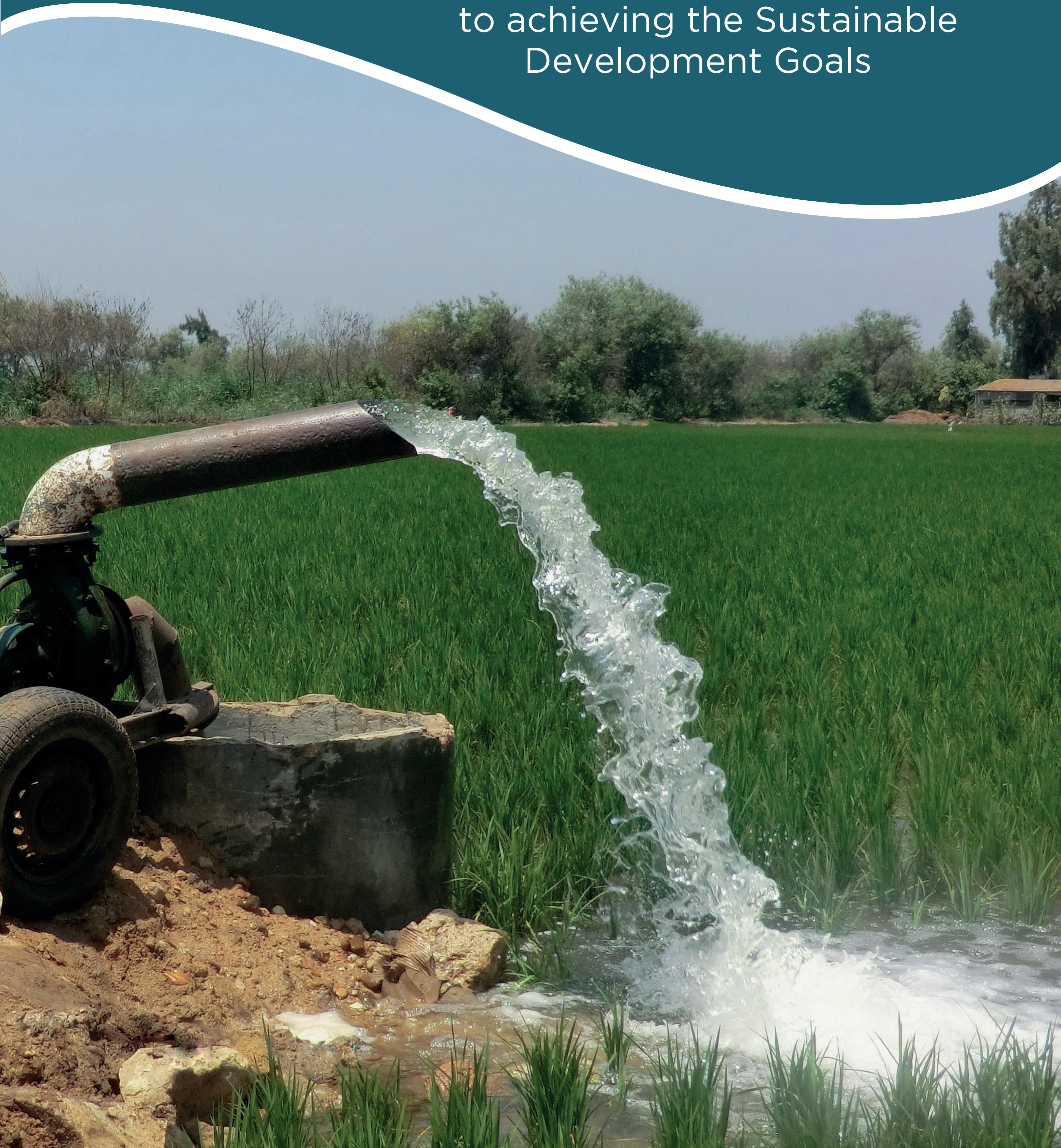
United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Hydrological
Programme

CONJUNCTIVE WATER MANAGEMENT

A powerful contribution to achieving the Sustainable Development Goals



Published in 2020 by the United Nations Educational, Scientific and Cultural Organization,
7, place de Fontenoy, 75352 Paris 07 SP, France

ISBN 978-92-3-100420-9 (print/pdf)

Photo cover: © François Molle/Flickr.com CC BY NC
Graphic design: Anna Mortreux

Printed by UNESCO

The author

Jac van der Gun is a Dutch groundwater hydrologist, professionally active since the early 1970s, mainly in water resources assessment, hydrogeological mapping, groundwater resources management, education and capacity building. He participated in numerous water-related projects, both in his native country and in a variety of countries in Latin America, Europe, Africa and Asia. In 2003 he was appointed as the first director of the International Groundwater Resources Assessment Centre.

Acknowledgments

The author and the editorial team of UNESCO's division of Water Sciences would like to express their warm gratitude to Alice Aureli, Michela Miletto, Paola Piccione, Marina Rubio, Stefano Burchi, Neno Kukuric, Marc Leblanc, Andrea Merla, Marco Petitta, Shamy Puri, Willi Struckmeier, Aurélien Dumont and Jaroslav Vrba for their contribution.

CONJUNCTIVE WATER MANAGEMENT

A powerful contribution to achieving
the Sustainable Development Goals

Preface

Sea water, atmospheric water, ice and snow cover, surface water, groundwater, soil water, water in the human water use chain and wastewater are all interconnected within the hydrological cycle. Water development planners and water resources managers should be aware of this and take it fully into account. Unfortunately, this is often not (or not yet) the case. In practice, fragmented approaches to water resources development and management prevail, in which water resources professionals tend to focus on one single water cycle component and overlook interactions with the other ones, or opportunities offered by these. This attitude – sometimes called 'hydroschizophrenia' – can be corrected by embracing the Conjunctive Water Management paradigm.

In the framework of UNESCO's Intergovernmental Hydrological Programme (IHP), and the GEF IW-Learn 4 project a number of meetings attended by water sector professionals were organized in order to explore and discuss Conjunctive Water Management.

This document intends to be an introduction to Conjunctive Water Management, with the general purpose to make the reader familiar with the concept and the specific purpose to provide guidance to water resources policy makers and planners. It starts off with defining Conjunctive Water Management, and then addresses successively the following subjects: how to put this paradigm into practice; potential benefits; governance provisions needed or desired; state of affairs of the implementation at field level; and, finally, recommendations and priorities for scaling-up.

The publication will be also a support material for the UNESCO-UNDP-GEF project on '*Fostering multi-country cooperation over Conjunctive Surface and Groundwater Management in the Bug and Neman Transboundary River Basins and the underlying aquifer system'.*

Table of Contents

1. Introduction

1.1 The water cycle and the linkages between its different components

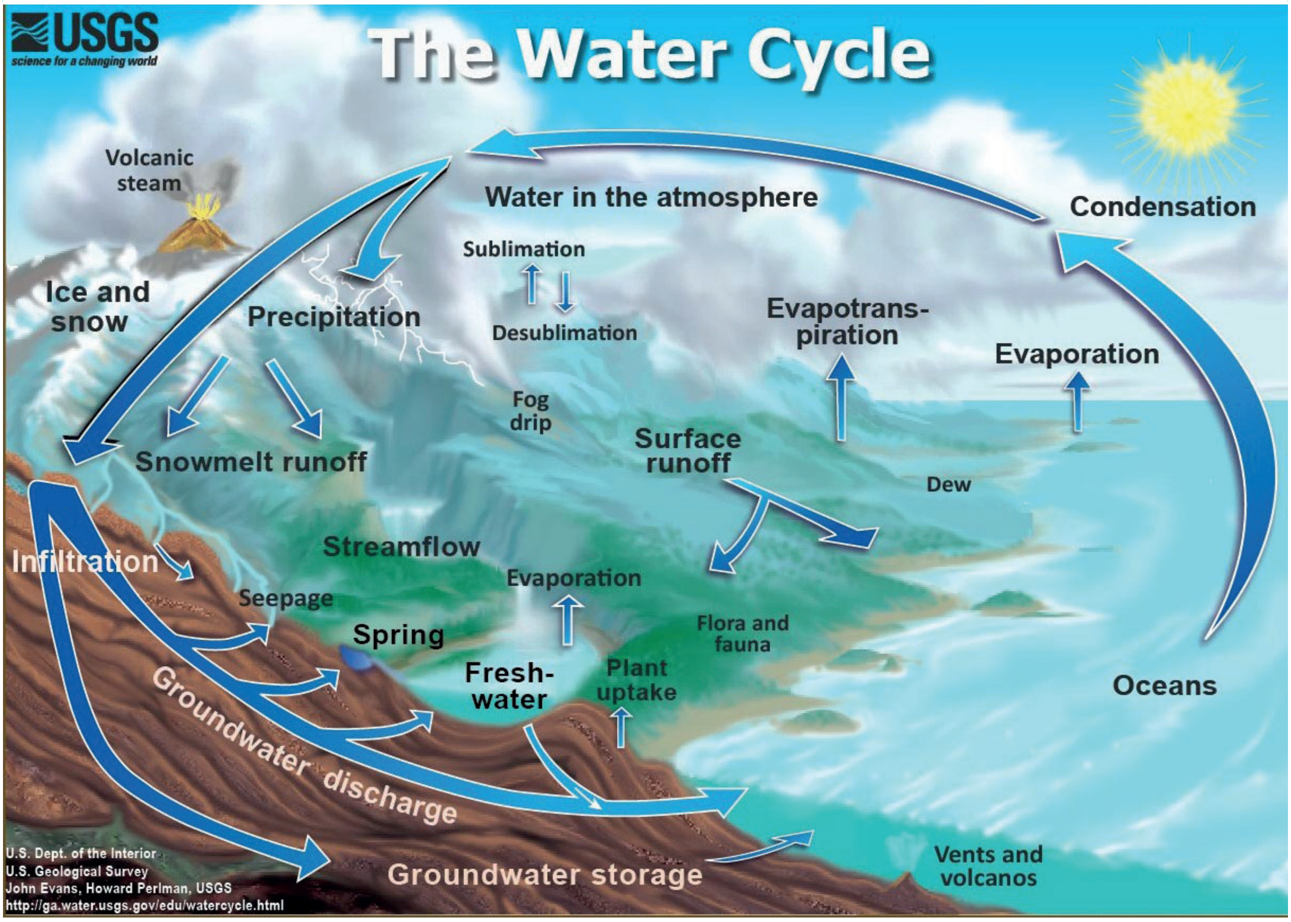
Water on our planet is present in different forms: atmospheric water (rain, snow, hail and white frost); seawater; ice and snow cover; surface water (overland flow and water in streams, lakes, reservoirs and ponds); subsurface water (soil water and groundwater); and water temporarily in the human water use chain (after use returned to the natural water system).

It needs to be emphasized that these different forms of water do not constitute different sources of water isolated from each other, but rather they are closely linked in what is called the *water cycle* (see Figure 1). Water tends to pass from one component to another, at different rates: water vapour in the atmosphere condensates and forms precipitation; precipitation on the land surface is converted to soil water, surface water and groundwater; widespread exchange of water occurs between streams, soils and aquifers; water abstracted and used by humans is returned to the terrestrial water systems discharge to the sea and by evapotranspiration directly to the atmosphere, while evaporation from the oceans forms the largest return of water to the atmosphere.

The different water cycle components are *directly linked* by their hydraulic connectivity in the natural water cycle, and *indirectly* by the human water use chain. In the latter there are often alternative water source options for meeting a certain water demand and for discharging used water; the choices made by people have repercussions for the state of each of the corresponding water cycle components.

From a water management perspective, the terrestrial waters are sometimes subdivided into so-called *'green water'* (water in the shallow, unsaturated soil zone), *'blue water'* (surface water and groundwater), *'grey water'* (wastewater without faecal contamination) and *'black water'* (sewage). Water resources development and management are primarily focusing on 'blue water', but –in spite of the linkages described above– the daily practice in most countries is characterized by a tradition of dealing with groundwater and surface water separately, without significant coordination.

Figure 1
Schematic picture of the natural water cycle (USGS, 2012)



Source: https://water.usgs.gov/edu/watercycle.html
Credit: U.S. Geological Survey

1.2 Definition of Conjunctive Water Management

Any approach to water resources management that takes the linkages within the water cycle systematically into account may be called 'Conjunctive Water Management'. The linkages can be *direct* (hydraulic connectivity in the natural water cycle) or *indirect* (human water use chain) Box 1 presents a tentative definition.

Worldwide, the stress on water resources is steadily increasing, because of population growth, urbanization, intensification of industries, agriculture and tourism, and rising economic welfare levels; and this stress is aggravated in recent years by the threats and impacts of climate change. Intelligent management of the water resources is required in order to cope with these growing challenges, and to achieve more resilience of the water systems and a higher level of water security at local and regional levels. The complexity of the water resources and their local context call for a comprehensive approach to water resources management, nowadays called Integrated Water Resources Management (IWRM, see Box 2). Among water professionals there are differences of opinion about how to interpret the designation 'integrated'. If this would imply a complete coordination at the operational level of all aspects that are in principle interrelated (both inside the water systems and beyond), then one might be sceptical about the feasibility of implementing IWRM (Biswas, 2004). Interpretation at normative and strategic levels, however, leads to a much more optimistic judgement. As emphasized by GWP (2000), certain basic principles underlying IWRM may be generally applicable, independently of the local context and the stage of economic or social development, but there is no universal blueprint as to how such principles can be put into practice.

Conjunctive Water Management is *only one dimension* of Integrated Water Resources Management – but a very import one.

Box 1
Definition of 'Conjunctive Water Management' (CWM)

Conjunctive Water Management is an approach to water resources management in which surface water, groundwater and other components of the water cycle are considered as one single resource, and therefore are managed in closest possible coordination, in order to maximize overall benefits from water at the short and at the long term.

Box 2
Integrated Water Resources Management (IWRM)

This paradigm has emerged more than half a century ago, but at the global level it is being embraced and promoted mainly since the 1990s. The Global Water Partnership (GWP) defines IWRM as "*a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*" (GWP, 2000). The IWRM concept may be considered as a useful framework and guide for broadening the approaches to water resources management (Snellen & Schrevel, 2004).

2. Putting the Conjunctive Water Management paradigm into practice

Conjunctive Water Management and its benefits will become reality only as a result of effective dedicated action. Table 1 lists typical activities and techniques to be considered for this purpose. These activities and techniques come under two main categories: those that have to play a role during area-wide water resources planning and those related to implementation at field level. At a lower level they are grouped under some tentatively defined 'immediate objectives' to clarify how they may contribute to water resources management benefits; but this classification is not rigorous, since certain activities may contribute to more than one of these immediate objectives. For example, wastewater management in the first place produces environmental benefits by the removal of pollutants, but the treated water may by recycling so to contribute to augmenting the available water resources (usually for non-potable uses). Each of these types of conjunctive management activities or techniques is briefly described below.

Table 1
Putting Conjunctive Water Management into practice: activities and techniques

At area-wide planning level	Activities and techniques at the level of implementation in the field		
Incorporating all water components	**Optimal selection of source of supply**	**Resource augmentation**	**Environmental control**
▪ Exploring and analysing hydraulic connectivities and exchanges of water ▪ Preventing 'double counting' ▪ Identifying promising opportunities ▪ Identifying hazards of harmful interaction	▪ Conjunctive use of surface water and groundwater	▪ Managed aquifer recharge (MAR) ▪ Watershed management ▪ Desalination of brackish and saline water ▪ Recycling treated wastewater	▪ Water level control in polder / low-low-lying and reclaimed areas ▪ Groundwater level control in surface water irrigated zones ▪ Restricting groundwater pumping to control surface water environmental flows ▪ Managing wastewater

2.1 Activities at area-wide planning level

Exploring and analysing hydraulic connectivities and exchanges of water

Exploring and analysing the hydraulic connectivities between surface water, groundwater and other components of the terrestrial water cycle form an indispensable first step towards Conjunctive Water Management. For each area concerned, the connectivities should be identified and the rates of water exchange between the components assessed. The underlying processes should be studied in order to enable predictions on water exchanges under modified boundary conditions.

This activity requires sufficient field data of good quality to be available, in particular monitoring data. Furthermore, it will benefit from modern tools for processing and analysis, such as Geographic Information Systems and numerical simulation models.

Avoiding 'double counting'

If surface water resources and groundwater resources in an area are assessed separately, then the sum of the outcomes overestimates the total blue water resources of the area. This is due to the exchange of water between streams and aquifers, which causes an overlap in the surface water and groundwater budgets (usually between 50 and 100% of the latter). In practice, this overlap is often overlooked, thus leading to 'double counting', which may cause a mismatch between water development planning and available water resources. Exploring and analysing the hydraulic connectivities and water exchanges properly (see the previous section) may help avoiding the erroneous practice of 'double counting'.

Identifying promising opportunities

Knowledge on the water regime within an area, including the hydraulic properties, the water quality and the time-dependent hydrologic behaviour of all water systems involved in the water cycle, will allow to identify promising opportunities for beneficial conjunctive water resources development and management. Important types of interventions are described below.

Identifying hazards of harmful interaction

Area-related knowledge may also reveal hazards of harmful interaction between different linked water systems in an area. Exploiting water from one system may have negative repercussions for another. Once the hazard has been identified, measures can be designed and implemented for mitigation or adaptation.

2.2 Specific activities and techniques for implementation at field level

Conjunctive use of surface water and groundwater

The fundamental idea behind conjunctive use is making optimal use of the available 'blue water' resources, by tapping at any moment the less costly or otherwise most attractive source or combination of sources (surface water, groundwater). This may lead to achieving benefits such as:

- higher total quantities of 'blue water' supplied and used;
- enhanced reliability of water supplies, since groundwater may act as a buffer during droughts, or as an emergency supply during and after disasters;
- lowest cost for a given water supply pattern.

Managed aquifer recharge (MAR)

Managed aquifer recharge is a strategy or group of techniques (see Figure 2) based on diverting and storing water into an aquifer, usually for its use at a later moment of time (e.g. as a buffer resource during dry seasons) or as a source of water for emergency situations (e.g. during severe long-term droughts or after accidental pollution of drinking water sources). Harvested rainwater, storm water runoff, surface water, treated wastewater and desalinised saline or brackish water are the main sources of water for managed aquifer recharge.

Potential benefits of MAR include:

- increase in the total available 'blue water' resources;
- more flexibility in the timing of using the blue water resources;

- excess surface water is prevented from being lost or from causing flooding damage;
- counteracting the encroachment of saline or brackish water into fresh groundwater bodies in coastal aquifers;
- improvement of the quality of used waters going to be recycled (e.g. by removal of suspended sediment from surface water);
- conservation of in-situ groundwater functions (e.g. maintaining ecosystems and stability of the land surface).

Important factors that are decisive for the successful application of managed aquifer recharge are: (i) the country's institutional and legal framework, (ii) access to relevant technologies and technical capacity (recharge techniques, waste water treatment technologies, professional human resources) and (iii) the presence of suitable sites characterized by a source of recharge water and an aquifer with sufficient storage capacity.

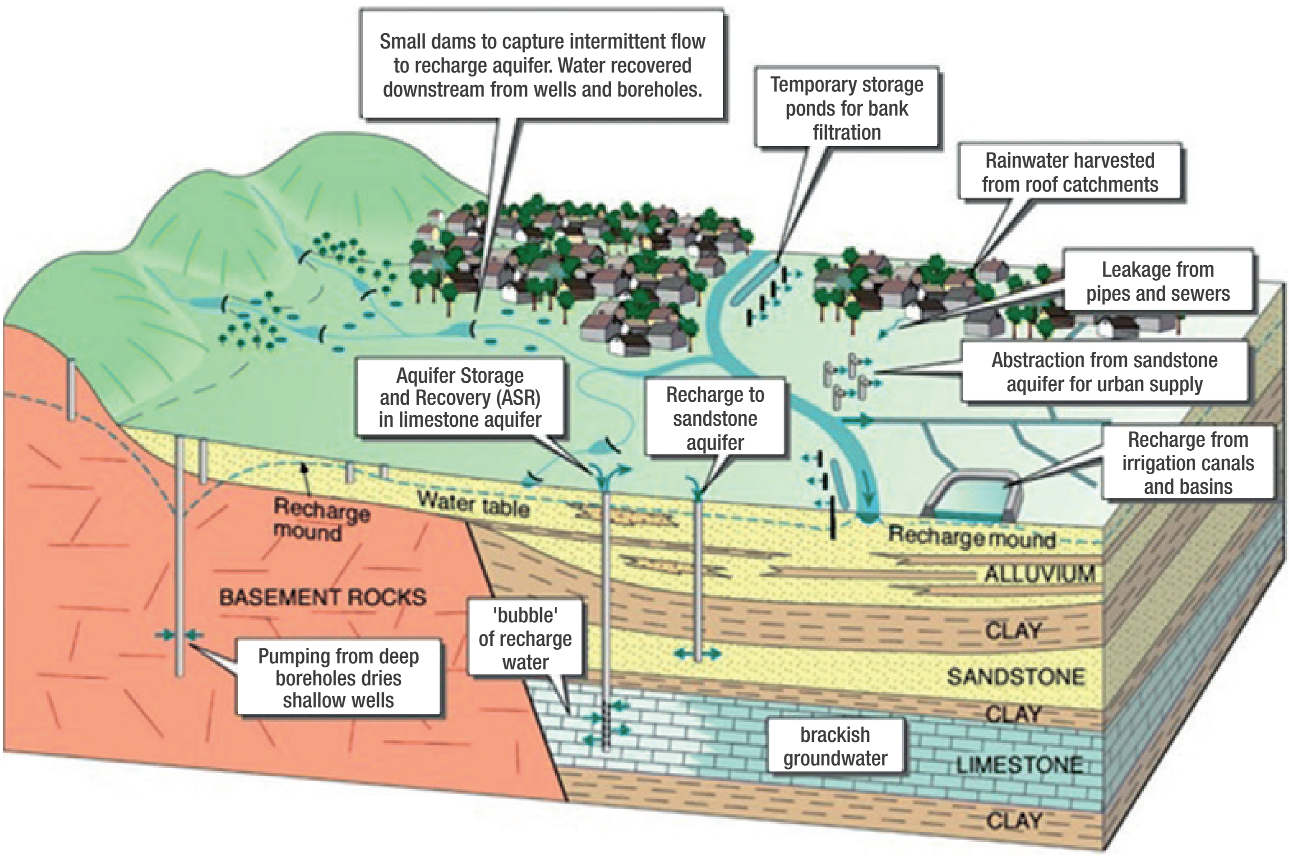
Watershed management

Watershed management aims at improving the living conditions of local communities by optimal and coherent use, protection and conservation of the land and water resources within the boundaries of hydrologically defined geographical units (watersheds). It is most often implemented in relatively small upland watersheds and may use a large variety of technical measures, usually with strong involvement of local stakeholders. Several of its technical components have in common with managed aquifer recharge that they pursue an increase in the locally usable water resources and in their availability during a larger part of the year. Watershed management, however, tends to focus less on groundwater recharge and more on soil moisture conservation by rainfall and runoff harvesting, on pollution control and on the reduction of soil erosion. Typical technical interventions include contour trenches, contour bunds, gully plugs, check dams, ponds and reservoirs, most of which intercept rain and surface water flows and convert them into soil water, groundwater and surface water storage.

Supplementing fresh-water supplies with desalinated brackish and saline water

This activity also contributes to increased water availability for supplies, and it may be particularly an option in coastal zones with limited fresh water

Figure 2
Impression of a variety of MAR techniques (Dillon et al, 2018)



resources. The quantities of desalinized water have to be monitored and carefully controlled because this water has to be included in the assessment of usable water resources in the context of Conjunctive Water Management. At greater distance to the sea, desalinised seawater becomes less attractive than desalinised local brackish groundwater, because of the considerable energy required for long-distance conveyance.

Recycling treated used water

In many areas use is made of opportunities to augment the available water resources by treating used water and recycling it for re-use, instead of dumping it to either surface water or subsurface water bodies. Usually there will be some restrictions in the purposes for which the recycled water can be used, depending on the type of treatment applied.

Water level control in polder areas

Polder areas are characterised by their flat topography, shallow water-tables and technical provisions to control these water-tables. Their overall purpose is to create and maintain optimal conditions for the current or envisaged types of land use (residential area, agriculture land, nature conservation area, industrial zone, etc.) The technical approach consists of keeping phreatic water levels at an optimum depth by manipulating water levels in the connected surface water system (ditches, canals, lakes, ponds). The most simple version is only designed for draining excess groundwater during wet periods and discharging it into connected surface water bodies). The more advanced versions – implemented for centuries already – have the additional aim to replenish groundwater and soil moisture during dry periods, by inducing inflow of water from the connected surface water bodies. In other words: they seek to maintain optimal groundwater and surface water regimes.

Groundwater level control in surface water irrigated zones

The primary purpose of surface water irrigation is to support crop growth by replenishing soil moisture, but as a side-effect it also creates or intensifies a physical link between surface water and groundwater systems. The downward percolating irrigation water losses form an additional source of groundwater recharge, which will affect the local groundwater level regime. Control of the groundwater levels requires surface water use to be planned in conjunction with groundwater management; this often leads to groundwater again being discharged into a surface water body.

Restricting groundwater pumping to maintain environmental flows

Baseflows of streams, water fluxes feeding wet ecosystems and other environmental flows may be negatively affected by groundwater abstraction. To maintain the environmental flows and functions properly, it sometimes may be necessary to restrict groundwater pumping. A Conjunctive Water Management approach is then required to define critical pumping levels.

Managing used waters and wastewater

A significant part of the volumes of water used by humans returns to the natural local water systems. It is important to ensure that these used waters and wastewater do not affect the usable fresh-water resources negatively, in terms of both water quantity and quality. In the case of irrigation, part of the applied irrigation water is bypassing the soil moisture zone and percolates downward, which under shallow-water-table conditions may lead to water-logging and eventually to soil salinity problems. As mentioned before, such problems can be controlled by draining the irrigated agricultural lands, thus triggering groundwater outflow into surface water bodies.

Most categories of water use produce wastewater, i.e. water that is more or less severely polluted. Treating this wastewater and allocating it optimally among the local water systems will reduce negative impacts (such as polluting soils and water in streams or aquifers) to a minimum. When feasible, treated wastewater may be recycled for re-use, which contributes to resource conservation and sustainability. Generally, pre-treated municipal and domestic wastewater, recharged into an aquifer, is considered a suitable source of water for irrigation and other non-potable purposes. Industrial wastewaters are often polluted by toxic components; consequently, they usually require relatively costly and technologically advanced treatment before they can be reused or safely discharged to water courses or aquifers.

3. Potential benefits of Conjunctive Water Management

3.1 More water resources available for use and lower risk of water shortages

It requires no explanation that desalination of brackish and saline water and recycling of treated wastewater contribute to increased quantities of water available for human uses. These techniques convert water unfit for most uses into usable water that satisfies certain water quality criteria.

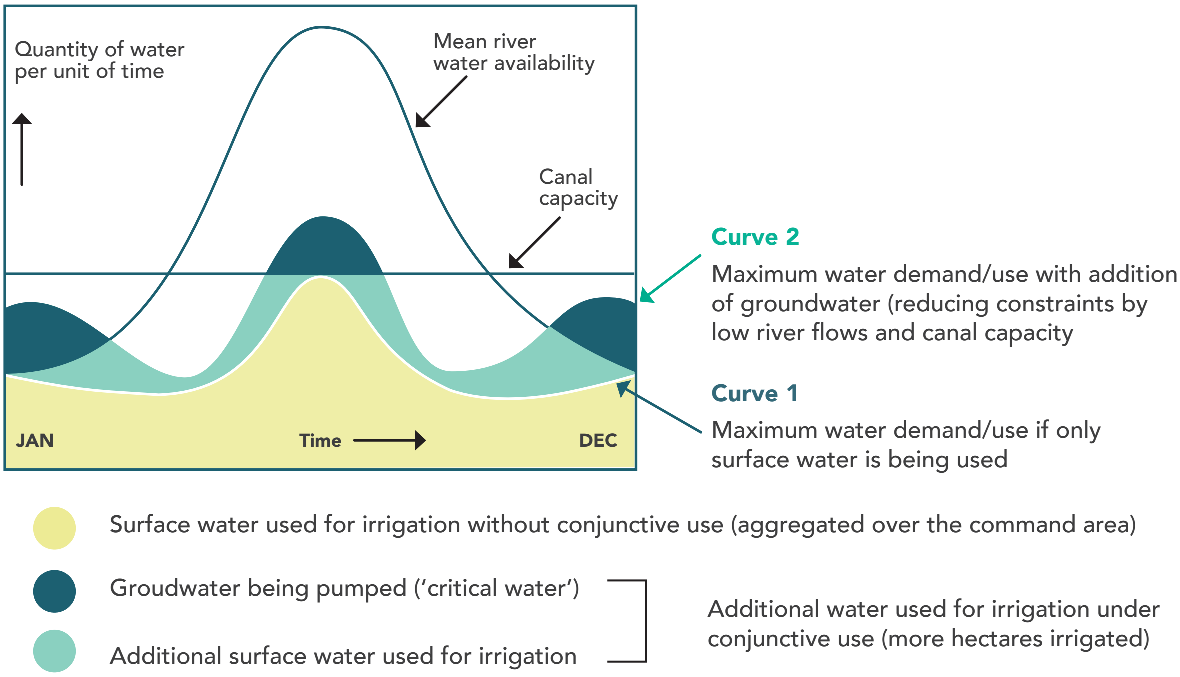
Managed aquifer recharge looks at first glance like merely rerouting water from surface water to the groundwater domains. Nevertheless, it also augments the usable quantities of water by safeguarding volumes of water that otherwise would be lost (by evaporation or outflow into the sea) and it keeps water in storage for use during critical dry periods.

Similar benefits are produced by *watershed management*. Rainfall- and runoff-harvesting, either for direct use or for augmenting soil moisture, and also small storage reservoirs, may reduce water availability downstream, but they enable the use of significant quantities of water that otherwise would be lost.

Conjunctive use of surface water and groundwater does not transfer water between these two different components of the natural water cycle, but it rather focuses at optimizing the mix of both in water use. Conjunctive use, often emerging spontaneously, pursues making maximum benefit from the strengths of each component: the usually comparatively large quantities and low development cost of surface water during wet periods and the availability and reliability of groundwater during dry spells. Experience shows that these properties lead in practice to more water being used (see Figure 3), more flexibility for the user and higher profits from water use. The latter in particular because the reliability of the groundwater component eliminates or reduces significantly the risk of unpredictable water shortages.

Combining groundwater and surface water in a single supply system (e.g. urban water supply) has the additional advantage that the system does not break down in case of pollution of surface water due to accidental release of pollutants or due to natural hazards. In such cases, additional groundwater readily can be made available as an emergency supply.

Figure 3
Graph showing how conjunctive use of surface water and groundwater in an irrigation command area may increase total water availability for irrigation (redrafted by the author after Carruthers & Stoner, 1981)



3.2 Water resources sustainability

Most of the forms of Conjunctive Water Management intend to increase the quantities of water available for human uses, either by improving water quality (by treating saline, brackish or polluted water), or by preventing that fresh terrestrial water is lost unused. Regarding the benefits of increased usable water resources there is a trade-off between their contribution to human water use and to the sustainability of water resources and related ecosystems. Water managers have to decide on the balance between these counteractive contributions. They should also be keen on the allocation to different users, e.g. when enhanced upstream water availability would reduce availability for downstream users.

Figure 4 shows schematically how Conjunctive Water Management may contribute to establishing sustainable development of intensively exploited aquifers.

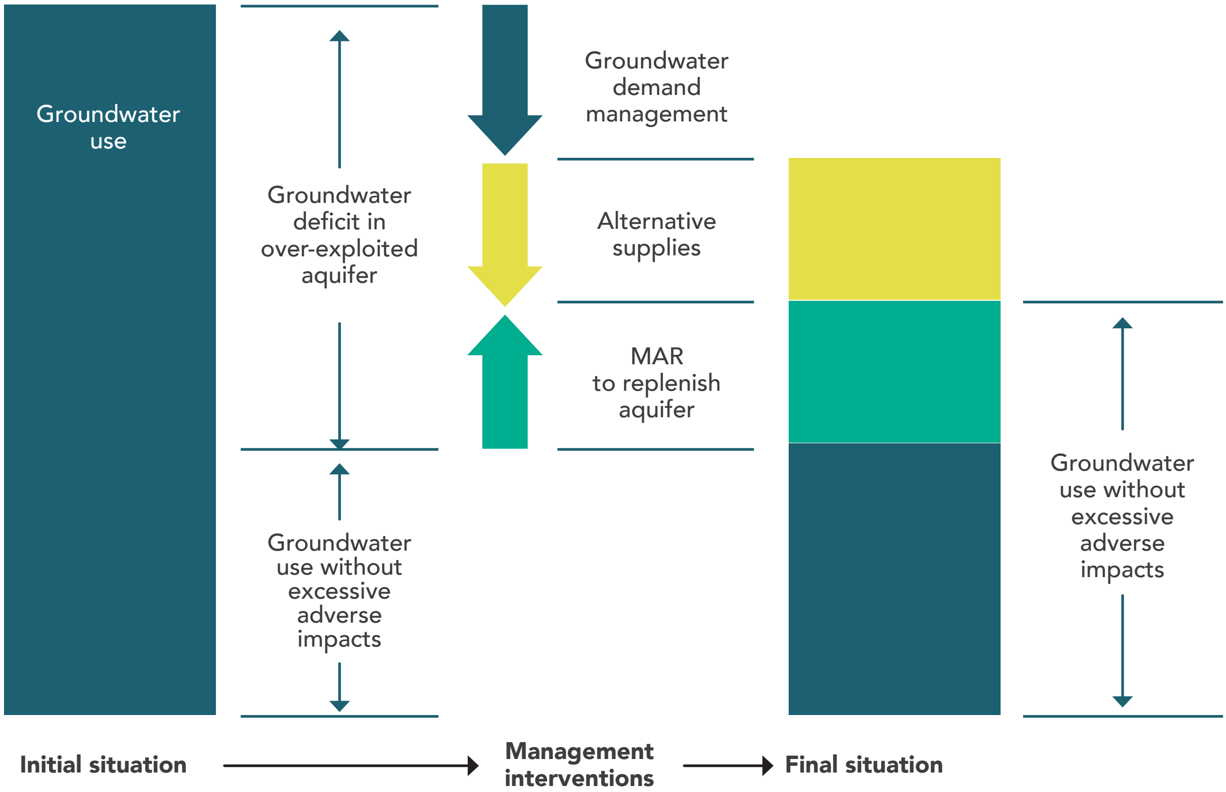
3.3 Environmental benefits

Amongst the environmental benefits of conjunctive water management we can consider the ones that are listed below:

Flood control

In addition to conventional civil engineering techniques, several of the Conjunctive Water Management activities contribute positively to flood control. Managed aquifer recharge and most of the watershed management techniques are based on intercepting overland flow or surface water flows and thus reduce the risk of flooding. Groundwater level control, either in polder areas or in surface water irrigated zones, usually creates more soil zone buffer space for intercepting overland flow during and immediately after rainfall events; in this way it contributes also to reducing flooding and the damage it produces.

Figure 4
Conjunctive Water Management as an approach to re-establish hydrological equilibrium in an overexploited aquifer (after Dillon et al., 2012)



Reduction of water pollution hazards and impacts

Uncontrolled discharge of wastewater and other used waters leads to environmental damage. Adequate wastewater management eliminates or reduces this damage, by removing pollutants carried by these waters (upgrading water quality by treatment) and by discharging the treated water to those blue water systems where it will do minimal harm, or even by recycling it into the water use chain.

Salinity control

Several of the conjunctive management approaches mentioned in the previous chapter have a potential impact on the encroachment of saline or brackish water into aquifers or lower reaches of rivers. An example is managed aquifer recharge in zones where fresh-water lenses are overlaying saline or brackish groundwater, such as practiced since the 1940s in the dune area of The Netherlands (Figure 5). In this particular case, treated river water is used for enhancing recharge through infiltration basins and injection wells.

Ecosystem conservation

Many natural water systems offer important ecosystems services. These are linked to hydrological features like shallow groundwater levels, springs, baseflow of streams and mineralisation levels of terrestrial and coastal waters. These features are essential for maintaining riparian and aquatic ecosystems, wetlands and oases. Diversion and abstraction of surface water, groundwater abstraction and other human interferences in the water cycle often modify the hydrological conditions to the extent that these ecosystems degrade or even disappear. Protection and conservation of valuable ecosystems require a good understanding of the interlinkages between the different components of the water cycle, often hidden for the layman's eye but revealed by field studies (see Figure 6). Conjunctive Water Management approaches help taking these interlinkages properly into account. In this context, attention should be paid to so-called Nature-Based-Solutions, designed to work with nature instead of against it (WWAP, 2018; GGRIP, 2019a and 2019b).

Figure 5
Managed aquifer recharge by open channels and infiltration basins in the Dutch coastal dune area, designed for groundwater salinity control (Photo: Harm Botman; Courtesy: Waternet, Amsterdam)

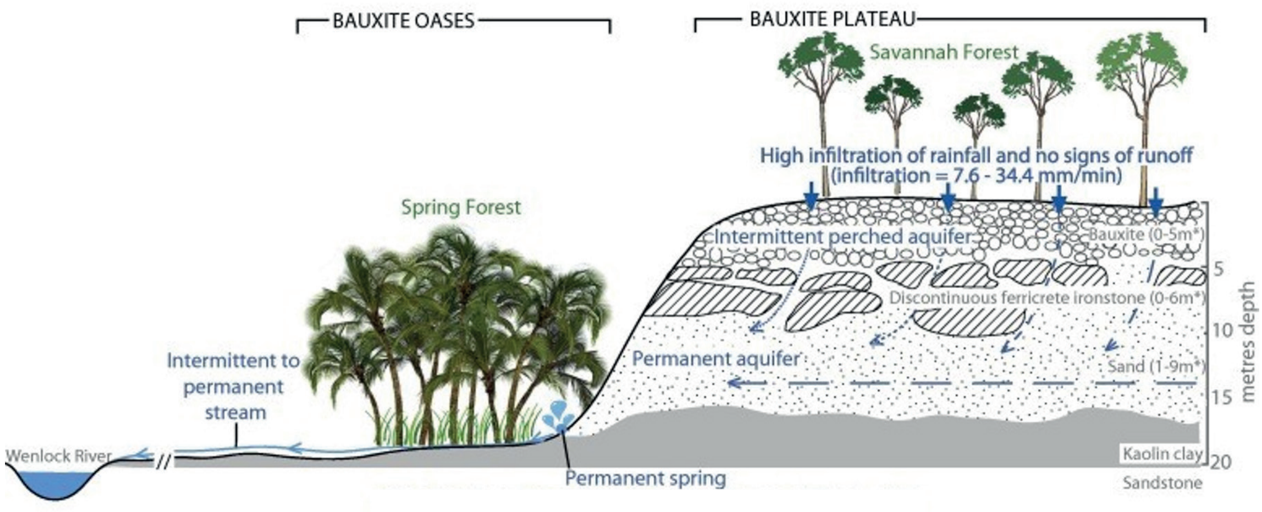
3.4 Economic and social benefits

The fact that spontaneous implementation of conjunctive use of surface water and groundwater by individuals is rather common suggests that it creates substantial economic or social benefits; otherwise, the practice would not prevail (Evans & Dillon, 2018).

Not only conjunctive use, but also the other Conjunctive Water Management techniques usually produce significant economic and social benefits, provided that they are properly tuned to the local conditions. In some cases, the efforts and benefits occur at the individual level (e.g. harvesting rain water from roof catchments to enhance domestic water security), in other cases they are shared by all inhabitants of a certain river basin or area. Implementing such measures for collective benefit is usually preceded by project or basin management plans that include a cost-benefit analysis; while raising funds for the implementation is another important preparatory activity.

Evidently, resources augmentation measures tend to produce particularly high benefits in water-scarce areas.

Figure 6
Permanent streams and lush oases are maintained by springs fed by groundwater from the bauxite plateaus in the Cape York Peninsula, Australia (Source: Leblanc et al., 2015)



3.5 Elimination or reduction of planning flaws and errors

Adopting a Conjunctive Water Management approach reduces the risk that attractive water resources management opportunities are overlooked, thus that water resources management plans are sub-optimal. It also reduces the incidence of planning errors resulting from not overseeing the entire local water situation. A still rather common error in this category is so-called 'double-counting' of the available surface water and groundwater resources in an area, especially if both water cycle components are developed and managed separately. This error results from ignoring the usually very substantial overlap between the groundwater and surface water budgets, since the lion's share of groundwater discharge around the globe is in the form of outflow into surface water bodies, while in certain settings a large share of groundwater recharge comes from surface water (Margat and Van der Gun, 2013). It goes without saying that eliminating or reducing planning flaws and errors produces benefits, either in terms of resources sustainability or environmental quality, or of economic or social benefits.

3.6 Synergy with high-level global policy priorities related to water

Important global priorities related to water, currently promoted by international organisations, are (1) the adoption of *Integrated Water Resources Management*, (2) adaptation to *Climate Change* and (3) the *Sustainable Development Goals (SDGs)*. The potential benefits of Conjunctive Water Management, as outlined above, are very well in line with the aims pursued by these global policy priorities, which confirms the synergy potential between them. They also help fulfil ambitions such as moving towards a circular economy.

As mentioned already in chapter 1, Conjunctive Water Management is one of the dimensions of *Integrated Water Resources Management* and thus implicitly contributes to its objectives. It does so in CC BY NC

particular by its potential of augmenting the usable water resources and its potential contributions to sustainability and to raising the socio-economic and environmental benefits of water.

Observed and predicted *Climate Change* is variable across the globe, but in many regions it is characterised by more extreme rainfall events and higher temperatures, leading – in turn – to increased risks of flooding and water scarcity. Conjunctive Water Management may help adapting to these manifestations of climate change. Most of the corresponding CWM interventions (see Table 1) have the potential to reduce water scarcity, while in particular MAR and watershed management measures may also significantly contribute to the reduction of flooding.

Figure 7 shows in highly simplified form the *Sustainable Development Goals (SDGs)*. Among these, SDG 6 ('Clean water and sanitation') is the one that is most explicitly linked to water resources management. Through the benefits described earlier in this chapter, Conjunctive Water Management may undoubtedly contribute to achieving the targets of SDG 6. More indirectly, it also contributes to achieving the targets of the majority of the other goals, especially SDG 2 (Food Security), SDG 3 (Good health and well-being), SDG 13 (Climate action) and SDG 15 (Freshwater ecosystem protection).

Figure 7
The 17 Sustainable Development Goals, adopted at a UN Summit in 2015 as part of the 2030 Agenda for Sustainable Development

4. Governance provisions needed or desired to facilitate Conjunctive Water Management

4.1 Data, information and knowledge

Planning and implementing Conjunctive Water Management at a river basin scale requires more than only generic knowledge on interactions between groundwater and surface water, such as reviewed by Sophocleous (2002). It requires also extensive knowledge about the local water resources systems, the water services they provide (human and environmental uses) and their overall local context. This local knowledge should be built on adequate information on the local systems and the interacting environment, based – in turn – on sufficient and reliable data, covering all relevant aspects.

Systematic data acquisition is done in the form of assessment studies (for time-independent data and a for 'snapshot' at a single moment of time) and monitoring activities (for time-dependent data), making use of both classical field work methods and innovative remote sensing and automatic monitoring techniques. Geographical Information Systems (GIS) and other modern ICT tools are helpful for processing the collected information efficiently and converting it into information. Once sufficient information is available, water accounting (FAO, 2018), numerical modelling and other types of analysis may contribute to gaining in-depth knowledge on the water systems' performance and on the water services. Such knowledge is indispensable for identifying water resources management needs, issues and opportunities.

Time series of groundwater and surface water quantity and quality are usually collected through *monitoring networks*. Their design and operation should preferably be coherent, also with those of meteorological and other related monitoring networks. The collected data form the building stones for information needed for developing, evaluating and adjusting water resources management strategies, but also for real-time operational management decisions (e.g. on water allocation or on water level control actions in the field). It needs to be emphasized that the collected monitoring data should be made easily accessible or disseminated as soon as possible among all stakeholders and agencies that have a role to play in Conjunctive Water Management in the area concerned. This includes sharing monitoring data sharing between neighbouring countries, in case of transboundary water bodies.

Numerical simulation models play an important role in the development of the required knowledge. At the one hand, they allow to deepen understanding of the local hydrological processes and to calculate water fluxes and transport of solutes and suspended matter. Fully-coupled physically-based models are preferred for this purpose, but at a regional scale, more loosely coupled schemes are often used due to limited data availability (Barthel and Banzhaf, 2016). At the other hand, these models can be used to explore and compare the merits of alternative future scenarios of human activities and their impacts on the local water resources. These simulation models may be integrated in a Decision Support System (DSS) or similar integrated modelling framework (GWP, 2013; Pierce *et al*, 2016; Pulido-Velasquez *et al*, 2016).

Optimal and permanent availability of data, information and knowledge on the local water resources and the water services provided is most likely to be achieved if dedicated institutions are established for this purpose.

4.2 Adequate institutions in charge of water resources development and management

From the institutional angle, Conjunctive Water Management can best be achieved where either there is a basin organization or where the national and local government agencies responsible for groundwater and surface water are part of the same ministry or organization. However, groundwater and surface water are in many countries under responsibility of separate water sector agencies, that often develop their activities without any co-ordination or co-operation. Where the management of surface water and groundwater is not under one roof, and institutional impediments to Conjunctive Water Management exist, a restructuring may be indicated; for example, by establishing a water resources apex agency. Even if institutional fragmentation remains, much progress can often be made by making provisions for good interinstitutional cooperation and close coordination between all projects in the water sector.

Involving local governments and communities in the conjunctive management of local water resources and strengthening their position is important. They have to play an active role in the sustainable use of their water resources, based on local experience, traditions and knowledge.

Education and training programmes, capacity building and empowerment of local water managers are meaningful actions in support of conjunctive management of the water resources.

4.3 Appropriate legal and regulatory frameworks

Legal and regulatory frameworks often are separate for groundwater and for surface water as well as for desalination and wastewater treatment and reuse (or even inconsistent between these two themes) and basic legal concepts may be incongruent (e.g. regarding water ownership and user rights). If these conditions form obstacles to the implementation of conjunctive management action, then the corresponding laws, regulations or mandates should be reformed. If essential laws and regulations are missing, then they should be established.

4.4 Water resources protection policies

One of the two main objectives of water protection policies, often dominant in industrialized countries, is *preserving the natural quality* of the water resources. Corresponding strategies usually include regulating land use and management of waste and wastewater.

The other main objective of water resources protection, particularly relevant in arid and semi-arid regions, is the *prevention of water resources depletion*. Demand management and augmentation of the water resources (e.g. by MAR or by recycling treated wastewater) are two main components of strategies to combat water resources depletion.

Water protection policies are based on the idea that preventing pollution and depletion is generally much less expensive than the cost of remediation of polluted water or substituting depleted water resources (if the latter is possible at all). Their implementation requires effective governmental and other water sector agencies, adequate legal and regulatory frameworks, sufficient funding, and support at both political and local stakeholder levels. Water resources protection management should be part of a (national) Water Master Plan or policy and be coordinated with soil protection, land use planning and abstraction of other natural resources, and it should take into account the vulnerability of water dependent ecosystems.

4.5 Water resources development and management planning

Conjunctive Water Management implies that a holistic view on water systems is adopted. This allows an unbiased conceptual model of the local natural water systems to be developed (covering both water quantity and water quality aspects), which will form the basis for strategic and operational water resources development and management planning. Integrated groundwater–surface water simulation models and other technical tools will enable the plans to be scientifically underpinned. Such tools will allow to predict and analyse interactions between groundwater and surface water, to identify options for promising interventions at field level, and to assess and compare the expected performance of each of these alternative options. The latter should not only take into account the direct net benefits of the interventions, but also their external impacts, including impacts on the long term.

4.6 Water and Gender

Data is the lifeblood of decision-making and water governance. Nevertheless, it is often impossible to integrate data on gender component and to conduct gender analysis in water projects, programmes and policies due to lack of data. There exists a lack of sex-disaggregated water data: less than a third of the countries disaggregate their statistics by sex on informal employment, entrepreneurship, violence against women and unpaid work. This stalls the progress in the collection of relevant scientific evidence on gender inequalities in the water realm and the development of programmes and policies that promote gender equality. Capacity development support is needed in many countries to strengthen skills in collecting and analysing sex-disaggregated water data to inform policy making.

In many countries, women are the main providers and managers of water at the household level. Access, use, management and authority over water resources are all highly gendered. For these reasons, women constitute distinctive key stakeholders in water policy.

Evidence shows that investing in the nexus between water and gender is crucial to achieving the 2030 Sustainable Development Agenda. In fact, enabling fair access and control of water resources is necessary to achieve women's empowerment and gender equality worldwide. The training material of the UNESCO World Water Assessment Programme (WWAP) most notably the 2019 UNESCO WWAP Toolkit on Sex-disaggregated Water data can help decision makers adopt data-driven, gender-transformative water policies and reach those left behind. The relationship between gender and water, and the recognition of women's roles in the management and conservation of water resources, are often not reflected in policy-making, or in the concession of rights to productive resources for women. A project on gender analysis of selected water data and indicators has been undertaken, using a the UNESCO WWAP methodology in the region of the Stampriet Transboundary Aquifer shared among Botswana, Namibia and South Africa, and a water and gender team has been activated for the sustainable management of the water resources.

A range of techniques associated with Conjunctive Water Management, such as rainwater harvesting or improvement of groundwater recharge through land management, are implemented at local level by local / rural communities. This represents an opportunity for a better gender balance in activities that contribute to water supply and enhance livelihood opportunities, especially if the promotion and implementation of these techniques are involving a participatory process.

5. The implementation of Conjunctive Water Management at field level: state of affairs

5.1 Conjunctive use of groundwater and surface water

As pointed out by Evans and Dillon (2018), present-day *conjunctive use of groundwater and surface water* may either have been emerging spontaneously at the farm scale ('unplanned' mode) or have been planned in a basin-wide or regional Conjunctive Water Management resources context. Although the planned version has the potential to produce much higher economic and social benefits, spontaneous conjunctive use prevails. Planned conjunctive use is difficult to implement since most of it has to be achieved by retrofitting management arrangements to already existing irrigation systems that use either surface water or groundwater. Except for the fact that there is always a certain resistance to changing existing systems, there are often also several governance-related obstacles such as: lack of awareness and knowledge about conjunctive use, differences in legal ownership and access modalities between groundwater and surface water, weak water resources management institutions and absence of basin- or aquifer based water resources management planning. For these reasons, planned conjunctive use is not yet wide-spread.

5.2 Managed aquifer recharge (MAR) and other forms of water resource augmentation

A recent paper by Dillon, Stuyfzand, Grischek *et al* (2018) presents a rather detailed world-wide overview of the evolution and current state of *Managed Aquifer Recharge* (MAR). Since time immemorial, human activities have resulted locally in significant unintentional increases in recharge of aquifers (e.g. by irrigation return flows). Artificial recharge, defined as recharge produced intentionally by human effort, has been practiced already in the 19th century in some countries, and its modern and more comprehensive equivalent – Managed Aquifer Recharge (MAR) – has been on the rise since the 1960s. MAR is an important water management strategy – alongside demand management – to enhance the quantity and quality of groundwater in stressed aquifers. MAR schemes vary from small to very large, while the techniques used fall roughly into four broad categories: streambed channel modifications, bank filtration, water spreading and recharge wells. Since the 1960s, the implementation of MAR has accelerated at a mean rate of 5% per year globally, but it is not keeping pace with increasing groundwater abstraction. MAR's current contribution to groundwater recharge has reached an estimated global rate of 10 km3/year, equivalent to 1% of the global rate of groundwater abstraction. More than half of the reported MAR capacity in the world corresponds to India and the US; Germany ranks third and is followed by Italy, Australia, Spain and The Netherlands. Dillon, Stuyfzand, Grischek *et al* (2018) estimate that MAR in principle might be expanded to around 10% of the current global groundwater abstraction. Not enough to stop current aquifer overexploitation, but potentially a significant contribution to achieving this goal, alongside with demand management and replacing groundwater by alternative supplies (see Figure 4). It should be noted that not all MAR schemes are exclusively focusing on water resources augmentation; some have important secondary objectives such as water quality control (including salinity) or flood control.

Water conservation measures as implemented nowadays under the umbrella of *watershed management* have been applied already since long – and still are implemented today – in a more or less spontaneous, uncoordinated and individual fashion. They range from roof catchments collecting rainfall to rather sophisticated systems of runoff harvesting that convert surface water into soil moisture. Integrating these and related soil conservation and agricultural measures within a single watershed management plan obviously enhances their joint effectiveness and tends to bring their benefits to entire communities instead of to a limited number of individuals only. The watershed management approach has gained significance following the 1992 Earth Summit in Rio de Janeiro (Förch and Schütt, 2005) and is applied in many parts of the world, both in wealthy and developing countries. It is difficult to assess the global volumes of water augmented by the indicated categories of water conservation measures – either unplanned or in a watershed management context – but they are certainly very large.

Nevertheless, watershed management, largely overlapping with what sometimes is called the 3R approach ("retention, recharge and re-use") may augment the availability of usable water enormously at relatively low cost in many parts of the world (Van Steenbergen and Tuinhof, 2009; MetaMeta and Acacia, 2018).

Tapping unconventional sources of water is another way of augmenting usable water resources. This category includes In the first place desalinizing brackish and saline water and making it available for drinking and other freshwater uses. According to the International Desalination Association (2018), in 2015 there were 18,426 desalination plants worldwide, with a aggregated capacity of 87 million cubic metres per day, serving more than 300 million people in 150 countries. Desalinised sea water is rather expensive, but may become more attractive in the future if improved desalination technologies make it cheaper. Under certain conditions (e.g. at large distance to the sea) local brackish groundwater may become preferred over seawater as a source for desalination.

A second non-conventional option is recycling and re-using treated wastewater. Untreated domestic wastewater has been used for centuries for irrigation and fertilization purposes, often not without causing health and environmental problems. After modern sewage systems and treatment methodologies became available, the recycling and re-use of treated effluent has significantly expanded, for purposes such as irrigation, recharge of aquifers, seawater barriers, industrial applications, dual-distribution systems for toilet-flushing and other urban uses. Several countries are already advanced in recycling treated wastewater and have ambitious plans to expand in the future. Water re-use offers a tremendous potential for relieving already strained water resource portfolios. However, apart from technological and economic factors, public perception remains a challenge to water re-use and associated biosolid applications to land (Angelakis and Snyder, 2015).

5.3 Measures primarily intended for environmental control

Prominent in this category is *water level control in polder areas*, which basically manipulates surface water systems in order to maintain groundwater levels within a desired range of depth. This technique has been in use for many centuries, originally mainly with a focus on draining and evacuating excess water during wet periods, more recently in some countries also on supplying water during dry spells. Approximately 167 million hectares of artificially drained agricultural land have been identified worldwide (Feick *et al*, 2005), of which probably the majority can be classified as polders.

Agricultural lands irrigated by surface water of allochthone origin tend to suffer from rising groundwater levels and water-logging, unless they are properly drained. *Drainage* of such lands has to be tuned to the interactions between surface water, soil moisture and groundwater, thus belongs to the domain of Conjunctive Water Management. Drainage is standard practice in modern surface irrigation schemes, but there is a legacy of schemes where adequate drainage has been missing for an extended period in the past, with the result that soils have become saline.

Area-wide intensive groundwater pumping may not only be a threat to the sustainability of the groundwater resources. It may also cause wetlands to degenerate, springs to stop flowing and the baseflow of streams to be reduced or even disappear. Such impacts, usually occurring in a relatively early stage of intensive pumping, can in principle be prevented if the hydrological interconnections are properly understood and *groundwater pumping rates are restricted*. In many arid and semi-arid regions this has not happened in due time, with the result that practically irreversible environmental damage has occurred at many locations. How wide-spread, where and to what extent groundwater pumping restrictions have been successful in conserving wetlands, springs and baseflows is difficult to assess.

Wastewater management can be associated with Conjunctive Water Management because it affects the water quantity and quality in the surface water bodies, aquifers or soil water zones into which the used waters – treated or untreated – are discharged. Important steps in wastewater management are: (i) wastewater collection (e.g. by sewers), which keeps wastewater isolated from clean freshwater resources; (ii) wastewater treatment, which removes some or virtually all harmful substances; and (iii) disposal, either to groundwater or surface water bodies, or to the water use chain (for re-use). During most of the time in history, dispersion and dilution have been the dominant – but not the best – practice for wastewater management, and this continues to be the most common practice in low-income countries. Primary and secondary treatment (removal of suspended solids and organic compounds, respectively) are nowadays obligatory in most high-income countries; while more advanced treatment there is triggered by greater understanding of the impact of wastewater on the environment and more sophisticated analytical methods (Lofrano and Brown, 2010).

Although re-use of raw or treated wastewater has a long history (e.g. for irrigation purposes), the interest in recycling and re-using wastewater is steadily growing. Embracement of the Circular Economy paradigm leads to a shift in the perception on wastewater: rather than as a nuisance it becomes also viewed as a valuable resource, allowing to recover and recycle useful water and solid matter (WWAP, 2017; IWA, 2018).

Finally, it should be noted that several of the methods and activities mentioned above – for instance MAR, many of the watershed management measures and land drainage – have multiple objectives, including flood control.

6. Suggested priorities and opportunities for scaling-up

The conjunctive water management paradigm should become a leading principle in all water resources planning activities worldwide. Even though its adoption can be observed in a substantial number of areas, much more abundant are the opportunities missed to enjoy the benefits from managing the different components of the water cycle in a conjunctive fashion. The reasons for this vary from one area or case to another, but it is clear that lack of knowledge and awareness, institutional and legal fragmentation and other governance deficiencies play a fundamental role. This is where systematic endeavours to scale up Conjunctive Water Management should start (see Box 3). In each particular situation, the gaps and flaws in water governance provisions should be assessed and then be removed or repaired to the extent required and feasible.

In principle, all discussed Conjunctive Water Management interventions have the potential to produce benefits, but the five types of field level activities listed in Box 3 seem to be the most promising ones at the global level. Evidently, they tend to have highest impact in water-scarce regions, where pressures of increasing population and climate change urge the local population to enhance water use efficiencies, reduce water use and water losses, augment the resources and prevent them to become unfit for use by contamination. A few comments on elements of Box 3 follow below.

Introducing *conjunctive water use* in irrigated areas combines the usually lower cost of surface water for farmers with the reliability of groundwater. Potentially this may produce huge benefits, but usually several governance obstacles (as depicted in chapter 5) have to be removed before it becomes feasible.

Managed aquifer recharge is conceptually more transparent for stakeholders. Its global potential is impressive, but large schemes may require considerable investments.

Watershed management is characterised by strong links between water management and land use. This, and the usually small-scale nature of the implemented measures favour intensive participation of local land owners.

Desalination is theoretically a very attractive method to augment useable water resources in coastal areas, given the nearly unlimited availability of seawater. In practice, energy requirements and cost of desalination are a limiting factor, but this may improve in the future.

Wastewater management is lacking or poorly advanced in most low-income countries, which implies that its rapid improvement has high priority there.

Recycling treated wastewater, finally, is a priority because it may on the longer term become an important cornerstone to water security in all parts of the world.

Effective Conjunctive Water Management requires the involvement of many actors (politicians, government agencies, water professionals and local stakeholders). Awareness raising should make them understand what Conjunctive Water Management is and what benefits it may produce. Active promotion is needed to develop their willingness to adopt the approach, to create motivation for co-operation and to put it on the agenda for budgets and support.

Box 3
Conjunctive Water Management: Recommended priorities for scaling-up

Governance measures:

- Creating awareness on CWM and its potential benefits
- Bridging or removing institutional barriers
- Making legal and regulatory frameworks compatible with CWM
- Aggregating knowledge on the local water systems
- Adopting CWM in water resources planning
- Raising funds for CWM interventions

Priorities for scaling-up at field level:

- Conjunctive use
- Managed aquifer recharge
- Watershed management
- Desalination
- Wastewater management and recycling

7. References

Angelakis, A. N., & Snyder, S.A. (2015). Waste Water Treatment and Reuse: Past, Present and Future, *Water,* 2015, 7, 4887-4895; doi:10.3390/w7094887

Barthel, R., & Banzhaf, S. (2016). Groundwater and surface water interaction at the regional-scale–A review with focus on regional integrated models. *Water Resources Management*, 30(1), 1-32.

Biswas, A. K. (2008). Integrated Water Resources Management: Is it Working? *Water Resources Development*, Vol 24, No 1.

Carruthers, I. and Stoner, R. (1981). *Economic Aspects and Policy Issues in Groundwater Development*. World Bank Staff Working Paper No 496.

Dillon, P., Fernandez, E.E. & Tuinhof, A. (2012). *Management of aquifer recharge and discharge processes and aquifer storage equilibrium.* IAH contribution to GEF-FAO Groundwater Governance Thematic Paper No; 4, Available from: www.groundwatergovernance.org/resources/thematic-papers/en/

Dillon, P., Stuyfzand, P., Grischek, T., *et al (31 authors)* (2018). Sixty years of global progress in managed aquifer recharge. Hydrogeol J, https://doi.org/10.1007/s10040-018-1841-z

Evans, R.S., & Dillon, P. (2018). Linking groundwater and surface water: conjunctive water management. In: Villholth, K.G., López-Gunn, E., Conti, K.I.,. Garrido, A. and Van der Gun, J. (eds.): *Advances in Groundwater Governance*, Boca Raton–London–New York–Leiden, CRC Press/Balkema, pp. 329–352.

FAO (2018). *Water accounting for water governance and sustainable development.* Food and Agriculture Organization of the United Nations, Rome.

Feick, S., S. Siebert & P. Döll (2005). *A digital global map of artificially drained agricultural areas.* Frankfurt Hydrology Paper 04, Institute of Physical Geography, Frankfurt University, Germany.

Förch, G., & Schütt, B. (2005). Watershed Management – An Introduction. Proceedings Lake Abaya Research Symposium, FWU Water Resource Publications, Vol 4, Siegen University, Germany.

GRIPP (2019a). *Overview on Groundwater-Based Natural Infrastructure*. Groundwater Solutions Initiative for Policy and Practice. http://gripp.iwmi.org/natural-infrastructure/overview-on-groundwater-based-natural-infrastructure/

GRIPP (2019b). *Guide for GBNI solutions.* Groundwater Solutions Initiative for Policy and Practice. http://gripp.iwmi.org/natural-infrastructure/guide-for-gbni-solutions/

GWP (2000). *Integrated Water Resources Management.* TAC Background Papers No 4, Global Water Partnership.

GWP (2013). *The role of decision support systems and models in integrated river basin management.* Technical Focus Paper, Global Water Partnership.

International Desalination Association (2018). Web page: http://idadesal.org/desalination-101/desalination-by-the-numbers/

IWA (2018). The Reuse Opportunity. *Wastewater Report 2018 of the International Water Association*, London.

Leblanc, M., Tweed, S., Lyon, B. J., Bailey, J., Franklin, C. E., Harrington, G., & Suckow, A. (2015). On the hydrology of the bauxite oases, Cape York Peninsula, Australia. *Journal of Hydrology*, 528, 668-682.

Lofrano, G., & Brown, J. (2010). Wastewater management through the ages: A history of mankind. *Science of the Total Environment*, Vol 408, No 22, Elsevier. Doi:10.1016/j.scitotenv.2010.7.062.

Margat, Jean, and Jac van der Gun (2013). *Groundwater around the World: A Geographic Synopsis.* CRC Press/ Balkema, Taylor & Francis Group, London, UK, xxviii+348 p. Available at: http://www.hydrology.nl/mainnews/1-latest-news/529-groundwater-around-the-world-free-download.html or https://www.un-igrac.org/resource/groundwater-around-the-world

MetaMeta & Acacia Water (2018). *Deal Book: Reaching the Millions.* 3R Partnership, The Netherlands. http://aquaforall.org/wp-content/uploads/2018/03/Deal-Book_Reaching-the-Millions_digitalversion.pdf

Pierce, S.A., Sharp, J.M. & Eaton, D.J. (2016). Decision Support Systems and Processes for Groundwater. In: Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J-D and Ross, A. (editors) (2016). *Integrated Groundwater Management: Concepts. Approaches and Challenges.* Springer, Open Access at SpringerLink.com. Available at: https://link.springer.com/ book/10.1007/978-3-319-23576-9

Pulido-Velasquez, M., Marques, G.F., Harou, J.J., & Lund, J.R. (2016). Hydroeconomic Models for Conjunctive Management of Surface and Groundwater. In: Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J-D and Ross, A. (editors) (2016). *Integrated Groundwater Management: Concepts. Approaches and Challenges.* Springer, Open Access at SpringerLink.com. Available at: https://link.springer.com/ book/10.1007/978-3-319-23576-9

Snellen, W.B. & Schrevel, A. (2004). *IWRM: for sustainable use of water – 50 years of international experience with the concept of integrated water management.* Ministry of Agriculture, Nature and Food Quality, The Netherlands.

Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. *Hydrogeology journal*, 10(1), 52-67.

USGS (2012). Web page: https://water.usgs.gov/edu/watercycle.html

Van Steenbergen, F., & Tuinhof, A. (2009). *Managing the water buffer for development and climate change adaptation.* Prepared under the aegis of the Netherlands Committee of the IAH. https://www.hydrology.nl/images/docs/ihp/nl/3r_managing_the_water_buffer_2009.pdf

WWAP (United Nations World Water Assessment Programme) (2017). *The United Nations World Water Development Report 2017: Wastewater, The Untapped Resource.* Paris, UNESCO

WWAP (United Nations World Water Assessment Programme) (2018). *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water.* Paris, UNESCO

This book is a contribution to the UNESCO IHP studies
on Groundwater Resources and Aquifer Systems

Contact Information:
Intergovernmental Hydrological Programme (IHP)
UNESCO, Division of Water Sciences (SC/HYD)
7, place de Fontenoy
75352 Paris Cedex 07 – France
Tel.: (+33) 1 45 68 04 16
ihp@unesco.org – www.unesco.org/water/ihp

9 789231 004209