Ecosystem-based Adaptation in Groundwater Management

July 2014

Preface

This report is part of the preparation phase for the project 'Ecosystem-based Adaptation in Groundwater Management' a joint effort of UNEP, IGRAC, IWMI and UNESCO-IHP. The objective of the project is to improve groundwater management taking an ecosystem-based approach and to provide a framework to identify ways in which the ecosystems services can be integrated in groundwater management. This report provides a literature overview of various ecosystem-based adaptation measures related to groundwater that could be implemented to improve ecosystems resilience and secure the ecosystem services.

July 2014

Nienke Ansems, IGRAC

Elizabeth Khaka, UNEP

Karen Villholth, IWMI

Table of Contents

Summary

Ecosystem services are the benefits people obtain from ecosystems. Most ecosystems are highly dependent on the hydrological cycle and water availability. The services provided by these ecosystems are therefore also directly, and indirectly, dependent on the availability and state of groundwater resources. Increased groundwater abstraction, increased groundwater contamination and climate variability, are affecting the functioning of ecosystems and thereby jeopardize the services these ecosystems provide. To successfully address the challenges of climate change and anthropogenic pressures on groundwater, ecosystems and their services, a holistic view is needed. For such interdependent challenges ecosystem-based adaptation (EbA) could be a promising approach. EbA is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. EbA addresses the crucial links between climate change, biodiversity, people, natural resources and ecosystem services.

Ecosystem-based adaptation measures

EbA approaches can support cost-effective adaptation against threats that result from multiple pressures. Protection and preservation of natural infrastructure does not replace the need for built infrastructure, but instead provides a complement multiplying the benefits received from healthy, functioning ecosystems. Various EbA measures could be implemented to secure groundwater resources and ecosystem services. The implementation of EbA measures can be based on either a certain ecosystem service, part of an ecosystem or one or several ecosystems. To successfully implement and increase the effectiveness of EbA for groundwater management it is important to conduct an integrated vulnerability assessment on the ecosystem of interest. As such, it will identify the main ecosystem services, main threats and adaptive capacity of the ecosystem. Within the ecosystem, critical zones can be indicated where EbA will be most beneficial. Because the hydrological system is interconnected on various levels, adaptation measures in these (local) critical zones can be used strategically for groundwater management on a larger, regional scale.

Protection of critical recharge areas

- *Groundwater recharge zones affect both the quantity and quality of water reaching aquifers. Therefore recharge zones are at the centre of preventing pollution and maintaining supply for both drinking water and groundwater dependent ecosystems. Currently, protection of groundwater recharge zones is primarily used in drinking water supply areas. Such protection schemes could be expanded to include ecosystems in critical groundwater recharge areas to improve their resilience and secure their services.*

Protection of Groundwater Dependent Ecosystems

- *A subset of ecosystems that are highly dependent on groundwater are groundwater dependent ecosystems (GDEs). GDEs are therefore particularly vulnerable to changes in groundwater supply and groundwater contamination. The hydrological connection and fluxes from (critical) recharge areas to GDEs are therefore of vital importance to sustain GDEs. Understanding the regional hydrogeology, the connection between recharge and discharge areas to and within GDEs, and the level of groundwater dependency of these ecosystems can help to support decisions about prioritization of adaptation measures. Protection schemes for GDEs and their services should be established accordingly.*

Protection and restoration of riparian zones and floodplains

- *Riparian zones are efficient in water quality improvement for both surface runoff and water flowing into and out of streams through subsurface or groundwater flow. The services of riparian zones should be better integrated with land use planning. Protection, restoration and providing space for riparian zones will improve overall water quality and quantity.*
- *Particular components of the riparian zones are floodplains, the area of land adjacent to a stream or river and flooded by the river. Floodplains represent natural filtering systems thereby improving groundwater quality and quantity. When a river is dissociated from its floodplain with levees or other flood control facilities, the natural benefits are either lost, altered, or significantly reduced. Reconnecting floodplains to the natural river system increases the river's ability to absorb storm water, improves water quality and reduces risk of flooding and flood damage.*

Adaptation of soil and vegetation cover

- *Modification of the vegetation cover will affect groundwater recharge processes. The establishment of tree, bush and other plant cover in river basins is widely used as a way of reducing runoff and increasing infiltration. The net increase of groundwater recharge depends on the balance between improvements in infiltration and relative changes induced in evapotranspiration.*
- *The soil plays a significant role in any groundwater protection strategy. Both the quantity and quality of groundwater depend on the water that moves down through the soil to the saturated zone. Good soil management can support protection of groundwater resources. Prevention of soil erosion is one way to improve groundwater quality.*

Investing in natural infrastructure

- *Investing in natural infrastructure can reduce or avoid costs and enhance water services and security. Measures to ameliorate the natural drainage system and increase groundwater storage include preservation of wetlands and lakes. Also the construction of (artificial) wetlands, basins, ponds and re-meandering, could emulate the positive services and contribute to improved groundwater recharge and groundwater quality.*

1. Introduction

1.1. Integrated vision of groundwater and ecosystem services

Groundwater is the most abundant source of fresh water on earth, counting for approximately 97% of non-frozen fresh water (Margat and van der Gun, 2013). It is connected to many goods and services people depend upon, including food and energy production. Over the years, groundwater levels have declined in many places around the world due to intensive use of the resource, particularly for irrigation and domestic water supply, coupled with climate change. If groundwater abstraction exceeds groundwater recharge for large regions and long time, overexploitation or persistent groundwater depletion will occur (Gleeson et al., 2010). Global groundwater depletion has been increasing since the 1960 and is likely to increase further in the near future (Wada et al., 2010). Though the depletion differs from region to region, the overall trend is similar and is not sustainable. Changes in groundwater levels can lead to degradation of ecosystems, water shortage and land subsidence. In addition, water pollution reduces the availability of useable water and results in environmental degradation of ecosystems.

Increased groundwater abstraction, increased groundwater pollution and climate variability, are seriously affecting the functioning of ecosystems and thereby jeopardize the services these ecosystems provide. Ecosystem services are the benefits people obtain from ecosystems. Ecosystem services can be of direct or indirect benefit to humans and can be categorized in provisional, cultural, supporting and regulating services (see table 1; MEA, 2005). These services include e.g. provision of food and water, supporting the hydrological cycle, flood regulation, but also cultural services such as aesthetic and recreational benefits. While the importance of ecosystem services is recognized, their existence is often taken for granted by their users (Bergkamp and Cross, 2005).

Indirect Benefits to Humans		***Direct Benefits to Humans***	
Supporting	**Regulating**	**Provisional**	**Cultural**
materials necessary for the production of other ecosystem services	Benefits obtained from processes such as air or climate regulation	Products gained from ecosystems	nonmaterial benefits derived by humans
Primary production Nutrient cycling Soil formation Hydrological cycle Habitat formation Pollination Seed dispersal	Gas regulation Climate regulation Disturbance regulation Biological regulation Water regulation Waste regulation Nutrient regulation Soil retention Disease regulation Flood regulation Water purification	Food production Fresh water Raw materials Genetic resources Medicinal resources Ornamental resources	Aesthetic Recreational Spiritual Historic Scientific Educational

Table 1. Ecosystem services can be sorted into four categories: supporting, provisioning, regulating and cultural services (adapted from Millennium Ecosystem Assessment, 2005)

Groundwater plays an integral role in sustaining certain types of ecosystems, and their associated ecosystem services. These ecosystems are dependent on groundwater fluxes, groundwater levels and groundwater quality. Groundwater does not only involve supplying quantities of water, but it also regulates the thermal and chemical regimes of the ecosystems (Margat and van der Gun, 2013). Since most ecosystems are highly dependent on the hydrological cycle and groundwater availability, most ecosystem services are directly and/or indirectly dependent on the availability and state of groundwater resources. Several services that have a direct dependency on groundwater availability are i.e.:

- Groundwater supplies almost half of all drinking water in the world (WWAP report, 2009).
- Groundwater plays a key role in food production, accounting for 43% of the global consumptive use in irrigation (Siebert et al., 2010).
- Storage and discharge of groundwater maintains and sustains river flows, springs, and wetlands (Morris et al., 2003).
- Groundwater acts as the primary buffer against the impact of climate variability and spatial variability in drought (FAO, 2003). Because it is stored deeper in the ground evaporation losses are low and water is less vulnerable to contamination. Groundwater, therefore, provides also significant opportunity to buffer high seasonal variations, by storing excess water during high rainfall periods.

To maintain and secure the ecosystems goods and services for present and future generations, protection of groundwater resources is of vital importance. Vice versa, deterioration of ecosystems will affect groundwater resources. This degradation has negative impacts on the recharge and quality of groundwater. For successfully addressing the challenges of climate change and anthropogenic pressures on groundwater, the ecosystems and their services, a holistic view is needed.

1.2. Ecosystem-based adaptation in groundwater management

The Millennium Ecosystem Assessment (MEA, 2005) reports that 60% of the ecosystems assessed are being degraded or used unsustainably. This environmental degradation affects the ecosystem services and reduces the resilience of ecosystems. A promising adaptation strategy to preserve ecosystems and ensure the provision of ecosystem services is ecosystem-based adaptation. Ecosystem-based adaptation (EbA) is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (CBD, 2009). EbA addresses the crucial links between climate change, people, biodiversity, natural resources and ecosystem services. It includes adaptation policies, and multi-level approaches to reduce the vulnerability and improve the resilience of ecosystems.

EbA is an emerging adaptation strategy that can also be applied to improve sustainable groundwater management. The overall aim of EbA in groundwater management is to preserve the quantity and quality of groundwater, and to improve the role of groundwater in ecosystem services for the benefit of present and future generations. It thereby mitigates the impacts on groundwater under changing conditions including, but not limited to, climate change. The sustainable use of groundwater comprises both the adaptive management and the effective protection of groundwater environments. Understanding groundwater in its environmental context is therefore fundamental. This report focuses on the role of groundwater in various ecosystems and their main ecosystem services. It thereby identifies the vulnerability of ecosystems to associated threats and provides potential EbA measures related to groundwater.

Box 1.1. Core Principles for Ecosystem-based Adaptation

- *Is about promoting the resilience of both ecosystems and societies.*
- *Promotes multi-sectoral approaches.*
- *Operates at multiple geographical scales.*
- *Integrates flexible management structures that enable adaptive management.*
- *Minimizes tradeoffs and maximizes benefits with development and conservation goals to avoid unintended negative social and environmental impacts.*
- *Is based on best available science and local knowledge, and fosters knowledge generation and diffusion.*
- *Is about resilient ecosystems, and using nature-based solutions at the service of people, especially the most vulnerable.*
- *Conduct integrated vulnerability assessments and impact projections with flexible criteria that address the linkages between human and environmental systems. Locate projects within robust national and sub-national frameworks to enhance long term chances of success.*

Box 1. The core principles and draft guidelines for integrating ecosystem-based approaches to adaptation on project and policy design, developed by the commission on ecosystem management (CEM) in June 2011 (Andrade et al., 2011).

2. Vulnerability of groundwater resources

2.1. Factors affecting groundwater dynamics

Climate change is altering the hydrological cycles. Subsequently, it affects groundwater recharge rates due to changes in precipitation patterns and evapotranspiration. Increased frequency and severity of floods and droughts are predicted, while rising sea levels may lead to saline intrusion into coastal aquifers. At the same time, the intensification of human activities and land use changes has caused an increased demand for groundwater. These activities are threatening groundwater services by the lowering of groundwater levels due to aquifer over-exploitation, drainage for agriculture, and dewatering due to infrastructure development and mining (Kløve et al., 2011). Figure 1 illustrates how climate change and land use pressure could affect groundwater flow dynamics on a local, regional and coastal scale.

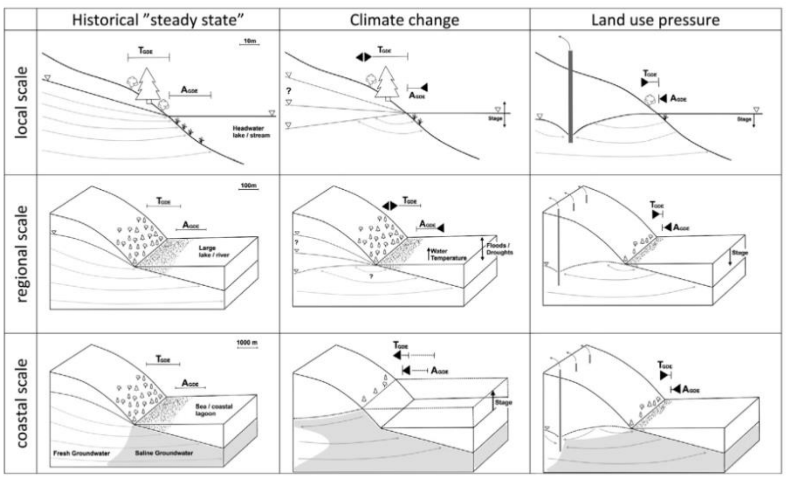

Figure 1. Impacts of climate change and land use pressure on groundwater levels and flow paths in terrestrial (TGDE) and aquatic (AGDE) groundwater dependent ecosystems at different scales of water bodies (adapted from Kløve et al., 2013).

The hydrogeological characteristics of aquifers determine for a large extent the vulnerability of ecosystems to these global changes. Unconfined aquifers, especially surficial and shallow aquifers, are more likely to have renewable groundwater and will be particularly sensitive to changes in variability and climatic conditions (Winter, 1999; Lee et al., 2006). Confined and deeper aquifers are more likely to have non-renewable groundwater and are therefore more vulnerable to increased demand for groundwater and abstraction (Kløve et al., 2013).

Pollution from nutrients, pesticides and heavy metals can affect groundwater quality. The aquifer's potential to groundwater pollution is mainly governed by thickness and hydraulic properties of the geologic formation above the aquifer. Generally, shallow unconfined aquifers are more vulnerable to pollution. The depth to groundwater determines the volume of soil through which a contaminant must travel. Where the soil is fairly deep, the processes of filtration, sorption and biodegradation can function more effectively.

Factors affecting groundwater quantity and groundwater flows

Climate Change

- Change in precipitation patterns
- Temperature change and increased evapotranspiration

Groundwater development and land use change

- Groundwater abstraction
- Accelerated (agricultural) land drainage
- Infrastructure development and urbanization
- Soil erosion

Factors affecting groundwater quality

Climate change

- Sea level rise causing salt water intrusion in coastal zones
- Thermal influence on groundwater

Groundwater development and land use change

- Salinization of aquifers due to agricultural activities
- Diffuse pollution of nutrients and pesticides in agriculture
- Increased input of organic contaminants and pathogens
- Leachate of heavy metals from urban, mining and industrial areas

Box 2. Main factors affecting groundwater quantify and quality. Indirect drivers can further intensify the impact of climate change and land use change; population growth and change in economic activity are both followed by increased demands of ecosystem services and groundwater. Political factors, such as decision-making processes and the extent of public participation (MEA, 2005) will influence the level of adaptation to these impacts.

2.2. A hydrological perspective: the critical zones

To better understand in which way and to what extent ecosystem-based adaptation can be applied in groundwater management, it is important to recognize the role of critical hydrological zones in ecosystems. These different zones perform divergent functions in the system and should be protected accordingly. Because the hydrological system is interconnected on various levels, these critical zones can be used strategically for groundwater management on a larger regional scale.

Groundwater recharge and discharge zones

Water moves into aquifers in groundwater recharge zones, and discharges out of aquifers at groundwater discharge zones. Groundwater recharge can be local, occurring from infiltration via surface water bodies, or diffused by percolation of precipitation through the unsaturated soil zone across the landscape (Döll and Fiedler, 2008). Common recharge areas include infiltration via rivers and lakes, in hills and upland areas, and alluvial fans along mountain fronts and marshes. Groundwater recharge of confined aquifers occurs mostly at outcrops, where the water enters the aquifers and moves down the dip beneath the overlying confining beds. Confined aquifers can also be recharged by leakage from overlaying unconfined aquifers.

The direction and speed of groundwater movement depends on hydrogeological characteristics such as the permeability and the porosity of the subsurface and the confining layers in the ground. The water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks. Groundwater discharges from the subsurface to oceans, springs, lakes and rivers or seep out of the ground into wetlands and marshes. Groundwater abstraction wells can also serve as discharge areas, especially larger volume wells, such as those used by municipalities. Examination of groundwater recharge and discharge zones and determination of groundwater flow directions will provide an indication of critical recharge areas where adaptation strategies for improved groundwater recharge will be most beneficial. Understanding the linkage between these areas can help to decide in prioritization of adaptation. The connections of groundwater recharge zones to discharge zones are in particularly important for the water supply to groundwater dependent ecosystems (GDEs). GDEs require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements to maintain the ecological processes and ecosystem services (Richardson et al., 2011).

In some ecosystem the relationship between recharge and discharge is highly dynamic and seasonal. For example, during the wet season in the Mekong Delta, floodwaters may have a higher hydraulic head (caused by increased water elevation of the river), and consequently water will move from the floodwaters into the aquifer system (recharge). In the dry season when river levels are low, water will gradually discharge from the aquifer system into the rivers, wetlands, and coastal zones.

Riparian zones and floodplains

A riparian zone is the interface between land and streams, rivers, lakes, reservoirs, and other inland aquatic systems that affect or are affected by the presence of water. The width of the riparian zone can vary greatly depending on the type of river, stream or catchment. Riparian zones perform a large variety of ecological functions. Riparian vegetation moderates flooding by slowing down flood water and allowing recharge of shallow aquifers. Riparian zones are also important for water quality improvement for both surface runoff and water flowing into and out of streams through subsurface or groundwater flow. Particular components of the riparian zones are floodplains, the area of land adjacent to a stream or river and flooded by the river. Floodplains of major rivers act as natural storage reservoirs, enabling excess water to spread out over a wide area (Ramsar, 2011). Floodplain represents a natural filtering system improving water quality with water percolating back into the ground and replenishing aquifers. When a river is dissociated from its floodplain with levees and other flood control facilities, the natural benefits are either lost, altered, or significantly reduced.

Groundwater - surface water interactions

Water management plans do not always consider groundwater as part of the water resources. However, groundwater and surface waters are interactive components of the hydrologic system and cannot be treated in isolation (Hancock et al., 2005). Groundwater – surface water interaction is frequent and relates both to water quantity and quality in both the surface water and the groundwater systems. For example, contaminated aquifers that discharge to streams can result in long-term contamination of surface water; conversely, streams can be a major source of contamination to aquifers. This interaction should be taken into account for adaptive management in ecosystems. The area where there is mixing of shallow groundwater and surface water is called the hyporheic zone and encompasses the areas both beneath, and laterally of, the bed of a river or lake. These zones offer great potential to provide natural treatment of organic compounds, nutrients, and pathogens in urban streams (Lawrence et al., 2013).

Fresh - salt water interfaces in coastal aquifers

Fresh groundwater is an important source of water supply in coastal areas. However groundwater abstraction in coastal aquifers could result in a decreased flux of fresh water towards the coastal discharge areas, thereby allowing the intrusion of salt water into fresh water aquifers (Fitts, 2002). Other contributors to saltwater intrusion include sea level rise and extended periods of droughts.

The movement of saline water into aquifers can lead to contamination of drinking water sources and impacts the ecosystem's flora and fauna. For sustainable groundwater management in coastal areas it is important to understand the temporal and spatial evolution of the fresh - salt water interface.

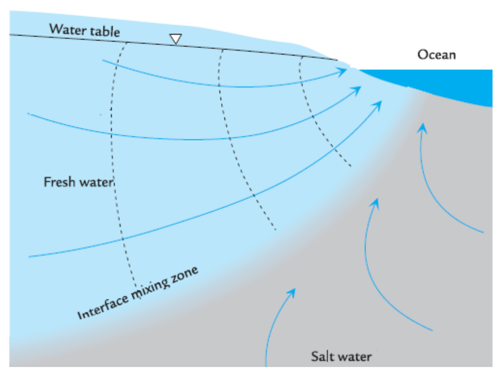

Figure 2. Fresh – salt water interface of an unconfined aquifer (illustration after Fitts, 2002)

3. Ecosystems: vulnerability and ecosystem services

The vulnerability of groundwater resources and ecosystems is a combination of the magnitude of the potential threats and the resilience of ecosystems to these impacts. Resilience is the capacity of an ecosystem to absorb disturbance without shifting to an alternative state and losing function and services (Carpenter et al., 2001). The response of ecosystems to change in conditions is variable. In some cases there is a threshold response, where beyond that an ecosystem will get damaged completely if conditions change beyond a critical level. In other cases there is a more gradual change in the health, composition or ecological function of the ecosystem considered (Margat and van der Gun, 2013). EbA can help to reduce the vulnerability and improve the resilience of ecosystems. This chapter gives a general description of various ecosystems and their main ecosystem services.

3.1. Groundwater dependent ecosystems

Groundwater dependent ecosystems are present globally in different sizes, and include i.e. wetlands, forests and oases. Ecosystem dependency on groundwater may vary temporally and spatially. For GDE management, both water quantity and quality are important to maintain habitat and biodiversity (Kløve et al., 2011). One way of classifying groundwater-related ecosystems is by their geomorphological setting (aquatic, terrestrial, coastal) and associated groundwater flow mechanism. On this basis a number of different classes are recognized (GW-MATE, 2006):

- natural discharge from relatively deep groundwater flow systems rising to form distinctive springs with associated (often unique) aquatic ecosystems
- wetland ecosystems related to the discharge of shallow (and sometimes perched) groundwater flow systems as seepages in land surface depressions
- groundwater discharge from extensive aquifers providing (in part perennial and elsewhere ephemeral) dry-weather flow in the upper reaches of river systems which represent aquatic ecosystems
- discharge of groundwater flow systems to coastal lagoons, which is critical in diluting salinity from marine influences and providing unique habitats
- some extensive semi-arid and humid terrestrial ecosystems without standing water, but with very deep-rooted phreatophytic vegetation extracting moisture directly from the water-table.

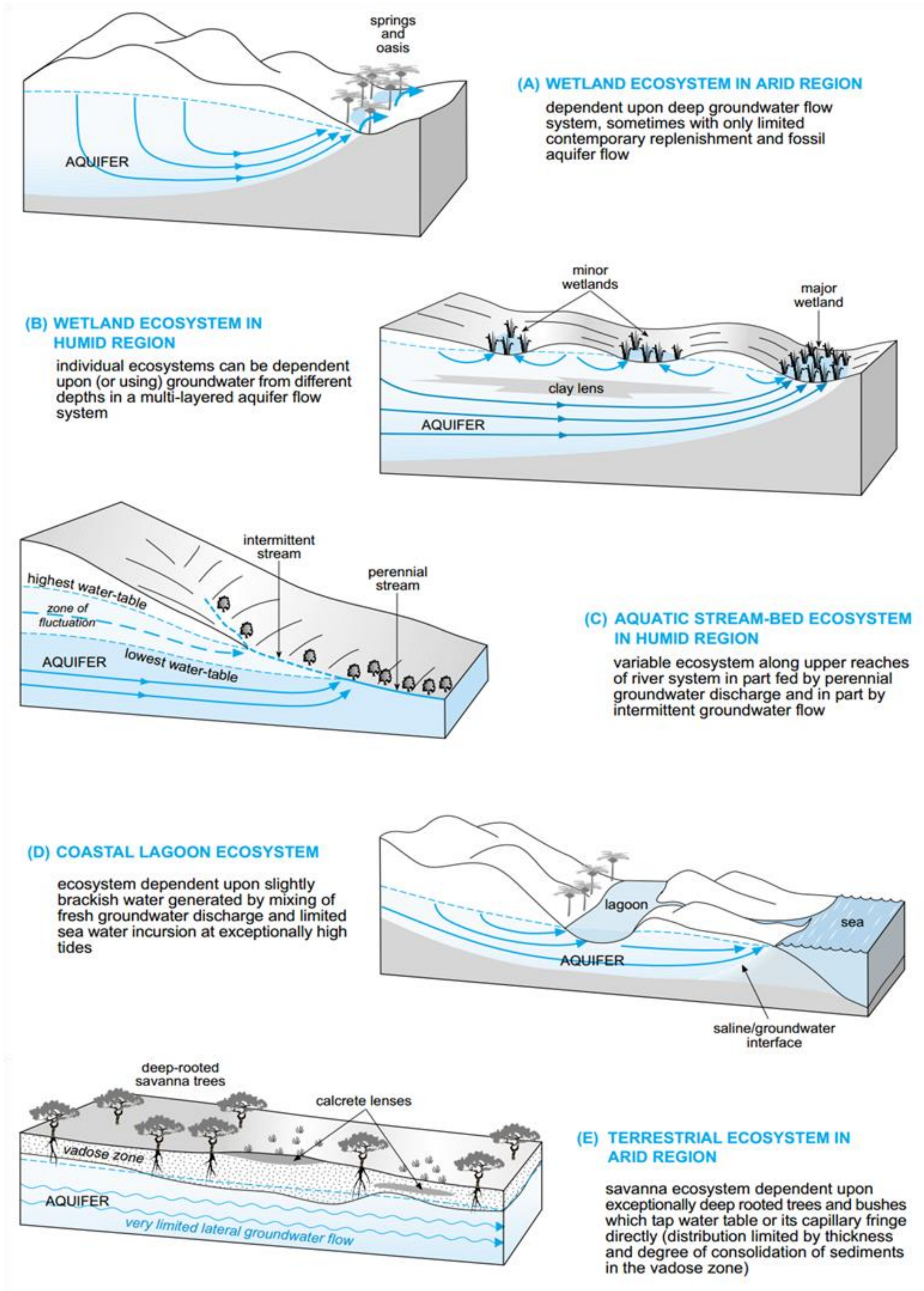

Figure 3. Main classes of groundwater related ecosystems and their associated groundwater flow regime (GW-MATE, 2006)

3.2. Wetlands

Ecosystem-based adaptation in wetlands

Main ecosystem services: supporting and regulating

Water quality improvement, flood mitigation, carbon capture and climate regulation

Major climate change impacts

Increased evapotranspiration, decrease in precipitation

Major anthropogenic impacts

Increased input of contaminants, overexploitation of groundwater

Adaptation main objectives

protection of groundwater dependent wetlands,
improve buffer capacity to climate extremes

Characteristics and role of groundwater

A wetland is a land area that is saturated with water, either permanently or seasonally. The factor that distinguishes wetlands from other land forms or water bodies is the characteristic vegetation that is adapted to its hydric soil conditions (Ramsar, 1971). The water found in wetlands can be fresh, salt or brackish water. Wetlands cover about 5-8% of the terrestrial land surface (Mitsch and Gosselink, 2007). Wetland ecosystems include swamps, peat lands, marshes, bogs, fens mangroves, springs, and oasis. One way to classify wetlands is on their water supply dependency, ranging from those primarily dependent on precipitation for their water supply and those primarily dependent on discharge from the regional groundwater flow system (Winter, 2000). Wetlands can also be hydrologically defined by their position within the hydrologic landscapes. The six main types of hydrologic landscapes are moutainous, plateau and high plain, broad basins (playas), riverine, flat coastal and hummocky glacial and dune (Winter, 2000).

Ecosystem services

Wetlands provide a diverse set of ecosystem services, including water quality improvement, coastal protection, flood mitigation and wildlife habitat (Mitra et al., 2005; Mitsch and Gosselink 2007). They offer various recreational services, provision of fisheries, timber and some wetlands also support agriculture activities. Through storage and slow release of water, wetlands can recharge groundwater, reduce peak flows during floods, and help maintain flow in rivers during dry periods (Environment Canada, 2004). Wetlands improve water quality by trapping sediments, filtering out pollutants and absorbing nutrients. In regions where they occupy a large proportion of the landscape, such as the Mackenzie River basin, the moist surface of wetlands may also have a moderating influence on climate by maintaining regional evapotranspiration, even during extended dry periods (Rouse et al., 2003).

Wetlands play a major role in the global carbon cycle. Globally, wetlands store an estimated 300 to 700 billion tons of carbon (Bridgham et al., 2006), representing around 20-30% of the Earth soil pool of carbon (Lal, 2008). The vegetation in wetlands can capture large amounts CO_2 from the atmosphere. However hydrological changes, mainly leading to changes in aerobic conditions, could result in the release of carbon back into the atmosphere. Hence, wetlands could be a sink or a source of carbon. Complex dynamics between increased CO_2 in the atmosphere and changes in the hydrological cycle determines if the wetlands function as a positive or negative feedback mechanism to climate change; this differ from site to site and is difficult to predict.

Vulnerability of wetlands

Due to their large wet area and shallow depths, wetlands are particularly vulnerable to water losses by evapotranspiration or increased water drainage due to land use changes. Any variation in climate that increases the relative importance of evapotranspiration compared to precipitation could result in drying out of wetlands (Environment Canada, 2004). This is mainly the case for wetlands that primarily depend on precipitation for their water supply. Wetlands fed by large deep groundwater systems tend to maintain a steady flow even under large climatic variations (Winter, 2000). These wetlands are more vulnerable to changes in groundwater fluxes and flow direction caused by groundwater abstraction in the area.

3.3. Agricultural ecosystems

Ecosystem-based adaptation in wetlands

Main ecosystem services: provisional

Food production, socio-economic benefits

Major climate change impacts

droughts, flooding

Major anthropogenic impacts

increase in fertilizers (nitrate and phosphate) leading to eutrophication, groundwater abstraction and irrigation salinity

Adaptation main objectives

food security and water resources management

Characteristics and role of groundwater

Agricultural lands are dynamic areas of crops, grasslands, forests, cattle, flora and fauna and water (Bebarta, 2007). An agricultural ecosystem is not constrained to the area of agricultural activity, but rather includes the region that is impacted by agricultural activities. It is therefore part of a larger landscape that could also include uncultivated land, drainage networks, and rural and urban communities. Agricultural irrigation is one of the most prominent uses of groundwater in the world. Around 38% of the world's irrigated area is irrigated with groundwater (Siebert et al., 2010). Globally, total groundwater use for irrigation is 43% of the total water use for irrigation (Siebert et al., 2010), while for example in India, the world's largest user of groundwater, about 65% of agricultural practices rely on groundwater for irrigation (Worldbank, 2010). Agricultural ecosystems are often associated with elevated nutrient input, leading to eutrophication of lakes, rivers, coastal waters and groundwater systems.

Ecosystem services

Agriculture is one of the main drivers of the world economy and food security. It supports the livelihood of the largest number of people worldwide and is vital to rural development and reducing poverty. Ecosystem services provided by ecosystems other than agriculture, such as clean water, carbon regulation, nutrient cycling or soil maintenance, are as important to sustain agricultural ecosystems (IUCN, 2008).

Vulnerability

The main challenges within the agricultural sector are to secure enough high-quality agricultural production while meeting the demand and conserve biodiversity and manage natural resources (IUCN, 2008). Because of the increased demand for food production and the global intensification of land use, there is increased pressure on groundwater resources in agricultural ecosystems. Climate variability can result into increased floods and/or droughts which can negatively impact the harvest season. Climate change can also affect agricultural systems by influencing the types of crops that can be grown (IUCN, 2008).

The use of fertilizers is a common agricultural practice to increase crop yields. However, fertilizers applied in excess, may leach through the root zone and contaminate groundwater resources. Nitrogen and phosphorus are the nutrients required in greatest quantities. Because N and P are also the essential nutrients for primary producers, alterations in their inputs to the environment strongly affect the structure and functioning of natural ecosystems (Smith et al., 1999) leading to eutrophic conditions. Eutrophication may cause harmful algal blooms, water column anoxia, and fish mortality, all of which have a negative impact on humans in terms of reduced environmental quality, potential health risks and increased management costs (Wetzel, 2001; Wilson and Carpenter, 1999).

Agricultural irrigation can lead to the rise in saline groundwater and the buildup of salt in the soil surface in irrigated areas. The major causes of irrigation salinity include over-irrigation of farm land, inefficient water use, poor drainage, allowing water to pond for long periods and allowing seepage from irrigation channels, drains and water storages.

3.4. Coastal ecosystems

Ecosystem-based adaptation in coastal ecosystems

Main ecosystem services: regulation and provisioning

Buffer zones, flood mitigation, stabilize coastlines, fisheries

Major climate change impacts

salt water intrusion due to sea level rise and extended periods of droughts

Major anthropogenic impacts

Groundwater abstraction leading to salt water intrusion, coastal erosion

Adaptation main objectives

Resources management, prevention of groundwater salinization

Characteristics and role of groundwater

Coastal areas are the most populated regions on Earth. Presently, about 40% of world population lives within 100 km of the coast. In coastal zones, different environments are linked such as marine, estuarine, freshwater and terrestrial areas. Examples of coastal ecosystems are coral reefs, mangrove forests, and salt marshes. In various coastal areas intense groundwater development has caused saltwater intrusion. The movement of the fresh water-salt water interface can have significant impacts on the biodiversity and ecosystem services.

Ecosystem services

Coastal zones provide many socio-economic services. Human settlements are often concentrated in the coastal zone because of the economic benefits provided from access to ocean navigation, coastal fisheries, tourism and recreation. Coastal ecosystems, such as mangroves have proven their value as buffers; they stabilize coastlines and can provide physical protection to against some of the damaging effects of storm surges.

Vulnerability

With global warming and sea-level rise, many coastal systems will experience a) seawater intrusion into fresh groundwater, b) increased levels of inundation and storm flooding, c) accelerated coastal erosion and d) elevated sea-surface and ground temperatures (IPCC, 2001). A one meter rise in sea level could displace nearly six million people across South Asia and 37 million people along the river deltas of East Asia (Dasgupta et al., 2007). The movement of saline water can lead to contamination of drinking water sources and impacts the ecosystem's flora and fauna. Once salt water has intruded into fresh water system it is very difficult to reverse the process. Particular vulnerable are already low-lying coastal zones and small island developing states. Another important risk in coastal ecosystems is the growth in human settlements. Population growth, and subsequently, increased groundwater exploitation is major risk to salt water intrusion.

3.5. Karst ecosystems

Ecosystem-based adaptation in karst ecosystems

Main ecosystem services

Water supply, carbon sequestration

Major climate change impacts

change in precipitation patterns

Major anthropogenic impacts

Groundwater overexploitation

Increased input of contaminants

Adaptation main objectives

water resources management

Characteristics and role of groundwater

Karst ecosystems are important landscape types that cover about 12% of the world's land area (Liu, 2013). Karst landscapes and aquifers consist of carbonate rock in which a part of the fractures have been enlarged by chemical dissolution. They are characterized by unique geomorphological and hydrogeological features, such as rapid infiltration of rainwater, lack of surface waters, and turbulent flow in a network of fractures, conduits and caves.

Ecosystem services

Karst terrains provide a great variety of habitats to many species, both at the surface and underground. They act as a natural sink for carbon thereby helping to mitigate climate change. In some countries, such as Austria or Slovenia, karst water contributes about 50% to water supply (Ravbar and Goldscheider, 2007). With over a hundred million people, China is the country where the largest number of people relies on karst water resources (LIu et al., 2006).

Vulnerability

Karst aquifers are particularly vulnerable to contamination. Because of their hydrogeological structure, contaminants can easily enter the aquifer. In the aquifer they can rapidly spread over large distances and impact springs or wells used for water supply (Goldscheider, 2005).

4. EbA measures for groundwater management

Over the last decades countries have increased their effort to recharge groundwater. However the focus has been more on artificial recharge techniques (MAR) with little consideration of the natural recharge processes. To what extent various EbA measures could be implemented, and the level of interventions, depends on the interaction of the hydrological system, the ecosystem services and the ecosystem vulnerability. The implementation of EbA measures can be based on either a certain ecosystem service, part of an ecosystem or one or several ecosystems. In some ecosystems, EbA cannot replace the need for built infrastructure, but instead could provide a critical complement, multiplying the benefits received from healthy, functioning ecosystems (Smith et al., 2010).

4.1. Protecting groundwater recharge zones

Efforts to protect groundwater should focus primarily on recharge zones because they are at the centre of preventing pollution and maintaining supply to meet ecosystem and human needs. Recharge zones control both the quantity and quality of water reaching the aquifers. Understanding the regional hydrogeology, the identification of groundwater recharge and discharge zones and determination of groundwater flow directions, will indicate critical recharge areas where adaptation strategies to protect groundwater recharge will be most beneficial. This method is also called groundwater zoning; the identification of different recharge and discharge zones for sustainable management of groundwater resources. Examples to protect groundwater recharge zones can be taken from groundwater protection schemes for drinking water supply regulations. Such schemes could be further developed to protect critical groundwater recharge areas in ecosystems thereby improving ecosystems resilience and to secure other ecosystem services besides drinking water supply.

Principal objectives of groundwater protection schemes

- protect quality and quantity of groundwater resources
- Identify threats to ground water
- Monitor to detect and prevent unacceptable risks
- Sustain baseflow and groundwater dependent ecosystems

Components of groundwater protection schemes include:

- *provide geological and hydrogeological information, so that developments can be located and controlled in an environmentally acceptable way*
- *Integrate the factors associated with the risk of contamination, focus attention on the higher risk areas and activities, and provide a structure within which control measures can be selected*
- *assist public authorities to meet their statutory responsibilities for the protection and conservation of groundwater resources*
- *Indicate inconsistencies and shortcomings of existing regulations*

(Adapted from Groundwater Protection Scheme of Geological Survey of Ireland (GSI, 2002).

4.2. Protecting groundwater dependent ecosystems

GDEs require access to groundwater on a permanent or intermittent basis. GDEs are therefore particularly vulnerable to changes in groundwater supply and groundwater contamination. The hydrological connection and fluxes from (critical) recharge areas to GDEs are therefore of vital importance to sustain GDEs. I*n order to maintain the required quantity and quality of water to sustain the ecological value of GDE's* The Water Allocation Plan and National Groundwater Committee (Government of Australia) are working on protection of GDEs. They identify the most valuable and sensitive GDEs in the region, and protect them by

- *reducing the amount of water that can be allocated in management areas with a high resource demand*
- *locate new water extraction points and commercial forests in areas where they do not reduce the groundwater level to a required level*
- *perform assessments of the impact of water allocation transfers to existing wells in the vicinity of high value GDE's*
- *use of buffer zones around GDE's to protects GDE's level of groundwater quantity and quality*
- *exclusion zones and license conditions that restrict extraction at critical times*

4.3. Protecting and restoring riparian zones and floodplains

Riparian zones are efficient in water quality improvement for both surface runoff and water flowing into and out of streams through subsurface or groundwater flow. The ability to retain nutrients and improve water quality increases with the width of the riparian zone. Protection, restoration and providing space for riparian zones will improve overall water quality. For example, riparian zones show a particularly high rate of removal of nitrate entering a stream; protection of these zones will support sustainable agricultural management. The services of riparian zones should be better integrated with land use planning. Specific land management practices that protect riparian zones (ATTRA, 2003) include:

- *Maintaining a vegetative cover over the soil throughout the year*
- *Avoiding overuse of fertilizers or manure that may be transported into riparian areas*
- *Protecting against loss of plant diversity and vitality in riparian areas*
- *Avoiding practices that artificially alter stream flow*

Particular components of the riparian zones are floodplains, the area of land adjacent to a stream or river and flooded by the river. When a river is dissociated from its floodplain with levees or other flood control facilities, the natural benefits are either lost, altered, or significantly reduced. Reconnecting floodplains to the natural river system increases the river's ability to absorb storm water, improving water quality and reducing risk of flooding and flood damage.

4.4. Soil conservation and adaptation of vegetation cover

The soil plays a significant role in any groundwater protection strategy. Both the quantity and quality of groundwater depend on the water that moves down through the soil to the saturated zone. Soil conservation practices can mitigate soil loss by altering land-surface characteristics such as topography, soil structure and vegetation cover (Zhang et al., 2007).

Vegetation cover influence the percentage of precipitation actually percolation into the aquifer. The establishment of tree, bush and other plants in river basins is widely used as a way of reducing runoff and increasing infiltration. This is often assumed to increase recharge and is advocated as a key measure to address groundwater overdraft. The net increase of groundwater recharge depends on the balance between improvements in infiltration, and the relative changes induced in evapotranspiration and increased surface water runoff. Therefore it is possible that in some cases, increased vegetation leads to a decrease of groundwater recharge. For example, the removal of forest cover has resulted in water levels to rise considerably in much of New South Wales, Australia (FAO, 2003).

Ecological soil-conservation approaches have benefits of cost efficiency, but may not be sustainable where evapotranspiration losses are high. Humid areas may be able to withstand the added transpiration losses due to agriculture, so these areas may be able to integrate agro-ecological approaches (Gates et al., 2011). In semi-arid areas extensive planting of non-native trees and shrubs could result in lowering of the water tables and decreased stream flows. In South Africa the invasion of alien tree and plant species are consuming much more water than the indigenous vegetation threatening biodiversity and effecting water quality and groundwater recharge (Binns et al., 2001) Conservation of native vegetation regions could increase recharge into underlying aquifer (Gates et al., 2011).

Various adaptation to soil and vegetation cover are listed below:

- *Efforts to reduce erosion of agricultural soils are critical to maintaining food security and environmental quality. Prevention of soil erosion is one way to improve groundwater recharge quality. Means to control erosion include physical and vegetation barriers, various types of passive and active terracing on slopes, and good cultivation and soil management practices.*
- *Well humified organic matter has a large adsorptive capacity for both organic and inorganic compounds, including most pollutants. Maintaining an active organic component in the topsoil through good soil and crop management enhances the soil's capacity to serve as a filter.*
- *Implementation of environmental regulation and beneficial management practices will help to minimize soil pollution and diminish pollution transport via surface run off or subsurface flow.*
- *In agricultural coastal zones where irreversible salt water intrusion has occurred, agricultural activities can adapt to grow crops that are salt-tolerant crops.*
- *The incorporation of more green spaces, including planting of trees, can play a role in urban adaptation by reducing heat stress and improving drainage during times of flood.*
- *Deforestation has increased river discharge in many basins worldwide because of reduced transpiration (Brown et al., 2005). Catchment thinning, the planned removal of vegetation (trees) in densely forested areas that are suffering from drought, can help to increase the amount of surface water runoff and increase stream flows.*

4.5. Implementation of Ecosystem based Adaptation

To successfully implement and increase the effectiveness of EbA measures for groundwater management, it is important to understand and recognize the vulnerability and interdependency of groundwater, ecosystem and the services in the area. Carrying out an integrated vulnerability assessment is a first and fundamental step to create a framework for EbA strategies adapted to the ecosystem of interest. A next step to implement ecosystem-based adaptation in groundwater management involves drafting guidelines to implement EbA. This will include groundwater governance, management implications and policy aspects of EbA. This will lead to the assessment and preparation of a policy publication on the social-economic benefits from EbA activities in protecting groundwater recharge zones and their impact to aquifers and GDEs, lessons learnt and policy implications for scaling up. There is a need for discussion of draft policy publication by the technical and policy makers at the regional intergovernmental level.

Framework for the implementation of EbA in groundwater management

Integrated Vulnerability Assessment

1. **Establishing present status and recent trends**
   - **a.** Validation and quantification of ecosystem services
   - **b.** Validation and quantification of groundwater resources
2. **Identify groundwater vulnerability and ecosystem resilience**
   - **a.** Indicate main drivers affecting groundwater dynamics and ecosystem services
   - **b.** Determine ecosystem adaptive capacity to multiple pressures

Implementation of Ecosystem-based adaptation

3. **Draft Ecosystem-based adaptation plan**
   - **a.** Formulate project design for EbA strategy
   - **b.** Measure and monitor impact of intervention
   - **c.** Evaluation of effectiveness of EbA

Box 2. Framework for the implementation of Ecosystem based adaptation in groundwater management.

5. Conclusions and the way forward

Groundwater plays an integral role in sustaining certain types of ecosystems, and their associated ecosystem services. Since many ecosystems are highly dependent on the hydrological cycle and groundwater availability, many ecosystem services are directly or indirectly dependent on the availability and state of groundwater resources. Efforts to protect groundwater should focus primarily on the recharge areas because it is at the centre of preventing pollution and maintaining supply for both drinking water and ecosystems.

However, the potential and implementation of EbA is still poorly developed. There is a need for increased awareness of policy makers on the contribution of EbA to the overall quality of groundwater and ecosystems. In order to develop policies for EbA, such as the establishment of groundwater protection zones, there is a need for improved access to scientific-based evidence of the applicability, effectiveness and the socio-economic benefits of these measures. This could be demonstrated by pilot studies in various ecosystems, thereby providing the required knowledge and guidance to improve environmental policies.

6. Terminology

Adaptation: The adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities

Agricultural ecosystem: A spatially and functionally coherent area of agricultural activity, and includes the living and non-living components involved in that area as well as their interactions

Aquifer depletion: Continued withdrawal of water from groundwater or a reservoir at a rate greater than the rate of replenishment

Artificial recharge: Augmentation of the natural replenishment of groundwater in aquifers by artificial means

Coastal aquifer: Aquifer extending into a coastal zone, usually having an interface with seawater

Critical recharge areas: Recharge areas with a critical effect on recharge Adaptation strategies for improved groundwater recharge will be most beneficial

Drainage: Removal of surface water or groundwater from a given area by gravity or by pumping

Ecosystem: System involving the interactions between a community of living organisms in a particular area and its nonliving environment

Ecosystem services: The benefits people obtain from ecosystems Ecosystem services can be of direct or indirect benefit to humans and can be categorized in provisional, cultural, supporting and regulating services

Ecosystem-based adaptation: The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change

Floodplain: The area of land adjacent to a stream or river and flooded by the river

Groundwater dependent ecosystems (GDEs): A subset of ecosystems that are highly dependent on groundwater, require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements to maintain the ecological processes and ecosystem services

Groundwater recharge: Process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation Groundwater recharge can be local, occurring from infiltration via surface water bodies, or diffused by percolation of precipitation through the unsaturated soil zone across the landscape

Groundwater recharge area: Area which contributes water to an aquifer, either by direct infiltration or by runoff and subsequent infiltration

Groundwater zoning:	Identification of different recharge and discharge zones for the sustainable management of groundwater resources
Hyporheic zone:	Area where there is mixing of shallow groundwater and surface water
Resilience:	The capacity of an ecosystem to absorb disturbance without shifting to an alternative state and losing function and services
Riparian zone:	The interface between land and streams, rivers, lakes, reservoirs, and other inland aquatic systems that affect or are affected by the presence of water
Salt-water intrusion:	Phenomenon occurring when a body of salt water invades a body of fresh water; it can occur either in surface or groundwater bodies
Urban ecosystems:	The cities, towns, and urban strips constructed by humans
Vulnerability:	The degree to which a system is susceptible to, or unable to cope with the adverse effects of climate change, including climate variability and extremes (IPCC 2001)." Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. In EbA the ecosystems and their vulnerabilities are included in the analysis together with the vulnerability of communities.
Wetland:	Land area that is saturated with water, either permanently or seasonally

7. References

Andrade, A., Córdoba ,R., Dave, R., Girot, P., Herrera-F, B., Munroe, R., Oglethorpe, J., Pramova, E., Watson, J., Vergara, W. (2011) Draft Principles and Guidelines for Integrating Ecosystem-Based Approaches to Adaptation in Project and Policy Design: A Discussion Document. CEM/IUCN, CATIE. Kenya, available at www.iucn.org last accessed on 8 May 2014

ATTRA - Appropriate Technology Transfer to Rural Areas (2003) Protecting riparian areas: farmland management strategies. Available at: http://www.virginia.edu, last accessed on 1 May 2014

Bebarta, K. C. (2007) Forest planning at landscape level, Ashok Kumar Mittal

Bergkamp, G. and Cross, K. (2006) Groundwater and Ecosystem Services: towards their sustainable use. International symposium on groundwater sustainability (ISGWAS), Gland, Switzerland

Binns, J.A., Illgner, P.M. an d Nel, E.L. (2001) Water shortage, deforestation and development: south africa's working for water programme. Land degradation development 12: 341-355

Borsje, B.W., Wesenbeeck van, B.K., Dekker, F., Paalvast, P., Bouma, T.J., Katwijk, M.M., Vries de, M.B. (2010) How ecological engineering can serve in coastal protection. Ecological Engineering 37:113-122

Bridgham, S. D., Megonigal, J.P. Keller, J.K. Bliss, N.B., Trettin, C. (2006) The carbon balance of North American Wetlands Wetlands 26, 889–916

Carpenter, S., Walker, B., Anderies, J. M. and Abel, N. (2001) From metaphor to measurement: resilience of what to what? Ecosystems 4: 765–781.

CBD - Secretariat of the Convention on Biological Diversity (2009). Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. Montreal, Technical Series No. 41

Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D., Yan, D.J., Consultant, I. and Floor, T. (2007) The impact of sea level rise on developing countries: a comparative analysis. Policy Research Working Paper 4136. Washington DC, World Bank.

Döll, P. and Fiedler, K. (2008) Global-scale modeling of groundwater recharge. Hydrology and Earth System Science 12: 863–885

Environment Canada (2004) Threats to Water Availability in Canada. National Water Research Institute, Burlington, Ontario. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. 128

FAO - Food and Agriculture Organization of the United Nations (2003) Groundwater Management - The Search for Practical Approaches Water Reports 25, Rome

Fitts, C.R. (2002) Groundwater Science, Academic Press, London, UK

Gates, J.B., Scanlon, B.R., Mu, X., Zhang, L. (2011) Impacts of soil conservation on groundwater recharge in the semi-arid Loess Plateau, China Hydrogeology Journal 19: 865–875

Genesis programme (2013) Global climate and land use change and its relevance for groundwater systems, policy brief#5. Available at: http://www.bioforsk.no, last accessed at 10 April 2014

Gleeson, T., VanderSteen*, J.,* Sophocleous*, A.A.,* Taniguchi*, M.,* Alley*, W.M.,* Allen*, D.M and* Zhou, Y. *(*2010*)* Commentary: Groundwater sustainability strategies*,* Nat. Geosciences 3: 378–379

Goldscheider, N. (2005) Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany. Hydrogeology Journal 13: 555-564

Goldscheider, N. (2012) A holistic approach to groundwater protection and ecosystem services in karst terrains AQUA mundi 3(2): 117-124

GSI - Geological Survey of Ireland (2002) Groundwater Protection Scheme available at www.gis.ie last accessed at 12 May 2014

GW-MATE (2006) Groundwater dependent ecosystems - the challenge of balance assessment and adequate conservation. Briefing Note Series, Note 15, GW-MATE/World Bank, Washington DC.

Hancock, P.J., Boulton, A.J., Humphreys, W.F. (2005) Aquifers and hyporheic zones: Towards an ecological understanding of groundwater. Hydrogeology Journal 13: 98–111

Holling C. S (1973) Resilience and stability of ecological systems. Annual Review of Ecology, Evolution and Systematics 4: 1–24

Holling C. S (1996) Engineering resilience versus ecological resilience. In: Schulze P. C, editor. Engineering within ecological constraints. Washington: National Academy Press. 31–44

Huq, N., Renaud, F. and Sebesvari, Z. (2013) Ecosystem based adaptation (EbA) to climate change - integrating actions to sustainable adaptation. Available at: http://www.climate-impacts-2013.org, last accessed at 16 April 2014

IPCC - International Panel of Climate Change (2001) IPCC Third Assessment Report "Climate Change 2001" and the Synthesis Report, Geneva

IUCN - International Union for Conservation of Nature (2008) Agricultural Ecosystems, Facts and trends. Available at https://portals.iucn.org, last accessed at 10 April 2014

Kaat, A. and Joosten, H. (2009) Fact Book for UNFCCC Policies on Peat Carbon Emissions (Wetlands International, Wageningen, The Netherlands

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kværner, J., Muotka, T., Mykra, H., Preda, E., Rossi, P., Uvo, C. B., Velasco, E. & Pulido-Velazquez, M. (2013) Climate change impacts on groundwater and dependent ecosystems, Journal of Hydrology

Kløve, B., Allan, A., Bertrand, G., Druzynska, E. Ertürk, A., Goldscheider, N., Henry, S., Karakaya, N., Karjalainen, T.P., Koundouri, P.B., Kupfersberger, H., Kværner, J., Lundberg, A., Muotka, T., Preda, E., Pulido-Velazquez, M., Schipper, P. (2011) Groundwater dependent ecosystems. Part II. Ecosystem services and management in Europe under risk of climate change and land use intensification, Environmental Science & Policy, 14:7 782-793, ISSN 1462-9011

Lal, R. (2008) Carbon sequestration. Philosophical Transactions of the Royal Society 363 815-830

Lawrence, J.E., Skold, M.E., Hussain, F.A., Silverman, D.R., Resh, V.H., Sedlak, D., Luthy, R.G. and McCray, J.E. (2013) Environmental Engineering Science. 30(8): 480-501.

Leblanc, M. J. et al. (2009) Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia. Water Resources Research 45

Lee, L.J.E., Lawrence, D.S.L., and Price, M. (2006) Analysis of water level response to rainfall and implications for recharge pathways in the Chalk aquifer, SE England. Journal of Hydrology 330: 604–620

Liu Y, Liu C, Wang S, Guo K, Yang J, et al. (2013) Organic Carbon Storage in Four Ecosystem Types in the Karst Region of Southwestern China. PLoS ONE 8(2): e56443

Margat, J., and van der Gun, J. (2013). Groundwater around the World. Leiden, Netherlands: CRC Press/Balkema

MEA - Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC

Mitra S, Wassmann R, and Vlek, P.L.G. (2005) An appraisal of global wetland area and its organic carbon stock. Current Science 88: 25 - 35

Mitsch and Gosselink (2007) Book Wetlands John Wiley and Sons, Inc, Hoboken, New Jersey

Morris, B.L. (2003) Groundwater and its Susceptibility to Degradation: a global assessment of the problem of options for management. Early Warning and Assessment Report series

Powell, N., Osbeck, M., Tan, S.B., and Toan, V.C. (2010) World Resources Report Case Study. Mangrove Restoration and Rehabilitation for Climate Change Adaptation in Vietnam World Resources Report, Washington DC. Available at http://www.worldresourcesreport.org, last accessed on 7 May 2014

Ramsar (1971) Convention on Wetlands of International Importance s Waterfowl Habitat. UN Treaty Series No. 14583

Ramsar (2011) Factsheet on wetland ecosystem services, available at http://www.ramsar.org, last accessed on 9 April 2014

Ravbar, N. and Goldscheider, N. (2007) Proposed methodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Slovenia. Acta Carsologica 36: 397-411

Richardson, E., Irvine, E., Froend, R., Book, P., Barber, S. and Bonneville, B. (2011), Australian groundwater dependent ecosystems toolbox part 1: assessment framework, National Water Commission, Canberra

Rouse, W.R., Blyth, E.M. ,Crawford, R.W. et al. (2003). Energy and water cycles in a high-latitude, north-flowing river system. Summary of results from the Mackenzie GEWEX study – Phase 1. Bull. Am. Met. Soc., 73-87.

Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T. (2010) Groundwater use for irrigation--a global inventory. Hydrology and Earth System Sciences Discussions 7(3): 3977-4021

Smith, V.H., Tilman, D. and Nekola, J.C. (1999) Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution 100: 179–196

Stauffer, F. in (2011) Groundwater Management Practices, CH15 Protection of Groundwater Environment Findikakis, A, N. and Sato, K. Taylor and Francis

Stomberg, J., Tiller, R.,and Richter, B. (1996) Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona, Ecological Applications 6 (1): 113–131

Stromberg, J.C. (1993) Frémont Cottonwood-Goodding Willow Riparian Forests: A Review of Their Ecology, Threats, and Recovery Potential, Journal of the Arizona-Nevada Academy of Science 27: 97–110

Trautman, N. M. and Porter, K. S. (2012) Factsheet: Water and the soil. Available at http://psep.cce.cornell.edu last accessed at 8 May 2014

Treidel, H., Martin-Bordes, J.J., Gurdak, J.J. (2012) Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations. International Association of

Hydrogeologists (IAH) – International Contributions to Hydrogeology. Taylor & Francis publishing, 414

Wada, Y., Beek van, L.P.H., Kempen, C.M., Reckman, J.W.T.M., Vasak, S. and Bierkens, M.F.P. (2010) Global depletion of groundwater resources. Geophysical Research Letters, 37:20

Wetzel, R. G. (2001) Limnology: Lake and River Ecosystems. Academic Press, London.

Wilson, M. A. and Carpenter, S.R. (1999) Economic valuation of freshwater ecosystem services in the United States: 1971-1997. Ecological Applications 9: 772-783

Winter, T. C. (2000) The vulnerability of wetlands to climate change: a hydrologic landscape perspective. Journal of the American Water Resources Association, 36: 305–311

Winter, T.C., (1999) Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal 7: 28–45

World Bank (2010), Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India, World Bank.

WWAP - World Water Assessment Programme (2009) The United Nations World Water Development Report 3: Water in a Changing World. Paris: UNESCO, and London: Earthscan.

Zhang S, Lövdahl L, Grip H, Jansson P-E, Tong Y (2007) Modelling the effects of mulching and fallow cropping on water balance in them Chinese Loess Plateau. Soil Tillage Res 93: 283 - 298

Appendix I

	Principle	Indicator
1	Flexible management structure	Adaptive management approaches
		Incorporate clear planning principles
		Promote existing best resource management practices
		Community based management
2	Knowledge based adaptation	Build knowledge and awareness
		Local science-management partnerships
		Best available science and local knowledge
		Culturally appropriate
3	Maximum stakeholder involvement	Maximum stakeholders
		Involving local communities
		Multi-partner strategy
		Collaboration and trust
4	Variety	Work with uncertainties
		Explore and priorities potential climate change impacts
		Explore a wide spectrum of adaptation options
		Understand trade-offs
5	Multi Scale Operation	Integration with development strategies
		Support sectoral adaptation planning
		Multiple geographic scales
6	Ensuring Governance	Accountable
		Transparent decision making
		Gender balancing
		Equity
		Monitor and evaluate systematically
7	Resilience building	Resilience vs resistance
		Manage climate variability
		Manage long-term climate change

Table x. Major principles and indicators of EbA (adapted from Huq et al., 2013)