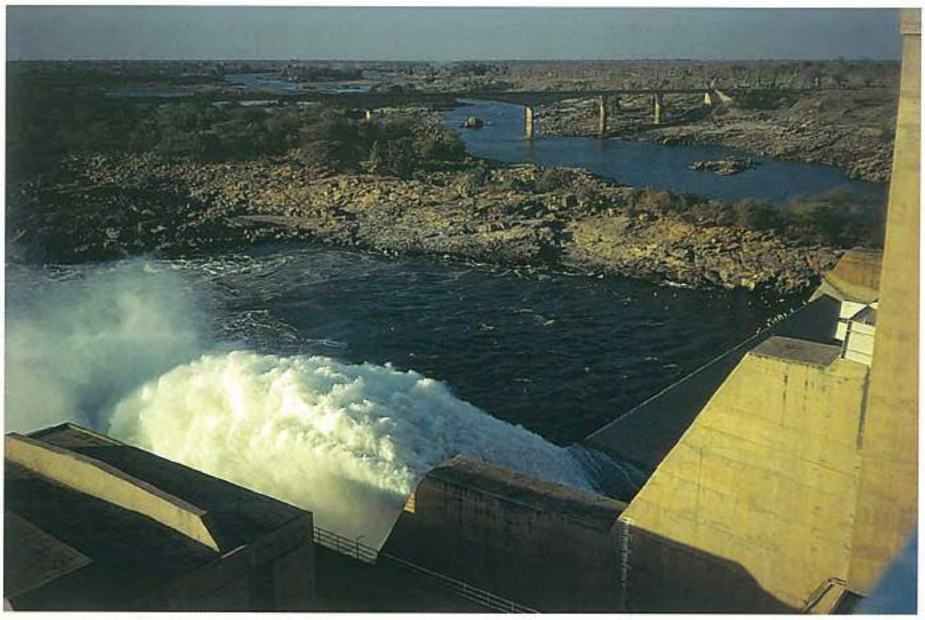
In some catchments the recognition of the great benefits of floods have been taken one step further, with creation of artificial floods*. For example, the construction of the Manantali dam on the River Senegal in West Africa to generate hydro-electric power and the construction of embankments along both banks of the river prevented inundation had many negative effects on the environment. Prior to construction natural inundation of the floodplain of the middle Senegal valley supported up to 250,000 hectares of flood recession agriculture, forests, which provided fuelwood and construction timber, and wildlife habitat. Because of the recognised delay between dam construction and installation of turbines, man-made floods were

Artificial floods on the Phongolo River

In the late 1960s, the Pongolapoort dam was constructed on the Phongolo River in north east South Africa near its borders with Swaziland and Mozambique, with a view to irrigating 40,000 hectares of agricultural land for white settlers, with no provision for hydropower generation[2]. No assessments were undertaken of impacts of the impoundment on the floodplain where 70,000 Tembe Thonga people were dependent on floods for recession agriculture, fishing and other wetland resources nor on the biodiversity of the Ndumu game reserve. In the event no settlers came to use the irrigation scheme. The dam changed the whole flooding regime of the river that led to a reduction of wetlands habitat and reduced the productivity of agriculture and fisheries. At the time of its completion, it represented a classic case of disastrous development and management.

In 1978, a workshop was held on the Phongolo floodplain to review the future of the dam and how to minimise the negative impacts on the floodplain. This led to a plan for controlled flood releases to rehabilitate the indigenous agricultural system and to benefit the fisheries and wildlife. However, initial releases of water from the dam were made at the wrong time of the year and crops were either washed away or rotted[3]. In 1987, the Department of Water Affairs and the tribal authorities agreed to experiment with community participation. As a result, water committees were established, representing five user groups: fishermen, livestock keepers, women, health-workers (both new primary health care workers and traditional herbalists and diviners) who were given the mandate to decide when flood waters should be released. These committees were very successful at implementing people's views and have led to improved management of the river basin to the benefit of floodplain users and the environment.

1 - Oberlin et al (1996)
2 - Breuwer et al (1996)
3 - Poultney (1992)



Water being released from Roseires dam, Sudan.

released from the dam. However, the releases made have been irregular and small, inundating only around 50,000 hectares. In a cost-benefit analysis, Horowitz and Salem-Murdock (1990) calculated that the best economic option is to use the Manantali dam both to release an artificial flood and to generate some hydro-power. There have also been experimental artificial releases on other Africa rivers, such as the Kafue and Logone[1]. A major problem is that most dams were not designed to make major releases and there is frequently poor coordination with local farmers and fishermen. The most successful example is that of the Phongolo is South Africa which involves local people in management of the dam.

1 - Acreman & Hollis (1996)

M. Acreman

Wetlands and groundwater

The interaction between groundwater and surface water is unique in some way to each wetland. This makes it difficult to define generalised relationships.

The importance of groundwater is easily over-looked, as it is out-of-sight and often out of mind. Yet it is a valuable resource throughout the Mediterranean because in many areas there is little surface water, since most rainfall either evaporates or percolates into the soil then into underlying rocks.

Groundwater occurs between the grains or within fine cracks of permeable rocks, such as limestone, chalk and some sandstones.

Water being pumped into a Caribbean wetland.

These water-bearing rocks are called aquifers. Groundwater emerges from aquifers as springs or can be pumped from wells or boreholes*. It is relatively cheap to exploit and normally of high quality, as the soils through which the water passes on its way from the surface to the aquifer act as a filter. Groundwater is often flowing, albeit very slowly, so it must be replenished by percolation of surface water to maintain a given level within the ground. Where aquifers exist along the coastline, there is normally a gradient towards the coast and groundwater discharges to the sea. Provided a certain level of groundwater is maintained the flow is strong enough to prevent the seawater from seeping into the aquifer.

However, when the groundwater is pumped from a coastal aquifer, the seawater can intrude. If pumping is excessive, the sea water may intrude as far as the well which becomes saline. In humid areas of the world, rainfall percolates into the ground to recharge aquifers. However, in arid areas such as the Sahara desert and Middle East very little recharge currently takes place. The groundwater in this area is some 10,000-20,000 years old and infiltrated when rainfall was substantially higher during glacial phases in high latitudes. This means that abstraction of water is not sustainable in the long term, as the resource will not be renewed (within the near future).

The relationship between wetlands and groundwater is complicated. Many wetlands exist because an impermeable layer of soil or rock restricts vertical movement of water. Peat bogs, from Ireland to Siberia, for example have extremely low permeability with little downward percolation of water. A common conclusion is that there is little interaction between wetlands and groundwater. Consequently, the concept that wetlands may recharge aquifers has been dismissed as improbable by many hydrologists.

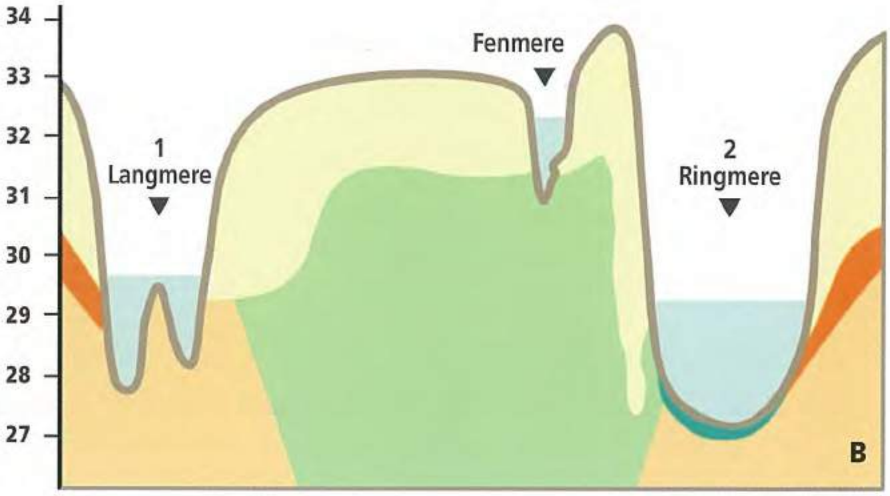
However, some wetlands arise where groundwater comes to the surface as springs. Furthermore, other wetlands, although fed by surface water, such as floodplains, exist on very permeable soils allowing rapid infiltration of water, which replenishes or "recharges" the groundwater.

The links between wetlands and underlying groundwater vary considerably, making it difficult to transfer the results of scientific studies from one site to another. For example, the Breckland Meres (Langmere, Ringmere and Fenmere) are three superficially similar base-rich wetlands in the east of the UK. Langmere is in hydrological continuity with the chalk aquifer and its regime is controlled by groundwater fluctuations. Ringmere has a less well-developed connection with the chalk due to a lining of organic matter but is still largely controlled by groundwater. In contrast, Fenmere is separated from the underlying chalk by clay alluvium and its water level is largely a reflection of the balance between rainfall and evaporation[1].

For some wetlands, that are linked hydrologically to an underlying aquifer, the interactions may vary depending on prevailing conditions.

When the water table is high the aquifer may be supplying water to the wetland (groundwater discharge), but as the groundwater level drops the hydraulic gradient reverses and the wetland may be supplying the aquifer (groundwater recharge). Similar effects have been reported for swamps in Belarus[2] which may be supplied by groundwater and may also serve as sources of groundwater recharge. Likewise, some wetlands dominated by Cypress trees recharge the groundwater, whilst in others there is little percolation[3].

Three wetlands (Langmere, Ringmere and Fenmere, UK), though visually similar at ground level, show contrasting connectivity with their underlying aquifers. This makes it difficult to transfer results of hydrological studies from one wetland to another [4].



1 - Denny (1993)
2 - Kiselev (1975)
3 - Heimburg (1984)
4 - MENR (1981)

Groundwater-fed wetlands

There are numerous examples worldwide of wetlands that are supported by groundwater, such as those in valley floors, where groundwater discharges as springs or seepages.

In Amboseli National Park in Kenya, water from Mount Kilimanjaro percolates through the porous lava emerging via springs in a series of small swamps. These are an important source of water for wildlife and a major attraction of the Park[1]. On the Spanish island of Majorca, extensive reedbeds in the S'Albufera wetland are maintained throughout the year by springs.

N. Granier / Bios

The Kilimanjaro within the Amboseli National Park.

Azraq

The Azraq oasis in Jordan is a traditional stopping point for camel caravans and an estimated 40,000 nomads depend on it for water and grazing.

The freshwater marshes within the wetland used to be fed by two springs supported by a regional aquifer. However, recent increases in pumping to provide water for the city of Amman have virtually dried these springs and have led to severe ecological degradation, agricultural decline and emigration. Recognising the importance of the wetlands in the oasis, some of the water abstracted from the aquifer is now pumped back to Azraq to help restore its valuable ecosystem[2].

1 - Acreman & José (2000)
2 - Fariz & Hatough-Bouran (1998)

Groundwater recharge

Some rivers and wetlands occur on permeable soils or rocks, which overlie an aquifer.

Water percolates downwards through the top layers and replenishes the groundwater reserve. This is termed groundwater recharge. Groundwater hydrologists recognise two principal types of groundwater recharge: direct and indirect. Direct recharge is the direct vertical percolation of water through the soil to the aquifer. Indirect recharge occurs when water first moves horizontally through the soil into a river or wetland, which overlies over permeable soils or rocks. Recharge then occurs through the bed of the river or wetland.

In the Mediterranean region, indirect recharge may be very significant. In the Messara valley of Crete, a little less than 50% of the recharge to the aquifer (around 10 million m^3 in 1971) occurs through the bed of streams in the catchment[1]. In a wet year this could exceed 19 million m^3 [2]. This is an important contribution to the aquifer since currently, around 22 million m^3 (1993 figures) is abstracted annually for agriculture (to irrigate olive trees and vines).

The floodplain of the Senegal River in West Africa contains very permeable soils[3]. Hydraulic connectivity between the different soil layers has produced a shallow aquifer that is recharged during floods rather than rainfall[4]. An area up to 25 km from the river along a dozen geophysical transects was studied and a network of 138 piezometers* installed between 1970 and 1972[5].

Kairouan floodplain, Tunisia

In central Tunisia, the rivers Zeroud, Merguellil and Nebaana recharge the aquifer with water during floods as they flow across the plains of Kairouan. Although the rivers are ephemeral and subsequently run dry the water that has infiltrated to the aquifer can be exploited throughout the year for irrigation. Around the city of Kairouan, the groundwater is artesian (ie. it will rise to the surface under its own pressure) and provides drinking water to the population. Without the recharge the wells would run dry.

1 - Bromley et al (1996)
2 - FAO (1972)
3 - BRGM (1982)
4 - GERSAR/CACG et al (1988)
5 - Illy (1973)

The piezometers showed that the surface aquifer is alternately recharged and drained by the river. Isotopic studies showed that the aquifer is recharged by vertical percolation of flood water. Infiltration of flood water was estimated at 250 million m^3 yr^{-1} with rainfall adding some 30 million m^3 yr^{-1}. Some 8 observation wells were examined and pumping tests undertaken near Matam. It was concluded that the aquifer (of more than 50 m of sands and gravels) "... is recharged when the river is in flood". This work did not study the deeper aquifers. The US$ 7 million Groundwater Monitoring Project covered the entire valley up to Manantali and involved the installation of hundreds of piezometers, creation of a database and three years of observations. No detailed analysis was undertaken of the middle valley by the Project, but later examination of the data[1] from the database revealed that flood water infiltrated into the floodplain aquifer and subsequently drained back into the river at low flows.

M. Acreman

Measuring groundwater levels in the North Kent marshes, UK.

1 - Hollis et al (1996)

Anthropogenic influences

Aquifers provide a valuable water resource for people throughout the world, but over-exploitation can lead to degradation of the processes which ensure the existence and quality of the groundwater.

The history of the Tablas de Daimiel wetland in Spain provides an example of how groundwater exploitation has affected the interaction between surface water and the aquifer. The Tablas is a marshland at the confluence of the Rivers Guadiana and Gigüela, at its most extensive, it covered some 15 km^2 with a depth of around 1 m. It is one of the two Spanish wetland National Parks. This status provides legal protection for the wetland itself but not for the catchment of the upper Guadiana which feeds it. The Tablas de Daimiel has been designated a Ramsar site and nominated as a UNESCO Biosphere Reserve. The wetland is sustained predominantly by discharge from the western Mancha calcareous aquifer, although surface flow from the Guadiana and Gigüela also helps support the wetland.

The aquifer has been intensively exploited for the past two decades, increasing from 200 million $m^3\ yr^{-1}$ in 1974 to 600 million $m^3\ yr^{-1}$ in 1987. The latter figure is greater than the estimated average recharge to the aquifer from the catchment of 200-300 million $m^3\ yr^{-1}$. This has led to a progressive decline in groundwater levels of 20-30 metres and reduced flows in the Guadiana river. In turn, this resulted in a change in the hydrological functioning of the Tablas de Daimiel to a recharge

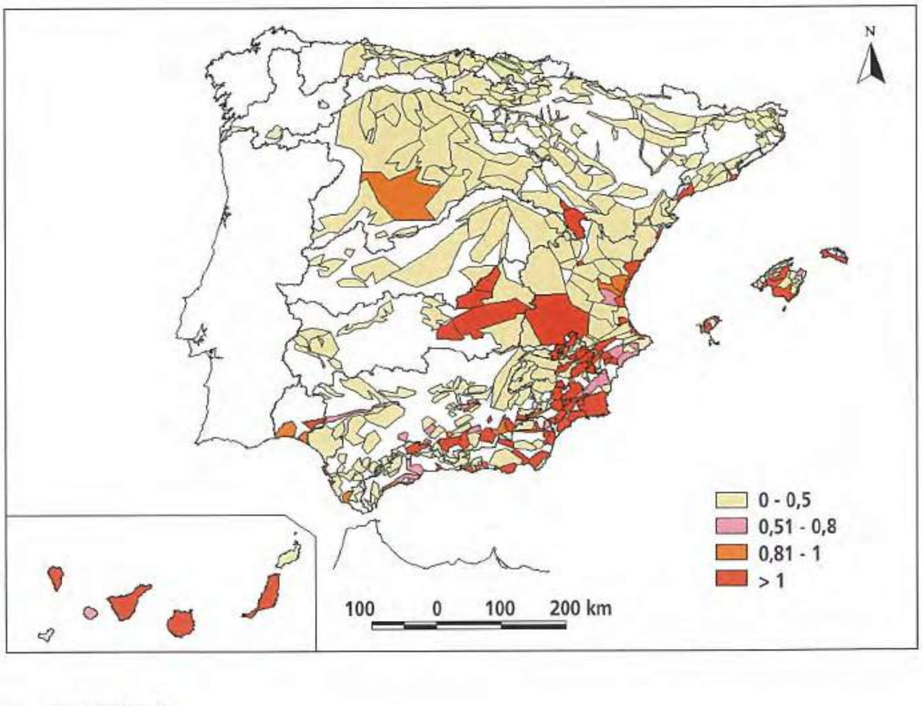
Water balance of Las Tablas de Daimiel with and without groundwater exploitation (millions m^3)[1].

	Inputs		Outputs	
Annual water balance before significant groundwater exploitation	Rainfall	7	Evaporation	9
	Surface runoff	210	Surface runoff	242
	Groundwater	45	Irrigation abstraction	11
	total	262	total	262
Annual water balance in current situation with significant groundwater exploitation (after SGOP, 1983)	Rainfall	7	Evaporation	9
	Surface runoff	124	Groundwater recharge	33
			Surface runoff	88
	total	131	total	130
Predicted future annual water balance with significant groundwater exploitation (after Llamas, 1989)	Rainfall	7	Evaporation	9
	Surface runoff	40-70	Groundwater recharge	40-70
			Surface runoff	0
	total	50-80	total	50-80

1 - After MIMAM (1998)

wetland rather than a discharge zone. The ecological impact of the groundwater use was significant. An experimental plan to restore the wetland was approved in 1988 by the Spanish Government. This consists of three actions: a) drilling of emergency pumping wells in the wetland; b) the transfer of up to 60 million m^3 of water from another catchment to the Gigüela; and c) construction of a reservoir to supply the wetlands. This plan has concentrated on the symptoms and not the cause. There is still a need to encourage farmers, through better education, to use less water either by more efficient irrigation, use of crops which require less water, or a charging scheme which will discourage heavy use.

Over-exploitation of the Garaet El Haouaria wetland in Tunisia destroyed the recharge function of the wetland with disastrous consequences. The Garaet covers 3,600 ha on the tip of the Cap Bon peninsula. This used to have an area of open water every winter which was of great importance on one of the major bird migration routes between Europe and Africa. It was used for hunting, grazing and fishing. However, in the early 1960s, drainage canals, each about 4 m wide, were constructed flowing directly into the sea to prevent surface flooding in winter. Landless farmers were moved in by the State and well digging began. Citrus orchards and market gardens with a demand of 7,000 million m^3 $year^{-1}$ for irrigation from shallow groundwater, which recharged the deeper aquifer. No attention was paid to the recharge process and the rapid drainage of water by the canals altered the hydrological balance and a reduction in recharge. Groundwater levels fell by 9 m between 1980 and 1995. Some wells have been abandoned because of salinity due to sea water intrusion.



Aquifers in Spain, where annual abstraction exceeds annual recharge[1].

1 - EEA (1998)


M. Acreman

The Messara valley in Crete.

This has led to emigration of young farmers leaving old people to scratch a living from rain-fed cultivation.

Wetlands used to exist on the Greek island of Crete at Phaistos (the site of Plato's utopian society) where the groundwater table reached the surface. However, in 1984, an extensive groundwater pumping network was installed to develop agriculture in the Messara valley upstream. The current annual abstraction is around 45 million m^3 which feeds 100 km^2 of olives and 22 km^2 of vines. Total recharge to the aquifer is about 20-30 million m^3 yr^{-1}. This abstraction rate combined with several years of low rainfall led to a fall in groundwater levels of 20 metres in 10 years and the wetlands have been completely destroyed.

Artificial groundwater recharge

Storage of water in underground aquifers has many advantages. In particular, there is no water loss through evaporation and water remains fresh within the ground.

Any method by which groundwater can be increased is thus potentially a great benefit for water resources. Disadvantages come in the form of the costs – of re-pumping the water from the aquifer and vulnerability to pollution from landfill sites or agricultural chemicals leaching through the soil.

Artificial recharge of aquifers is not a new idea, – it has been practised for 30 years in Israel –, but is being developed more widely as an option as population increases have put pressure on water resources. It is particularly useful technique in hot arid countries where rainfall may be infrequent and evaporation is high. In North Africa and the Middle East rainfall is generally very low (less than 500 mm per year). Furthermore, much of this may fall as intense storms each lasting only a few hours creating flash floods, much of which evaporates. To make best use of this water, groundwater recharge dams have been built in some locations. These are sited where an aquifer is near the surface and the soils are very permeable. The dam creates a temporary artificial wetland, holding-back flood water and allowing it to percolate through the soil and into the aquifer. A disadvantage of the system is that sediments brought down by the flood waters

A. Crivelli

Reservoir and fish ponds in Northern Israel.

build-up behind the dam and seal the bed of the reservoir and thus impede infiltration. However, at many sites the soil is removed and used on agricultural land as it is often very fertile.

There is potential for artificial recharge in other areas of the Mediterranean. Proposals have been put forward, for example, for the Gaza Strip[1]. Groundwater recharge currently takes place through the bed of Wadi Gaza, which could be doubled by construction of small weirs to create a 50 hectare temporary reservoir. This would assist the serious water stress problem within the Gaza Strip where withdrawals of water from the aquifer exceed the freshwater recharge by 39 million m^3 yr^{-1} and the safe yield by 49 million m^3 yr^{-1}. Artificial recharge is also being employed for water resources management in more humid areas such as the Netherlands, where water from the Rhine is being used to recharge the aquifer in the sand dunes near Amsterdam, to increase water supply.

Artificial recharge of aquifers is another example of making best use of a natural process to benefit mankind, working with nature rather than against it.

Artificial recharge in Israel

There are two schemes within Israel that make use of floodwaters to recharge the groundwater. The Shiquma scheme, north of the Gaza Strip and the Nahalei Menashe scheme near Caesarea. At Shiquma, a small dam has been constructed to create a reservoir which holds flood water. The water is then pumped to large depressions (infiltration basins) in the sand dunes near the coast where it percolates into the ground to recharge the dune aquifer. The average annual recharge is around 3.5 million m^3.

The scheme has suffered from clogging of the bed of the infiltration basins with fine sediments, that form crusts in the dry season and inhibit percolation. In addition, pumping costs make the water expensive, US$ 0.3 m^{-3} (this compares with a cost of US$ 0.8 m^{-3} for desalinisation of sea water). The Nahalei Menashe scheme does not suffer in the same way from sediments as the flow is diverted into a reservoir that is off-line and the water flows by gravity to the infiltration basins.

1 - Bloom et al (1995)


ALASKA

Water needs of ecosystems

All wetlands, including coastal lagoons, deltas and estuaries, require fresh water and associated sediment and nutrients to survive.

Sustainable management can only be achieved by linking all parts of the catchment from the headwaters to the coastal zone through flows of fresh water.

It is the presence of water for some significant period of time that changes the soils, its micro-organisms and the plant and animal communities, such that wetlands function in a different way from

Mangroves, like these in the Indus delta, Pakistan, requiere freshwater to survive.

either fully aquatic or dry habitats. It is self-evident therefore that wetlands need a supply of fresh water. This is also true for coastal wetlands, such as estuaries and lagoons, which require fresh water at certain times of the year.

With water stress facing many Mediterranean countries, it seems an immense task just to manage water so that there is enough for domestic, agricultural and industrial uses, thus providing water to other users, such as "the environment" is given a low priority. Indeed the situation is often presented as a conflict of competing demand, as though it were a matter of choice between water for people and water for wildlife. However, wetlands provide locally important food sources (fish, shellfish, duck) and building material (such as reeds), grazing land (for cattle, sheep and goats) and wildlife and landscapes that attract millions of tourists. Eight of the 29 globally threatened species of birds occurring in the Mediterranean are wetland species. They include Marbled teal *(Marmaronetta angustirostris)* White-headed duck *(Oxyura leucocephala)* and Dalmatian pelican *(Pelecanus crispus)*. The Camargue wetlands of southern France, for example, generate some 2 million Euro per year just from hunting, and 1,275 Euro per hectare from reeds for thatching[1]. In addition, thousands of tourists pay for the sheer pleasure of riding on horse-back through the marshes. Thus whilst people need access to water directly to drink, grow crops and drive industry, providing water to wetlands means using water indirectly for people.

J. Roché

Marbled teal.

1 - Mathevet (in press)

Lagoons

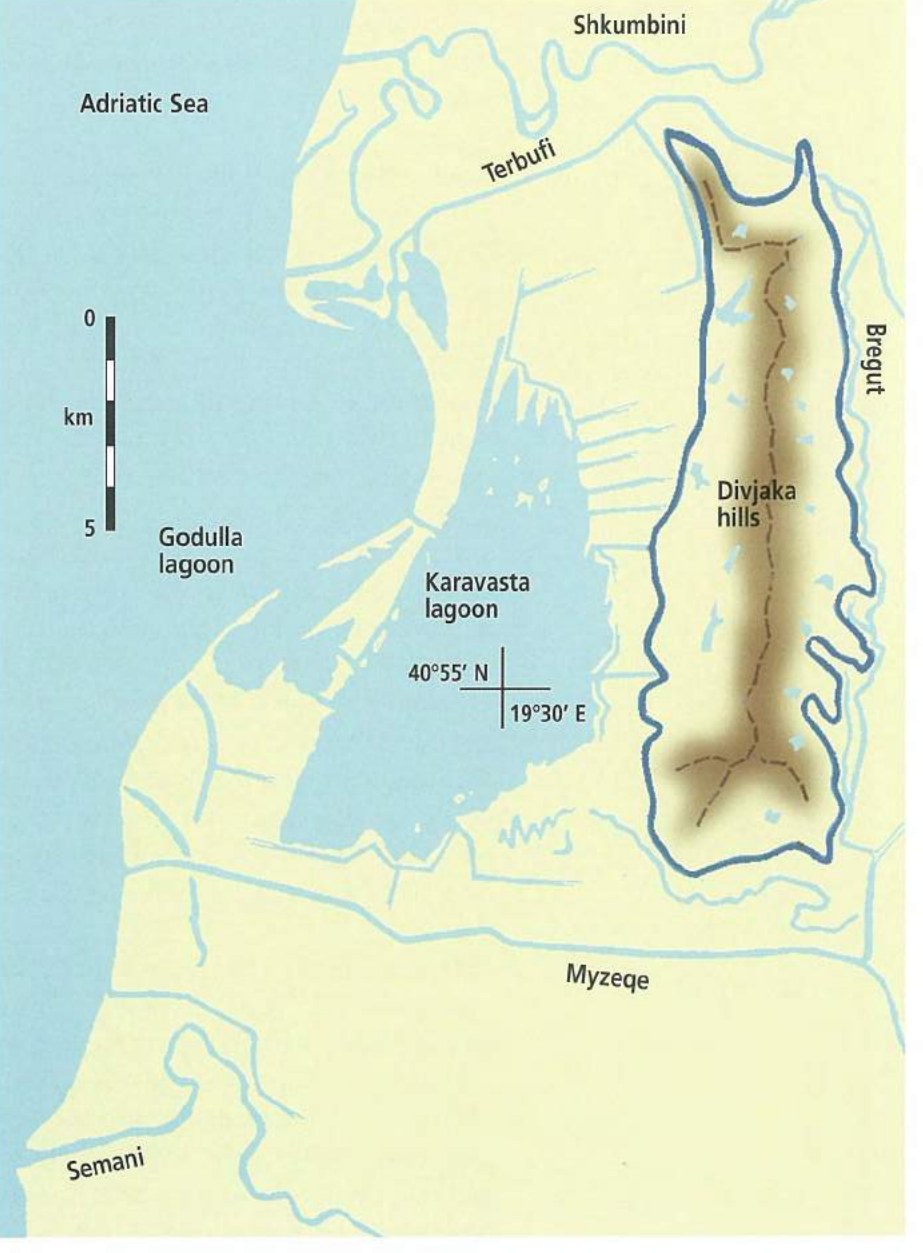
The numerous lagoons around the Mediterranean coast, covering a total of 6-700,000 hectares, are an important part of the environment supporting important fisheries and other wildlife habitats.

Although they are connected to the sea and contain saline water, they require inputs of fresh water function. This is often not appreciated by engineers and many lagoons have become starved of fresh water due to diversion of water upstream for irrigation and other uses. The integrated management of any catchment requires that all connections of flowing water are maintained from the headwaters to the coastal zone (the continuum concept), including coastal lagoons. Conserving lagoons requires an understanding of their hydrological functioning.

A lagoon is a small shallow lake adjacent to the coast and connected to the sea by a narrow channel. Their origin varies but they normally occur where a freshwater stream is prevented from reaching the sea by sand dunes and forms a lake on the landward side. The water level rises until a path to the sea is found (such as a low point in the dunes). The hydrology of the lagoon is critical to its ecological functioning. During the summer dry season, evaporation is high, fresh water flows from the land into the lagoons are low and sea water enters through the channel, hence salinity within the lagoon rises. This situation is reversed in the winter when evaporation is low and streams fill the lagoon with fresh water, lowering the salinity and discharging water from the lagoon to the sea. The outflows from the lagoon in late winter stimulate the fry of important fish species, such as mullet (*Mugil* spp.) and eels *(Anguilla anguilla)* to enter the lagoon. The warm shallow water of the lagoon is extremely productive and once inside, the fish grow and mature, feeding on organic detritus in the mud and on algae and invertebrates. They remain in the lagoon for several years and are caught in traps as they leave the lagoon. Greece alone has around 43,500 hectares of lagoon that yielded 2,000 tonnes of fish in 1981.

Subtle changes to the hydrology of the lagoon can have serious consequences. Reduced freshwater inflows result in thermal stratification (leading to low oxygen availability) and lack of dilution, which creates very high salinity. Furthermore, high concentrations of nitrates and phosphates from agricultural fertilisers leads to eutrophication (excess plant growth which uses all available oxygen). Altering the size of the channel connecting the lagoon to the sea can also have harmful impacts. At the Etang de Leucate, in the south of

France, the opening to the sea was enlarged to allow tourist boats to enter a marina. The salinity of the lagoon water rose from 30 to 38 grams per litre leading to a 75% fall in fish yields.



Karavasta lagoon supports an important fishery and habitat for rare birds such as the Dalmatian pelican. However, water management for agriculture has caused severe degradation.

Karavasta lagoon

Karavasta lagoon is Albania's first Ramsar site and lies on the Adriatic coast, some 75 kilometres south of the capital Tirana, between two river deltas (the Shkumbini and Semani).

The area around the lagoon has been completely drained for agricultural purposes, through a system of ditches, embankments and pumps. In particular, a drainage canal virtually encircles the lagoon preventing surface water from the land entering the wetland.
In addition, many small reservoirs have been built in the headwaters of the streams that flow towards the lagoon.

The lack of fresh water reaching the lagoon has two impacts. First, the salinity increases due to lack of freshwater to dilute the lagoon and second, flows of low salinity water from the lagoon to the are sea reduced, diminishing recruitment of young fish. Due to low inflows and high evaporation during the summer, Karavasta lagoon has become hyper-saline (48-58 g per litre). Water that does reach the lagoon is high in nutrients from agricultural fertilisers. A risk of hyper-eutrophication exists when temperatures reach 30°C in June. The functioning of the ecosystem is only maintained by persistent winds that re-oxygenate the water body and re-suspend sediments. The main commercial fish in the lagoon are mullet and eels, which depend on the lagoon's water and sediment qualities. The total sustainable yield is 100-150 tonnes per year. However, catches have dropped in recent years due to over-fishing and a decline in water quality. The lagoon is in desperate need of additional fresh water. A potential solution would be to divert water from the main rivers to restore the lagoon but these are heavily polluted. The preferred option is to construct marginal wetlands (such as reed beds) around the lagoon, which will remove the nutrients from the in-flowing ditches [1].

A. Crivelli

Fishing installation in Karavasta lagoon.

1 - European Commission (1996)

Deltas

Many of the large rivers that flow into the Mediterranean, including the Nile, Ebro, Rhone and Po, have extensive deltas.

Like lagoons they have often been neglected in old style management plans for the catchment upstream and have been starved of essential freshwater and sediment creating coastal erosion problems, saline intrusion, loss of agricultural land and a decline in species.
The connectivity of the river and delta is an essential part of the functioning of the catchment's ecosystem.

Deltas are formed from sediment brought down by the river from erosion upstream and deposited as the rivers energy drops on reaching the sea. The distinctive shape of the delta (which gives it its name) results from migration of the river across the deposits.
The normal process is for a delta to build outwards into the sea as more sediment arrives from the river. Often the weight of the sediment ? "results in compaction of the lower sediment layers" rather than "depresses the sea floor" and so the edge of the delta remains static, although the process of building continues. Consequently, any reduction in supply of sediment to the delta can lead to the delta degrading, retreating and subsiding into the sea, creating major problems for coastal defence engineers.


G. Marcoaldi / Bios

The Po delta.

Deltas provide rich agricultural land and many have been converted to rice cultivation. Some 65% of the Ebro delta in Spain is now under rice cultivation and only 20% is natural (10% sandy environments, 5% lagoons and 5% marshes). Nevertheless, the Ebro delta is still rich biologically, providing a permanent or temporary home for around 180,000 birds including 330 species, 81 of which breed regularly and 28 do so occasionally. Until the creation of the National Park on the delta in 1986, hunting was a major activity with between 35,000 and 50,000 birds shot per year. However, maintenance of the delta, whether for wildlife or agriculture, requires the input of freshwater and sediment. The construction of dams along the Ebro (culminating in two major reservoirs at the end of the 1960s: the Mequinenza and Ribarroja) has significantly reduced flows and sediment input has declined to 1% of its original volume. The delta has stopped growing,

Effects of the Aswan dam on the River Nile

The high dam at Aswan on the River Nile in Egypt was completed in 1968. Its primary purpose was to provide irrigation water and the area of irrigated land was increased by 0.5 million hectares between 1970 and 1990, helping to feed the rapidly expanding population which rose from 30 to 52 million in same period.

In addition generators were installed with a capacity of 2,100 megawatts, which allowed industrial expansion. Water in the Aswan dam is drawn down at the start of the wet season to allow sufficient storage of flood water.

However, this starves the floodplain and delta of sediment and nutrients. The loss of soil fertility has had to be compensated by an annual application of 13,000 tonnes of lime-nitrate fertiliser, which has polluted both surface and groundwater. Nutrients brought to the sea by the river supported a rich sardine fishery, but since construction of the dam, fish catches have declined from 22,618 million tonnes in 1968 to only 13,450 million tonnes in 1980 and catches are still falling. Fish populations have also declined in the lower Nile.
Of the 47 commercial species present in 1948, only 17 now exist.

The Nile delta is composed of sediment brought down by the river. The reduction in silt load has certainly contributed to recent retreat of the delta by some 2 km between 1971 and 1988. But the geomorphological history of the delta is complex and the relationship not simple.

Nevertheless, coastal protection works have, and will continue to cost, millions of dollars per year. Because of reduced freshwater flows and over-pumping of groundwater, saltwater has intruded into the aquifers underlying the delta to 30 km inland, contaminating sources of drinking and irrigation water.

1 - Biswas (1991)

but subsidence and sea-level rise are continuing. It is anticipated that the relative sea-level will be 0.7 metres higher by the year 2100, submerging approximately 50% of the delta beneath the sea. Even if agricultural areas are protected by embankments, water logging and salt water intrusion will be major problems.

Similar problems to those being experienced in the Ebro delta are feared for the Goksu delta in southern Turkey. At present the Goksu river is currently one of the few remaining un-dammed and un-canalised major rivers in Turkey with a delta of substantial ecological importance. Infiltration through the bed of the river helps replenish the groundwater resources of the delta. The delta itself is home for 327 different local and migratory bird species (including 12 globally threatened species) as well as valuable coastal fisheries. It receives about 1,000,000 visitor days per year and 80% of the population is employed in agriculture (mainly rice, wheat, fruits, vegetables and flowers). Amongst the many development schemes proposed for the Goksu catchment, the Kayraktepe dam poses the greatest threat to the river and its delta. The dam will impede water, sediment and nutrient flows to the river resulting in erosion of the delta.

The Göksu river, Turkey, one of the last mediterranean river without dams.

A. Crivelli

The delta at the mouth of the River Indus delta in Pakistan has many functions and products, in which the mangrove trees play a vital role[1]. By breaking the force of wind and waves, they protect the coast and Port Qasim from damage. Wave height can reach six metres in the open sea beyond the mangroves, but in the sheltered creeks the maximum recorded height has been 0.5 metres. Mangroves also stabilise creek banks, which maintains channel width. This focuses the currents, reducing sedimentation by encouraging scouring of the channel bed. The creeks are thus self-cleaning and able to maintain their geometry naturally. Without mangroves Port Qasim would need expensive engineering works such as sea walls and constant dredging costing around US$ 1 per cubic metre and thus would not be economical. The mangroves also support extensive fisheries. In 1988, 29,000 tonnes of shrimps were landed making up 68% of Pakistan's US$ 100 million fish export. Inhabitants of the delta harvest leaves for cattle fodder which are very nutritious and branches for fuel wood exceeding 18,000 tonnes per year. In addition the delta has a very diverse wildlife ranging from crabs to dolphins and herons and has a high tourist potential. However, the mangrove ecosystem relies on inputs of fresh water and sediment from the Indus river, both of which have been reduced drastically by construction of dams and irrigation schemes upstream, leading to degradation of the delta. These findings reinforce earlier global assessments of mangrove forests worldwide that indicate the complexity and productivity of coastal wetlands increases with high freshwater availability[2]. The Indus Water Accord, signed in 1991, detailed the agreed distribution of Indus water between the provinces and that which would be released to the delta. A figure of 10 million acre feet (MAF) per year (equivalent to 390 m^3sec^{-1}) was thought to be "optimal". However, it was never specified how this water would be distributed during the year; whether it should be a constant low flow or a short duration flood peak. In reality, large floods cannot be totally controlled upstream and they lead to relatively high flows to the delta at certain times. However, in non-flood years the delta may receive almost no fresh water.

It is clear that deltas perform important functions and provide valuable resource. However, these can only be conserved by maintaining flows of fresh water and sediment from the catchment to the delta. Engineering works that break this connection can lead to degradation. Restoring freshwater flows and sediment delivery to a delta can be part of the new paradigm producing a sustainable solution to current problems, such as coastal erosion and saltwater intrusion – thus working with nature rather than against it.

1 - Meynell & Qureshi (1995)
2 - Lugo & Snedaker (1974)

In-shore wetlands

At the 1993 workshop on the water resources of the Zambezi[1], there was a consensus amongst the engineers that water which was not harnessed for production or human use was a "waste", particularly water which reaches the sea.

The idea that water is wasted if not harnessed is not new, Napoleon said that "if I were to rule a country like Egypt, not a single drop of water would be allowed to flow into the Mediterranean". However, the value of many coastal wetlands is directly proportional to the freshwater inflows. For instance, fresh water from the Zambezi supports extensive inshore fisheries on the Sofala bank at the mouth of the river. This provides Mozambique with an important source of foreign income worth some US$ 50-60 million per year. Shrimp abundance is directly related to wet season freshwater runoff and earnings could be increased by US$ 10 million per year by correctly releasing flood waters from the Cahora Bassa dam which are not currently utilised[2].

Likewise, a positive relationship between freshwater runoff and shrimp production was found for the Tortugas grounds off the Florida peninsula of USA[3]. These estuarine wetlands receive water from the Everglades National Parks and further demonstrate the close link between ecosystems through the hydrological cycle.

Ensuring freshwater flows to all parts of the catchment, including lagoons, deltas and the coast, is part of sustainable catchment management in the new paradigm of working with nature rather than against it.

1 - Matiza et al (1995)
2 - Gamelsrød (1992)
3 - Newbold & Mountford (1997)

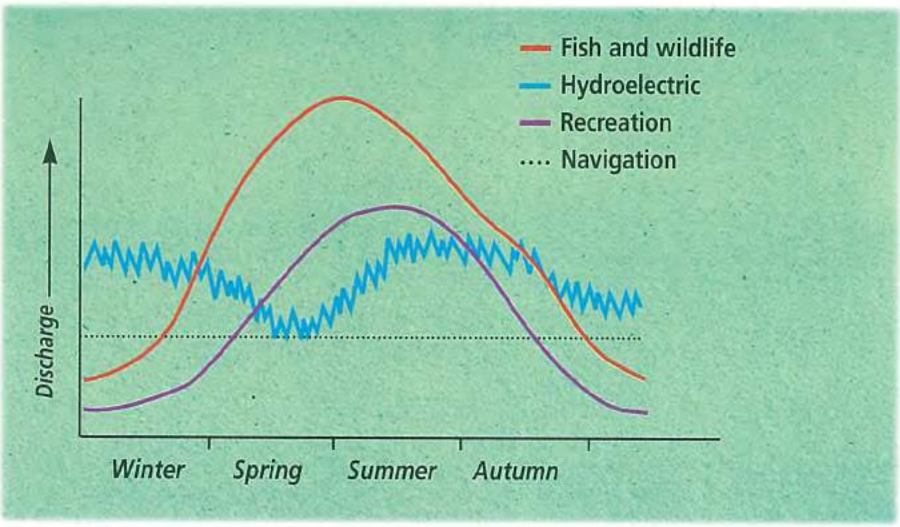
Rivers and floodplains

River engineers are often faced with the difficult challenge of satisfying competing uses of rivers.

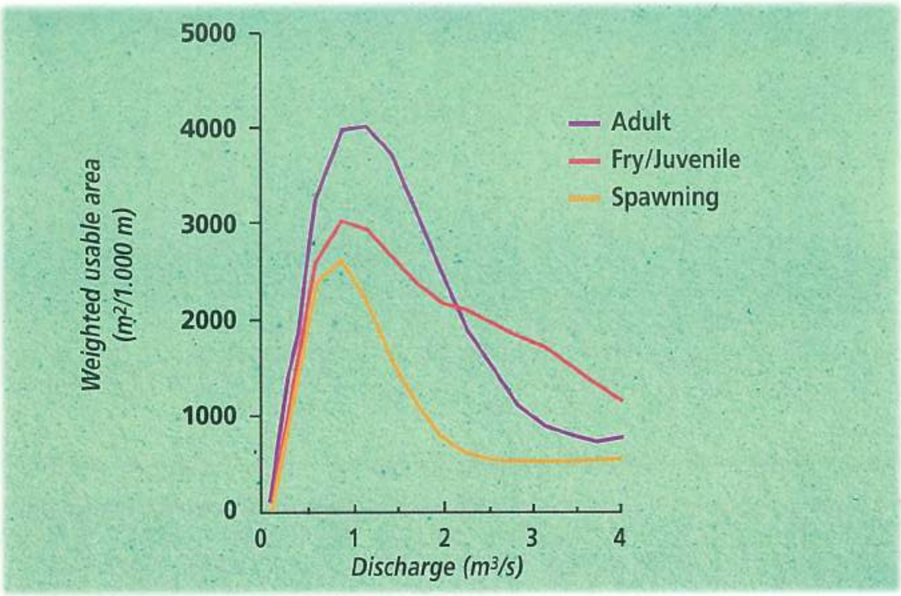
The expertise of the engineer has been in optimising a river's ability to evacuate flood water, dilute effluent, supply water to agriculture, industry and the public, produce a navigation route and, at times, form a natural protective barrier in times of war.

But clean water alone does not produce healthy river, the river is a living system, whose natural processes maintain the channel structure and its ability to recycle waste such as sewage effluent and agricultural fertilizers. The new paradigm of working with nature rather than against it requires that the ecosystem be maintained.

The water needs of riverine ecosystems and their various component species is a complex issue that has been the subject of considerable study world-wide. The acacia trees in the riverine forests of the Indus river valley require inundation from flood water for their moisture, which also brings important nutrients. At least in their early stages of growth, the trees must be flooded for at least 10 days per year. Once acacias are about 8-10 years old their roots are normally able to reach the permanent water table. Common reeds *(Phragmites australis)* on the other hand require water-logged soils, but can tolerate short periods of drying[2]. Some species have specific requirements during particular life stages. The Palla fish of Asia, for example, requires a minimum depth of 1.8 metres for breeding.



River flows vary accordingly to the use of the river. A natural flow hydrograph, with a period of floods and low flows is required to support fish and other wildlife. For recreation (such as boating and general amenity) lower flows are acceptable, whereas for navigation of major ships a constant water level is ideal. If the river is dammed for hydro-power generation, the flow regime becomes radically different. Allocating water within a specific river, to reconcile conflicting uses, is a major issue facing catchment planners.



The graph shows changes in stream physical habitat (indexed by weighted useable area) with flow for the different life stages (adult, fry/juvenile and spawning) of brown trout (Salmo trutta) in the River Allen, a groundwater fed river in southern England. In all cases the relationship between physical habitat and discharge is non-linear with habitat availability peaking at approximately $1m^3s^{-1}$. At discharges above and below this level, physical habitat availability declines[1].

Research by the US Fish and Wildlife Service on the flow requirements of riverine species led to the development of a computer-based system called PHABSIM (Physical Habitat Simulation) that relates river flow to the requirements of certain species, such as fish. Many species have preferences for certain physical conditions within the river, such as water depth or flow velocity. This preference may change as the individual grows. Any change in these characteristics, say a reduction in depth, therefore produces a direct change in the available habitat for this species. Hydraulic models within PHABSIM, which require calibration using field measurements, determine the spatial variation in depth and velocity and predict how these change with flow.

M. Acreman

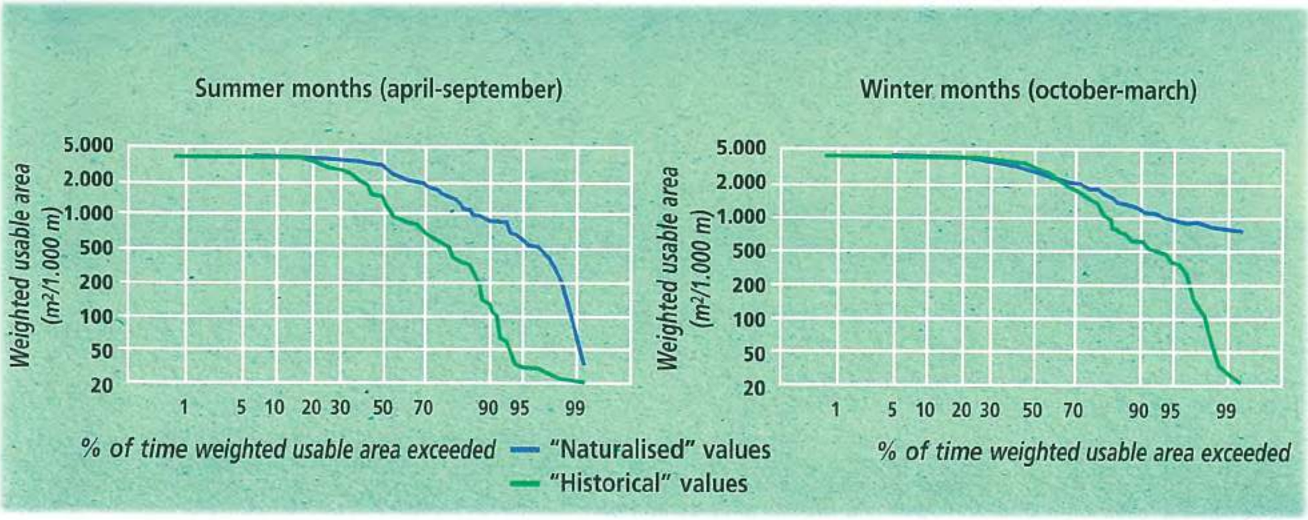
Application of hydro-ecological models, such as PHABSIM, require collection of substantial field data.

1 - Johnson et al (1993)
2 - Newbold & Mountford (1997)

PHABSIM has been used to estimate the ecological effects (in terms of available physical habitat) for historical or future anticipated changes in flow caused by abstraction or dam construction. The method has been adapted for use in many countries including France, UK, Norway, Canada, Austria and New Zealand. Clearly a method like PHABSIM is appropriate for species which are very sensitive to river flows, such as drift feeding species (like salmon and trout). There is some evidence that if the flow conditions are suitable for these species, they will also be suitable for species less sensitive to flow. Thus salmon and trout have been considered as indicator species for setting river flow requirements.

More generalised methods have been developed to establish river flow needs based on expert opinion and stakeholder views. New South Wales, Australia, has a climate similar to many parts of the Mediterranean having an average annual rainfall of around 500 mm, concentrated in the winter months. Water from the major rivers, such as the Murray and Murrumbidgee, supports a major irrigation industry in an otherwise arid area, where many river reaches naturally dry-up in the summer. The NSW Government has recognised that the long-term economic viability of the region depends on the continued health of the rivers. In recent years, algal blooms have increased and native fish numbers have declined, whilst alien species have invaded. So the government has introduced new reforms to allocate water sharing between direct water users and the environment, but to achieve this through local community involvement. From an average annual flow in the Lachlan River of 1,300 million m³, 60% of which occurs in four months (June to September), 20 million m³ has been allocated to a "High Security Environmental Contingency". The Lachlan catchment

Habitat duration curves, illustrating the time that given levels of habitat are equalled or exceeded during the time periods assessed. These curves are presented for the predicted habitat availability under actual (i.e. with flow levels artificially reduced) and naturalised conditions (i.e. with the artificial influence on flow removed – in this case by using a groundwater flow model). They demonstrate how physical habitat is reduced. In this case, for the brown trout at the fry and juvenile stages under summer low flow conditions in particular. This is of particular relevance to this species, where a lack of habitat for a particular life stage at a critical time of year means that the overall population of that species is limited [1].



1 - *Johnson et al (1993)*

M. Acreman

Floodplain, Burkina Faso.

has three storage dams whose capacity totals 1,406 million m³. Water is released from the dams at different times of the year to achieve a range of river flow objectives that include:

- protecting natural water levels in river pools and wetlands during periods of no flow;
- maintaining or restoring the natural inundation patterns and distribution of floodwaters supporting natural wetland and floodplain ecosystems;
- mimicking or maintaining the natural flow variability in all streams.

The problem is that the precise link between flow patterns and the objectives (reducing algal blooms, conserving native fish species) is not known. Rather a system of adaptive management is undertaken where different flow regime options are tested under the stringent constraints of water availability.

In some environments, it is clear that the main priority is to conserve the flooding regime of a river. Studies of the Hadejia-Nguru floodplain in northern Nigeria[1] showed the importance of the floodplain inundation in maintaining fisheries, wetland forests and agricultural land. However, flooding had been greatly diminished by the construction of major dams upstream of the wetlands, from which water is diverted to support intensive cereal production. Economic analysis of the wetlands and of the Kano River project[2], one of the major irrigation schemes, showed that the net economic benefits of the wetland were at least US$ 32 per 1,000 m³ of water (at 1989 exchange rates), whereas the returns from the crops grown on the

1 - Hollis et al (1996)
2 - Barbier et al (1991)

Kano river project were only US$ 0.15 per 1,000 m³. When the operational costs were included, this drops to only US$ 0.0026 per 1,000 m³!

This analysis did not include the value of hydrological functions of the wetlands, including groundwater recharge. Since it had been demonstrated that water was more efficiently used in the wetlands than for intensive irrigation, representatives from the responsible authorities including state water boards, River Basin Development Authorities and government departments met to discuss options. They agreed unanimously that artificial flooding should have a central role in the integrated development of the catchment. One of the main recommendations was that "flooding in the wetlands made possible by artificial releases from dams in the wet season should be maintained to make possible the production of rice, dry season agriculture, fuelwood, timber, fish, wildlife, as well as biodiversity and groundwater recharge"[1].

Few dams have been constructed with the capability of making large-scale releases to create artificial floods. Even those that can pass large quantities of water still trap a major proportion of sediment. Water

Many species of fish spawn only on inundated floodplains.

M. Acreman

1 - HNWCP/NIPSS (1993)

Defining a target flow regime

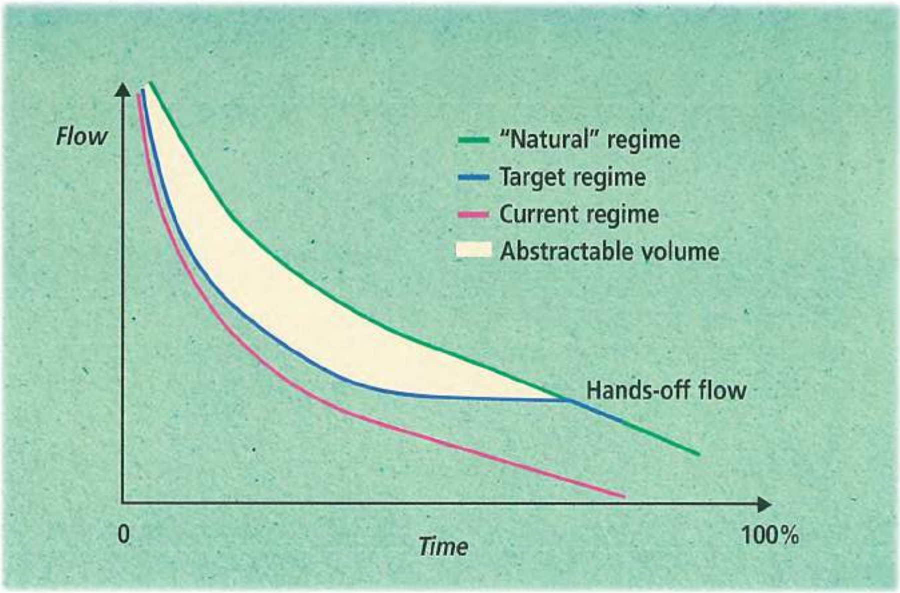
A method for defining a target flow regime has been developed[1] that allowed for the needs of abstractors, but maintained high flows to flush out sediment and low flows to conserve fish habitat. They recognised that river flows vary naturally, from floods to completely dry river beds. Consequently a target flow regime must be specified in a statistical framework e.g. the river would be expected to dry-up naturally once every two years for three months.

The flow duration curve is a tool used by hydrologists to describe the relationship between flow magnitude and the amount of time that flow is equalled or exceeded. The natural flow duration curve for a hypothetical river is shown by the solid line below[2].

The target flow regime objective can be defined in terms of a new flow duration curve. Hydro-ecological models, such as PHABSIM hydro-ecological models have been used to define a range of critical flows.

Threshold ecological flow* – which sustains minimum habitat to keep target species alive

- Adequate ecological flow – which sustains low flow habitat for target species
- Desirable ecological flow – which sustains connectivity between all reaches of the river for target species
- Optimum ecological flow – which maximises usable habitat for target species
- Channel maintenance flow – which maintains and cleans silt from the channel



Natural, current and target flow duration curves for a hypothetical river. The difference between the natural and target curves defines the volume that can be abstracted. It is noteworthy that the target curve joins the natural curve. If the flow is at or below this level, no abstraction of water should take place. It is sometimes called a "hands-off flow"[2]

1 - Petts et al (1996)
2 - from Evans (1997)

Digging a well en Cameroon.

released from a reservoir may also be very different in character to that normally found in a river, for example it is often much colder and nutrient-poor. Consequently, although there is opportunity to manage dams in a more environmentally-friendly manner in the future, there are still major constraints on conserving or restoring downstream ecosystems.

Conclusions

An understanding of the hydrological cycle is fundamental to the management of water resources and the aquatic environment.

The Mediterranean is characterised by strong seasonal variations in hydrology (warm wet winters and hot dry summers) but rainfall and temperature, and hence evaporation, river flows, sediment movement, recharge to groundwater and water availability, vary greatly from year to year. In extreme cases the entire year's rainfall may arrive in a few torrential storms. In attempts to reduce floods and make water supply more reliable for agricultural, domestic and industrial users, water engineers have sought ever-increasing control of the hydrological

The building of the "Trois gorges" dam in China is a good example of what should not be done.

J. Roché

Flood in the Kizilirmak river, Turkey.

cycle. The Mediterranean region now possesses thousands of dams, embankments, diversions and inter-catchment transfers. Whilst these "hard engineering" solutions have had many short-term benefits, they tend to work against nature in solving hydrological problems, thus they may not be sustainable in the long term. They have had many negative consequences on the natural environment including loss of fisheries, coastal erosion in deltas and even worsening the impact of major floods.

Over the past few decades, there has been increasing awareness of the importance of wetlands and other natural systems. Not only do they support valuable fisheries, waterfowl and provide a lucrative tourist attraction, but many play a crucial role in the hydrological cycle, reducing floods, absorbing pollutants, improving water quality and performing groundwater recharge. As a result of the increasing awareness of the vital role of ecosystem functions, a new paradigm has developed where sustainable solutions are sought that work with

• Design team	Approximate era
• Engineers	• pre World War II
• Engineers + economists	• post World War II
• Engs + economists + environmental specialists	• late 1970s
• Engs + economists + environmentalists + sociologists	• late 1980s
• Engs + economists + environmentalists + sociologists + affected people	• early 1990s
• Engs + economists + environmentalists + sociologists + affected people + NGOs	• mid 1990
• Engs + economists + environmentalists + sociologists + affected people + NGOs + public acceptance	• early 2000s

Evolution of groups involved in the planning of water development projects in developed countries[1].

1 - After Goodland (1997)

nature rather than against it. In some cases now, environmental specialists are employed in water planning and options development to complement the traditional skills of the engineer.

Engineers are beginning to recognise the benefits of the ecologist's view of the river as a living system. This includes the linking of upstream-downstream elements of the catchment from headwater wetlands to estuaries, deltas and coastal lagoons ("the river continuum concept"). It also encompasses the lateral links between the river and riparian wetlands and views floodplain inundation as the driving force for river life (the "flood pulse concept"). At the same time ecologists are starting to understand the problems and constraints faced by engineers when solving difficult issues under tight financial and time

An integrated approach

Many different government departments and agencies have an interest in water and wetland resources including those responsible for irrigation, energy, fisheries, navigation, flood defence, environment and water resources.

In addition there are many non-governmental groups, such as local conservation clubs, private industry, farmers' co-operatives and recreation (fishing, sailing) clubs, all of who have a stake in water and the wetland environment. The tradition has been for each sector to work separately, following its own goals and objectives, which may be in conflict with other sectors. Furthermore, development projects are often focused in one part of the catchment, without due regard for impacts upstream or downstream.

The great benefit of wetlands is that they cut across many sectors, providing water resources, flood protection and wildlife habitat at the same time, across a whole catchment.

However, wetland conservation may be difficult to justify in individual sector projects, hence the need for a holistic and integrated approach. Holistic, through considering the whole catchment, so that developments in one part of the catchment are not adversely impacting on other parts. Integrated, so that the total benefit to all sectors is realised.

The responsibility for water developments (public water supply, irrigation, flood control) has primarily been with engineers who are trained in construction techniques and normally seek a structural solution to problems, such as building dams, diversions and embankments. They need to receive a broader education, which includes the hydrological functions of wetlands, so that the opportunities for the use of natural systems can be more fully exploited. In addition, planners and decision-makers should be exposed at a general level to wetland functions and how to make best use of wetland science to underpin sound policy development and decision making.

Pumping well water in a village in Cameroon.

constraints. The search for sustainable options for hydrological management requires the closer co-operation between engineers, ecologists and other disciplines, such as geomorphologists, economists, sociologists and the views of local communities.

Historically, planners and policy-makers have considered forestry, agriculture, industry, housing and wildlife conservation as legitimate land uses. The hydrological impact of such land uses (whether positive or negative) has only been a secondary consideration. In a water-stressed region, such as the Mediterranean, water management should be viewed as a legitimate land use. That is to say, areas of the catchment, such as wetlands and headwater forests, can be managed primarily to achieve their potential for improving the hydrological cycle for the benefit of man.

To achieve sound hydrological management the following should be considered:

- Planning and management at the catchment-scale, including coastal zones, deltas, lagoons and, inter-tidal mudflats
- Involve all stakeholders in the process, including water agencies, local authorities, non-governmental organisations and, local communities
- Make all hydrological data available to all stakeholders so that an open debate on water allocation can be achieved

- Undertake data collection and research on the hydrological cycle in the Mediterranean to understand fully the natural variability and impacts caused by man, including climate change

- Train engineers to appreciate the natural hydrological functions of wetlands and other ecosystems and train ecologists to understand the practical problems of water management faced by engineers.

- Ensure that all water users, including ecosystems are considered equitably when allocating water, which may mean making artificial flood releases from dams.

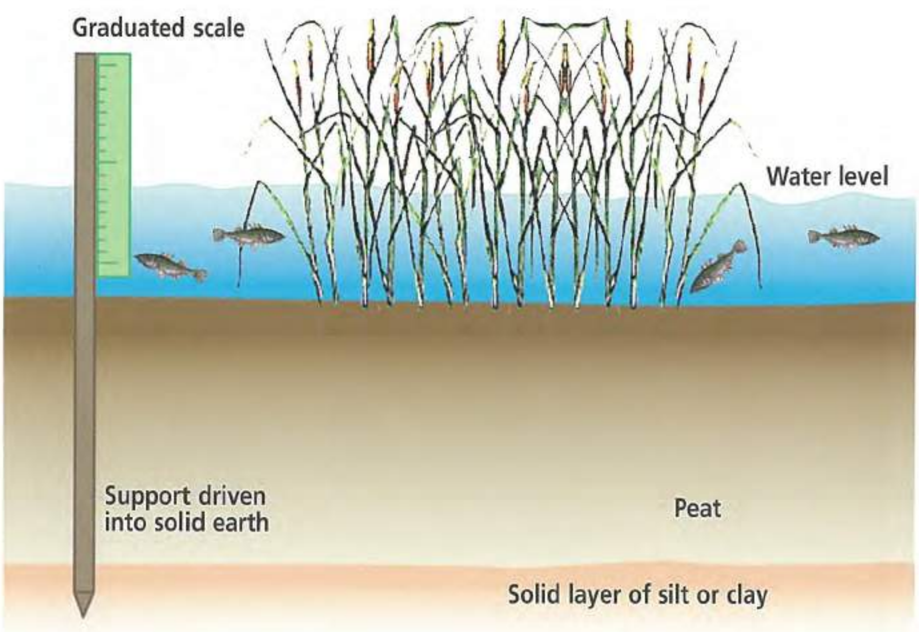
- Embrace ecological concepts such as the "river continuum concept" and the "flood-pulse concept" in hydrological management.

Annex A
Measuring the water balance

Surface waters

The measurement of stored water within a wetland is very important. Volume can not be calculated directly, but is determined indirectly. By topographic survey of the wetland, the relationship between water level and volume of water can be derived. This is called a hypsometric curve*. The curve is used to calculate the total volume given a water level (or change in volume given two successive water levels). The curve must be checked periodically in wetlands where sedimentation changes the topography, as occurs, for example in the Sebkhet Kelbia wetland in Tunisia (see figure page 45).

Water levels in open water can be easily measured using a simple graduated board securely mounted on a post anchored to firm substrate. A problem with wetlands is often the lack of firm ground close to open water. It is well known, for example, that peat expands and contracts according to its water content and thus ground level rises and falls. It is therefore essential that the level of the staff gauge is checked against a near-by fixed datum point. In some wetlands,



Water level in a wetland needs to be related to a fixed datum. The ground surface in a wetland may rise and fall depending on the moisture content. In this case, the water level board must be planted into bed-rock or a solid soil layer.

water levels vary in different parts of the system, in which case it is necessary to make measurements in several locations.

An alternative approach to estimating the volume of water is to record the areal extent of flooding from satellite images or aerial photographs and apply an average depth (calculated from a number of field measurements) to estimate water volume stored in the wetland. This particularly appropriate to large or very complex wetlands. This approach was used in the Sudd wetland of Sudan[1] and in the Hadejia-Nguru wetlands of Nigeria[2]. An automated approach to estimating surface water area, called SHYLOC (System for HYdrology using Land Observation for model Calibration) has been developed[3] for use on large expanses of open water including Lake Karla in Greece and for networks of drainage ditches, for example on the North Kent Marshes in the UK.

Storage of water within the soil is monitored by the measurement of the elevation of the water table within a piezometer. This is a hole of around 5 cm diameter dug to a depth below the expected lower limit of the water table. The hole is lined with a plastic or steel tube to ensure that the water table potential is recorded at a fixed point (the lower limit of the tube). It also stops the sides collapsing. It is important to note that the level that water will stand in the piezometer is not the upper limit of saturation, but the level at which soil water pressure is equal to atmospheric pressure. The measurement of water table level cannot be easily converted to total volume of soil water, but two measurements (plus a knowledge of areal extent) can yield an estimate of change in volume which is required for water balance calculations.

Precipitation

Precipitation is the main input to the wetland water balance, whether it falls directly on the wetland or on the catchment above and arrives as stream flow or spring flow. Rainfall can be measured by a simple storage vessel, normally emptied daily. If rainfall for shorter durations is required a recording rain gauge can be used. Continuous gauges register changing water level in the gauge on a chart, whereas tipping bucket gauges records the number of tips in each hour of a small bucket (as the bucket empties itself when full) within the gauge which has a known volume, usually 0.1 mm or 0.5 mm. The gauge must be sited away from trees or buildings that can create a rain shadow, a rule of thumb for the distance is 1.5 times the height of any object. The gauge should also not be exposed to high winds, which create air turbulence around the gauge and may deflect raindrops away, leading to underestimates of rainfall. Since rainfall varies spatially, the World

1 - Sutcliffe & Parks (1987)
2 - Thompson & Hollis (1995)
3 - Shepherd et al (1997)

Meteorological Organization recommends a minimum gauge density of one gauge per 600-900 km^2 in flat areas in temperate, Mediterranean and tropical climates. Weather radars and satellites are now available to measure the spatial variation in rainfall which typically provide output in cells of 1 or 25 km^2. However, the accuracy is often low and the system requires calibration from conventional gauges. The measurement of snowfall is considerably more difficult than for rainfall. Some rain gauges are heated in winter with candles, for others the snow collected in a gauge is melted. A better method is to measure the depth of snow on the ground and to convert this to a water equivalent using the density of snow (10 cm of snow is approximately 1 cm of water).

Stream flow

Runoff into, or out of, a wetland is measured at a site by deriving a relationship between streamflow and stream water level, known as a stage-discharge rating curve. This curve is defined by making a number of measurements of flow using a current meter at various water levels and plotting these on a graph. Alternatively a structure may be built in the river, such as a weir, for which the rating curve is known theoretically. However, such structures are expensive and may interfere with migration of fish and other species. Once the curve is defined it can be used to convert water level records to flow rate. For rivers whose flow rates vary slowly, such as groundwater-fed rivers, water level can be measured daily on a staff gauge. For rivers whose flow rate varies rapidly a float connected to a chart or solid state logger is required.

Soil and groundwater

Interactions between wetlands and groundwater, whether inputs from springs or outputs via recharge, are very difficult to measure. A pragmatic approach has often been to measure the other components of the water balance and, using the concept of conservation of water volume, assume that any mis-match between volume is due to groundwater exchange.

For example, if the evaporation and stream outflow from a wetland exceed rainfall and stream inflow, the difference may be assumed to be groundwater recharge. Infiltration of water through wetland soils can be measured using an infiltrometer*. For example, 1.5 m lengths of 100 mm diameter plastic pipe were inserted vertically into the soil of the Hadejia-Nguru wetlands in Nigeria[1]. The infiltrometers were filled with water and the level measured every three days. The tops were sealed to prevent evaporation. The recorded a mean infiltration rate was around 15 mm day^{-1}.

1 - Schultz (1976)

Isotopes* can provide a useful method for measuring groundwater recharge. Isotopes are atoms of a given element (such as oxygen in water) that have a different atomic mass, but the same chemical properties. Thus although river water and groundwater may be chemically the same, their isotopes may be different and this provides a label to determine their origin. Analysis was undertaken of the concentrations of naturally occurring isotopes of hydrogen and oxygen in rain water, river water, flood water and groundwater in the Hadejia-Nguru wetlands in Nigeria[1]. Linear relationships were found between concentrations of deuterium and O18 isotopes in rainwater, floodwater and groundwater, but river water exhibited a more variable relationship. This was because "... evaporation causes deviation from a linear relationship because the hydrogen is fractionated faster than the oxygen". These findings indicated that the composition of groundwater and river water were the same only at high river levels when the floodplain wetlands were inundated. It was therefore concluded that groundwater recharge occurred during flooding of the wetlands.

Spring flow can be measured directly by constructing a water-tight chamber around the spring with an outlet, normally a V-shaped notch, for which the relationship between water level in the chamber and outflow rate is known. An alternative method is to quantify the aquifer properties that feed the spring. The specific yield of an aquifer is the volume of water that can drain freely by gravity to a spring. This can be calculated by pumping tests, which involves pumping water from a well and recording the time taken for the well to return to the same water table height.

Evaporation

Evapotranspiration includes a number of processes by which liquid water is changed into gaseous water vapour: evaporation from open water, soils and other surfaces and transpiration from plants. Evapotranspiration rates are controlled by several variables.

First, the temperature and humidity of air. Warm dry air can take up water vapour more rapidly than when cold or already moist. Second, wind speed. As evaporation takes place the air becomes saturated and less able to take more moisture. Thus the stronger the wind, the more rapidly the moist air is carried away and replaced by drier air which allows more evaporation to take place. Third, solar energy, normally measured in terms of the number of sunshine hours. The change in state of water from a liquid to a gas requires 2.47 x 106 J/kg at 10°C (590 calories per gram). Solar radiation, or sunshine, provides the total input of energy, but some of this will be absorbed by the soil and some will be reflected, leaving the balance to drive evaporation.

1 - Schultz (1976)

Fourth, moisture availability. Clearly, there may be a high potential for evaporation on a hot, dry, windy day, but if the soil is dry no evaporation will actually take place.

Transpiration rates also depend on solar energy, wind and air humidity and the ability of the plant to keep its leaves supplied with water. In 1802, Dalton defined the basic components for evaporation from open water. In 1948, Penman proposed a method, that has now become a standard, for using basic meteorological measurements to estimate evapotranspiration from "... an extended surface of short green crop, actively growing, completely shading the ground, of uniform height and not short of water". Later research developed correction factors for different crops or where water supply is limited. More recently instruments have been developed specifically for measuring evapotranspiration such as Hydra, produced by the Institute of Hydrology in the UK. Estimation of evaporation using meteorological principles thus requires the measurement of the following variables:

- air temperature – thermometer
- humidity – wet and dry bulb thermometer or hygrometer
- wind speed – anemometer
- incoming short-wave solar radiation – sunshine recorder or radiometer
- reflected long-wave radiation – radiometer
- soil temperature – thermocouple or heat flux plate

A more practical approach to the measurement of evaporation is the lysimeter*. This is an area of wetland, commonly about 10 m^2, that is isolated hydrologically from its surroundings by an impermeable layer, such as plastic sheeting. Water is pumped into or out of the lysimeter such that the soil moisture levels are equivalent to the surrounding wetland. Inputs to the lysimeter are thus rainfall and inward pumping and outputs are outward pumping and evaporation. By carefully monitoring rainfall and pumping rates, the volume of evaporation can be quantified.

A typical evaporation rate from open water may be 5 mm day^{-1} in the Mediterranean. Whilst a complete coverage of water by water lilies has been found to reduce evapotranspiration by 15%, evapotranspiration from plants that rise above the water surface (and have large surface area of leaves and stems) such as water hyacinth may exceed open evaporation by 50%)[1]. However, these rates will vary during the year, for example evapotranspiration from reeds (Phragmites) has been found to vary from 96% of open water evaporation in April to 123% in August as function of the growth stage

1 - Anderson & Idso (1985)

of the plant[1]. Some figures suggest that some evapotranspiration from some plants may be many times that of open water. This is often the case when the wetland is small and isolated within arid land. Any flow of warm, dry air from the surrounding land provides additional energy to the wetland, thus radically increasing evapotranspiration. This is called the "oasis effect".

1 - Gilman (1998)

Some published figures for evapotranspiration from different wetland plants (given as a multiple of open water evaporation)

Climate	Espèces	High growth	Low growth	Annual	Source
• Tropical savannah	*Eichhornia crassipes*	1.35	1.02	1.15	Brezny et al, 1973
	Ipomaea aquatica	1.24	1.01	1.1	Brezny et al, 1973
	Brachystegia	1.35	0.3	0.8	Balek & Perry, 1973
• Steppe	*Scriptus acutus:*	2.0	0.7	1.35	Steams & Bryan, 1925
• Desert	*Eichhornia crassipes*	1.44		1.44	Anderson & Idso, 1985
	Nymphaea	0.95		0.95	Cooley & Idso, 1985
	Tamarix galica	2.0	0.35	1.02	Turner & Halpenny, 1941
	Typha latifolia	1.62	0.77	1.18	Blaney et al, 1938
• Australia	*Typha*		0.6	0.6	Linacre et al, 1970
• Uganda	*Papyrus*		0.6	0.6	Rijks, 1969
• Central Europe	*Phragmities*	1.80	0.8	1.2	Smid, 1975
• Mediterranean	*Scirpus acutus*	1.5	1.1	1.25	Muckel & Blaney, 1945
	Scirpus acutus	1.2	2.0	1.35	Blaney & Muckel, 1955
• Humid sub-tropical	*Eichhornia crassipes*			3.2	Penfold & Earle, 1948
				3.7	Timmer & Weldon, 1967
				5.3	Rodgers & Davis, 1972
• Humid maritime	*Sedge*	0.74	0.81		Beltman, 1988
	Calamagrosits canescens	1.1	2.0	1.55	Priban & Ondok, 1980
	Phragmites australis	1.8	0.8	1.2	Smid, 1975
	Phragmites australis	2.0	1.2	1.6	Newson & Gilman, 1983
	Phragmites australis	0.96	1.23		Gilman et al, 1998
	Sphagnum	1.5	0.9	1.2	Egglesmann, 1963
	Sphagnum	1.45	0.9	1.14	Bay, 1966
	Sphagnum	2.5	2.0	2.25	Clymo, 1970
	Sphagnum	0.8	0.6	0.7	Johansson, 1974
	Typha latifolia	2.5	2.0	2.25	Kovarik, 1958
• Humid continental	*Typha*	0.8	0.7	0.75	Eisenhlor, 1979
	Thuja occidentialis	1.0	0.7	0.85	Munro, 1979

Glossary

Albedo: radiation reflectivity of a soil or vegetation surface.

Aquifer: a layer of rock containing (or able to contain) water.

Artificial flood: water released from a reservoir to create a flood downstream.

Artificial recharge: water spread over permeable soils overlying an aquifer to induce recharge.

Borehole: a vertical hole drilled to reach an aquifer through which water is pumped to the ground surface.

Climate change scenario: a possible future climate, not necessarily a prediction of scenario: what will happen.

Desertification: dryland degradation through vegetation and water loss.

Ecological flow: river flow required to maintain an aquatic species or ecosystem.

Eutrophication: high levels of nutrient leading to excess plant growth which depletes available oxygen in the water.

Evaporation: movement of water from plants, soil and open water to the atmosphere.

Flood: hydrologists' definition – a rapid rise in river level or flow general definition – inundation of normally dry land.

Flood desynchronisation: altering of the timing between rainfall and the resulting flood.

Flood frequency curve: the relationship between the size of floods and their rarity.

Flood peak: the maximum water level or flow reached during a flood.

Floodplain: flat land on the side of river inundated during high flows.

Flood pulse concept: lateral connectivity between rivers and their floodplains with the inundation of floodplains as the main driving force behind river life, not a problem that needs eradicating.

Geographical information system: a computer facility that references data according to its location.

Groundwater recharge: the movement of water to an aquifer.

Hydrological model: the characterisation of hydrological processes by mathematical equations.

Hypsometric curve: the relationship between water level and volume of water in a wetland

Infiltration capacity: the rate at which surface water can percolate into the soil.

Infiltrometer: a large tube inserted vertically into the soil and filled with water, the rate of loss of water is equal to the infiltration capacity of the soil.

Isotopes: atoms of a given element (such as oxygen in water) that have a different atomic mass, but the same chemical properties – isotopes of river water and groundwater may be different.

Low flow: river flow during an extended dry period.

Lysimeter: an area of wetland, commonly about $10m^2$, that is isolated hydrologically from its surroundings by an impermeable layer, such as plastic sheeting, so that losses can be accurately measured.

Over exploited aquifer: an aquifer from which water is abstracted at a rate that exceeds the long term recharge rate.

Piezometer: a vertical steel or plastic pipe inserted in the ground (approx 5 cm diameter), the water level within which indicates the water table level at the base of the pipe.

Precipitation: movement of water from the atmosphere to the ground, including rainfall, snow and dew.

Ramsar: short name for the Convention on Wetlands, named after the town in Iran where the convention was signed in 1972.

Ramsar sites: important wetlands designated under the Convention on Wetlands.

Residence time: the length of time water stays within the wetland.

River continuum concept: the ecosystem linkages and flows of energy upstream and downstream from a river's source to the coastal zone.

Sediment delivery ratio: the proportion of material eroded from a catchment that reaches a river.

Special Protection Areas: areas important for the conservation of wildlife designated under the EC Directive 79/409.

Turnover rate: the time taken for the entire volume of water in a wetland to be changed can be calculated.

Water balance: the accounting of water volumes (as ice, water or water vapour) within the hydrological cycle using the principle that no water is loss or destroyed.

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Station Biologique de la Tour du Valat

Founded in 1954 by Luc Hoffmann, the Tour du Valat biological station is a private organization, managed by the Sansouire Foundation, whose work is recognized to be in the public interest. A team of approximately 80 people devotes itself to scientific activities, the management of the domain, and conservation actions.

An effective nature conservation policy must be based on scientific knowledge obtained from rigorous research. With this necessity in mind, the Tour du Valat has set up a research program on the functioning of wetlands, and more particularly that of reedbeds, temporary marshes, and rice paddies. It is also involved in long-term studies of colonial waterbirds in the Camargue and Mediterranean region. The conservation department makes great efforts to promote the transfer of knowledge obtained by researchers and managers by developing management plans for the Mediterranean wetlands, setting up training sessions, informing and supporting policies promoting the rational management of these resources, and publishing works of popularization.

Within this context, the Tour du Valat has given itself the mission ***"of putting an end to the loss and degradation of Mediterranean wetlands and restoring them"***.

CONVENTION ON WETLANDS
CONVENTION SUR LES ZONES HUMIDES
CONVENCIÓN SOBRE LOS HUMEDALES
(Ramsar, Iran, 1971)

The Ramsar Convention

The Convention on Wetlands, signed in Ramsar, Iran, in 1971, is an intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources, as a means to achieving sustainable development throughout the world. As of March 1999, there were 114 Contracting Parties to the Convention, with 970 wetland sites, totalling 70.6 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance.

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