Analytical Framework for Assessing Groundwater Resources with a Focus on Nature Based Solutions as Interventions

Authors:
Aaron Firoz, Zryab Babker, Ian McNamara, Santiago Penedo, Lars Ribbe - ITTrms e.V.
Antonio Cardona, Javier Castro - Universidad Autónoma de San Luis Potosí

Main author and contact: aaron.firoz@gmail.com

Supported by:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
based on a decision of the German Bundestag

Executive Summary

The context

Water insecurity is a growing global concern. The increasing imbalance between water supply and water demand in many parts of the world, and in some areas exacerbated by a changing climate, have made water availability and water scarcity are becoming an increasingly pressing issue. The role of groundwater and aquifers in buffering the effects of climate variability on water supply is increasingly acknowledged (Green, 2016), but can only be fully realized with a more robust understanding of groundwater resources and our dependencies on them.

Created in 2011, the Latin American Water Funds Partnership, is an agreement between the Inter-American Development Bank (IDB), the FEMSA Foundation, the Global Environment Facility (GEF), the German Ministry of Environment (through the International Climate Initiative) and The Nature Conservancy (TNC), with the goal of improving and contributing to water security in Latin America and the Caribbean through the creation and strengthening of Water Funds. To achieve this goal, the Water Funds are financial and governmental/political mechanisms that unite public and private stakeholders as well as civil society with the aim to contribute to water security and sustainable river basin management with nature-based solutions (NBS) and sustainable management policies.

In this context, the Water Funds aim to:

- Provide scientific evidence that contributes to improving knowledge about water security;
- Develop a shared and actionable vision of water security;
- Summon together actors who, through collective action, promote the political will necessary to achieve significant, positive and significant impacts;
- Positively influence water governance and decision-making processes;
- Promote the implementation of NBS and other innovative projects in the basins; and
- Provide a cost-effective mechanism to invest resources for water sources in basins.

As more Water Funds are developed in cities dependent on groundwater, it is important to ensure the sustainable management of groundwater systems to help combat water scarcity. This can serve as a cost-effective approach for regions to reduce the risk of groundwater overexploitation or depletion while at the same time enhancing supply resiliency and protecting groundwater-dependent ecosystems, among other co-benefits (Rohde et al., 2018).

One of the key ways in which the Water Funds contributes to water security is by promoting the protection and restoration of natural ecosystems. There is the potential to enhance the sustainability of groundwater resources through NBS to an extent that far exceeds the extent of current watershed conservation programs. Thus, it is important to inform the decision makers that this opportunity hinges in part on the business cases for water users regarding the benefits of NBS compared to conventional engineering solutions.

Currently, limited literature is available regarding NBS for sustainable groundwater resources management. Compounding this problem, many actors who wish to implement these interventions in their own region lack the examples and proper assessment tools to undertake such tasks in a robust manner. Guidelines that provide step-by-step approaches to groundwater resources assessment are available; however, they typically: i) are difficult to apply in data-scarce regions; ii) are very technical and therefore difficult for non-experts to apply; and iii) have a limited (or non-existent) focus on the potential of NBS and their quantitative evaluation across the life cycle of a project.

The Groundwater Resources Assessment Framework (GRAF)

To address these shortcomings, we present a simplified groundwater resources assessment framework (GRAF, see Figure A1) that combines the quantification of the components of groundwater resources with the sustainable yield concept and assesses potential interventions using NBS as well as offering guidelines to assess their performance.

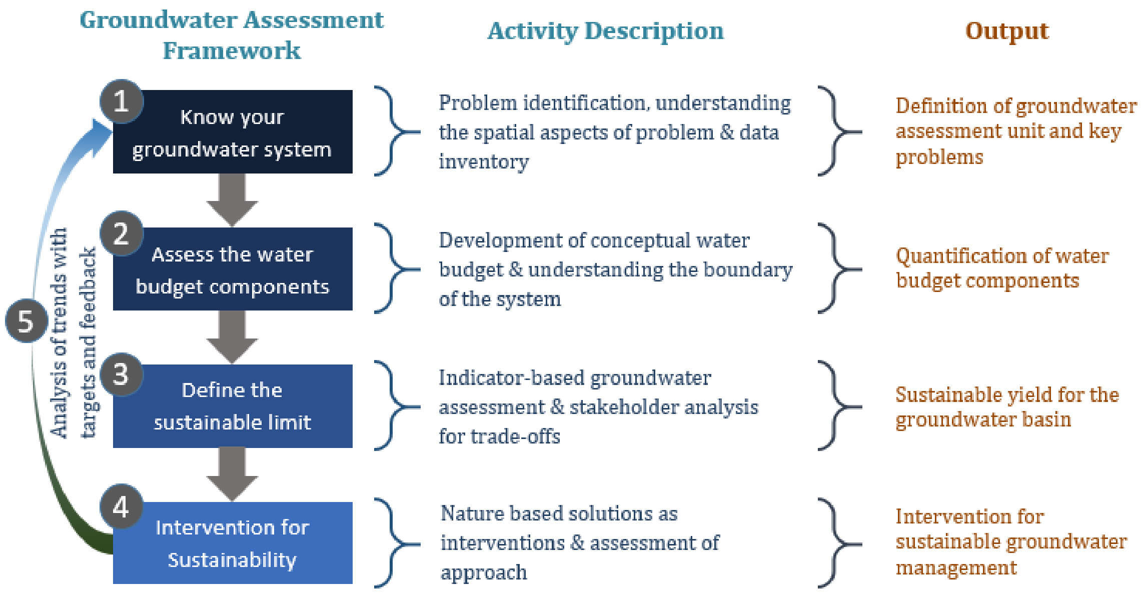

Figure A1: The groundwater resources assessment framework (GRAF) and associated analyses needed to assess the sustainable yield concept of groundwater assessment and intervention options for implementing nature-based solutions

Using available data and information along with an understanding of the identified groundwater problems of the selected area, the first step of the GRAF is to select the spatial domain of the groundwater system. The second step is to develop the conceptual water budget of the groundwater system, which quantifies the components of the water cycle and is then used to assess the state of the system. An indicator-based assessment method is then applied to ascertain the status of the aquifer and through multi-stakeholder involvement, the sustainable yield concept is then applied. This process is linked to the drivers, pressures, state, impact, and response (DPSIR) framework, which helps the user categorize the causes of the problem and identify where particular interventions are required.

This framework, consistent with the goals of the Water Funds, promotes NBS as interventions to improve groundwater sustainability and overall water security. In order to achieve this, the delivery of a sound methodology for quantitative evaluation of NBS is vital. This report therefore also includes a dynamic assessment methodology to allow evaluation of the effectiveness of NBS for groundwater interventions across the life cycle of a project.

This Framework and the Water Funds Literature

Water Funds are organizations that design technical, financial and governance mechanisms around the common goal of contributing to water security in a given watershed by promoting NBS within a sustainable watershed management vision. For more than 15 years and in many watersheds, Water Funds have enable downstream water users to invest in targeted activities aimed to improve water quality and quantity.

With this experience, The Nature Conservancy have generated multiple guidance resources for Water Fund practitioners around the globe. This document is oriented toward decision makers, scientists and non-scientists who are interested in groundwater resources assessment and NBS, and complements the current Water Funds resources and documentation already available.

For Water Fund practitioners interested in setting a new project, we recommend that this framework is read together with the Water Funds Field Guide (2018) and Water Funds: Conserving Green Infrastructure (2012). For scientists willing to support Water Fund data gathering and analysis, we recommend that they also read A Guide to Monitoring and Evaluating Water Funds (2019) and A Primer for Monitoring Water Funds (2013).

This document is focused on providing guiding material for the development of the science component of Water Funds, focused on groundwater resources and the potential impact of NBS towards achieving water security. For relevant literature and interactive material on the other components of Water Funds such as governance, finance and communications, the ideal starting point is the Water Funds Toolbox website.

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1. Introduction

Globally, water plays a vital role in supporting life and functioning ecosystems while at the same time contributing to socioeconomic development. Groundwater quantity assessment frameworks typically focus on the water balance (which uses hydrogeological information) and may incorporate additional elements and economic information. Such frameworks can be considered useful tools for guiding water management at different decision-making scales, particularly when concerning the quantitative management and efficient allocation of water resources (European Commission, 2015). However, most of these frameworks contain sophisticated and technical approaches that require comprehensive data and use of numerical models, making them difficult to apply broadly, especially for non-experts and in data-scarce regions.

1.1 Existing Groundwater Assessment Frameworks

In many countries, there are several national laws dealing with groundwater, irrigation laws, regulations and decrees, as well as formal and informal norms for groundwater development and use. These procedures define instruments devised to manage groundwater. Some of the instruments include groundwater rights and concessions. Among the Latin American and Caribbean countries, groundwater is formally managed by government agencies (such as ministries of water resources, environment, agriculture or even energy), using different conceptual methodologies. Aquifer management strategies differ depending on many variables such as the size of the countries and aquifers, population densities and irrigated areas.

Groundwater management requirements and strategies are dynamic and change over time; for example, for aquifers with incipient stress (few local conflicts between users), only relatively simple management tools are needed (e.g., appropriate well spacing according to the aquifer properties). On the other hand, when an aquifer is in a stage of unstable development (e.g., excessive uncontrolled extraction with water quality deterioration and conflicts between stakeholders), specific and detailed regulatory framework with demand management and/or artificial recharge are urgently needed (Giordano & Villholth, 2007). Groundwater management instruments can be employed at any stage of aquifer use; however, in most countries (especially in developing countries), collection and systematization of information begin only when environmental and social problems derived from major aquifer stress are identified (Giordano & Villholth, 2007).

Groundwater use rights (permits, concessions, licenses, entitlements) are typically assigned based on water availability. Groundwater balances are often applied to determine the water availability for any specific aquifer. For example in Colombia, the Environmental Management Program (PMAA) outlines water management at the aquifer level, incorporating environmental or social problems (such as water depletion and/or contamination, conflicts between users, etc.). The Colombian framework designates the use of groundwater balances using numerical models as the main management tool, although simplified water balances are also helpful when available information is limited (MADS, 2014). Mexico is another example where national regulations for groundwater management define a methodology for groundwater availability estimation using the water balance approach (NOM-011-CNA-2015; DOF, 2015). The average annual water availability for any aquifer in Mexico is determined from the estimation of the total recharge with the subtraction of ecological requirement and the total groundwater extraction for the aquifer. Total annual recharge is estimated from the change of water storage in the aquifer plus the total estimated and measured water discharges (total water output, including natural discharge, baseflow, spring discharge, evapotranspiration, groundwater lateral flow outside of the aquifer, and well extraction). In addition, the strategy for the evaluation and management of transboundary aquifers in the Americas define groundwater availability as the sustainable water volume that can be extracted from an aquifer without producing a reserve decrease, without deterioration of water quality and ensuring the preservation of ecosystems within the country boundaries (UNESCO, 2015). Total recharge estimated from a water balance approach, in all the involved countries sharing the aquifer, is the basis for the determination of water availability.

An alternative approach is used for many other countries such as USA and India; they have adopted the concept of safe yield (in terms of annual recharge) as the sustainable extraction limit. Groundwater development in Australia allows a more conservative approach to sustainable yield; they recognize that any substantial aquifer development will modify the natural water balance in the aquifer, producing some environmental or social impacts. They therefore interpret sustainability as the "social acceptability of impacts" (Herczeg & Leaney, 2002). In fact, the important character of society for the sustainable yield definition includes a range of technical as well as social, environmental and economic factors, and public participation and feedback is necessary to determine the sustainable concept (ARMCANZ, 1996). From this concept, the National Groundwater Committee of Australia (2004) defined the nationally accepted definition of sustainable groundwater yield in Australia as "*the groundwater extraction regime, measured over a specified planning timeframe, which allows acceptable levels of stress and protects dependent economic, social, and environmental values"*. They implemented the sustainable yield as an extraction regime rather than just a volume, facilitating the subdivision of groundwater management units into zones.

1.2 Why Do We Need a New Framework?

We can see that some groundwater assessment frameworks make use of the water balance and that several national frameworks are moving towards the incorporation of sustainable yield. Our framework provides a general approach to assess groundwater resources using the water balance and the sustainable yield, and is transferable to different regions around the globe and to aquifers at varying spatial scales. More importantly, this framework addresses and links three key concerns that are typically not addressed in existing frameworks:

- It is implementable in situations ranging from high data availability to data scarcity (using simplified methods for the latter)
- It can be implemented by both experts and non-experts in the field of groundwater
- It includes a general evaluation of NBS as interventions

The main objective of this framework is to simplify the assessment of groundwater resources. Application of this framework allows the user to quantify the components of groundwater resources in the context of the sustainable yield concept and examine the potential to implement NBS as interventions. Furthermore, the framework provides a dynamic assessment methodology for decision makers to evaluate the effectiveness of NBS interventions across the life cycle of a project. The framework is centered on the water balance approach, which specifies that the rate of change in water stored in a hydrogeological unit (e.g., groundwater basin, catchment, aquifer level) is balanced by the rates at which water flows in and out of the unit. In addition, this framework considers the ecological, economic, social and human requirements of the system.

Box 1: Safe yield or sustainable yield?

Safe yield is the amount of groundwater that can be withdrawn from an aquifer without producing an undesired result (Todd, 1959). Any withdrawal higher than the safe yield is defined as an **overdraft**. Many alternative definitions of safe yield have been published, and an extended definition of safe yield is the "attainment and maintenance of a long term balance between the annual amount of groundwater withdrawn by pumping and the annual amount of recharge" (Sophocleous, 1997). In practical applications, the safe yield of a groundwater basin is often calculated as a percentage of the natural recharge (Zhou, 2009). A misperception among many hydrogeologists and water resources managers is that the development of groundwater is considered to be 'safe' if the rate of groundwater withdrawal does not exceed the rate of natural recharge. Implementation of this 'safe yield' policy has resulted in continuous decline of groundwater levels around the world, streamflow depletion and loss of wetlands and riparian ecosystems (e.g., Sophocleous, 2000). This shortcoming of safe yield led to calls for a new paradigm shift towards the sustainable yield concept, which accounts for the entire water cycle.

Sustainable yield

Alley and Leake (2004) viewed the journey from safe yield to sustainability as a transition in our understanding of the dynamic nature of groundwater and its linkage across the biosphere and to human activities. Today, it is widely recognized that pumping can not only affect surface water supply for human consumption, but also the maintenance of streamflow requirements for fish and other aquatic species, the health of riparian and wetland ecosystems, and other environmental needs. How much groundwater is available for use depends on how **changes in recharge and discharge affect** the surrounding environment and the **acceptable trade-off between groundwater use and these changes**. Achieving this trade-off in the long-term is a central theme in the evolving concept of sustainability (Alley et al., 1999; M Sophocleous, 2000; Alley & Leake, 2004). The basin sustainable yield should be a compromise solution, where the yield is low enough to ensure that the groundwater body can be sustained by recharge without unacceptable environmental consequences but also that the yield is high enough to cause neither economic nor social problems (Zhou, 2009). Therefore, the basin sustainable yield should consider the following:

- The sustainable pumping rate should be defined by the water balance equation. This means that the sustainable yield rate (i.e., sustainable rate of groundwater extraction) and residual discharge are balanced by natural recharge and induced recharge (including groundwater re-entering the system after being extracted).
- Environmental constraints (i.e., considering groundwater as part of an integrated water and ecological system).
- Groundwater extraction should cause neither the excessive depletion of surface waters nor the excessive reduction of groundwater discharge to springs, rivers, wetlands, and phreatophytes.
- Economic constraints require maximizing groundwater development to fulfil water demand for irrigation and industrial use.
- The safe access of good quality groundwater for drinking water supply and an equitable distribution of shared groundwater resources by all. Downstream users should have the same water rights as the upstream users; rural communities should have the same water right as urban inhabitants. Groundwater extraction should not damage the existing water user rights of spring and surface water.

Many groundwater resources assessments consider issues of demand and yield without directly addressing a fundamental question concerning groundwater resources, i.e., how should the sustainable yield of a groundwater basin be defined? This framework elaborates numerous considerations that must be addressed in defining sustainable yield so that the definition can be more useful in practical groundwater management aspects. These include: the consideration of the spatial and temporal aspects of the problem, the development of a conceptual water balance, the influence of system boundaries, the need to examine water demand as well as available supply for all water users, the need for stakeholder involvement, and the issue of uncertainty in our understanding of the components of the hydrogeological system.

In this framework, the components of water balance are assessed through an indicator-based approach to define the state of the groundwater system under consideration. Furthermore, the potential to explore NBS as interventions to improve the groundwater system are included. This framework supports: integrated groundwater resources management and decision-making at multiple scales; a critical review of current water allocation mechanisms between and within water sectors; the definition of the sustainable water yield; and the identification of interventions that enhance the sustainability of groundwater resources.

This framework supports scientists, Water Fund managers, and decision makers all over the world, in establishing and applying water balances as essential tools for the effective management of groundwater resources. The sustainable yield concept, coupled with an indicator-based assessment, provides a guideline for intervention mechanisms, with a priority for NBS.

Box 2: The benefits of applying this framework

By applying this framework, the user will:

- Improve their understanding of whether particular groundwater resources are at risk.
- Support the identification of groundwater problems and contribute to shared knowledge, facilitated through comparable data, harmonized definitions and common understanding of groundwater assessment mechanisms.
- Obtain an overview of the spatial and temporal variability of water resources.
- Determine and quantify the gap between actual groundwater status and good groundwater status, which needs to be bridged with appropriate measures.
- Identify how to best target efforts when selecting measures to improve the state of groundwater resources.
- Develop a solid base for additional water resources assessment and management such as: runoff estimation, groundwater recharge potential and ecological flows
- Develop the ability to combine and structure hydrological and socioeconomic information on multiple variables (climate, water resources, water uses, etc.)
- Identify priority data and possible “data gaps”.
- Facilitate the implementation of NBS to address groundwater problems.
- Assess the effectiveness of NBS interventions in addressing groundwater problems.

It is also important to monitor the progress and benefits of an NBS intervention and its performance over time. This framework therefore includes a dynamic assessment methodology supporting time-based NBS performance tracking and monitoring using performance indicators. This simple methodology can be used to facilitate decision-making, NBS project deployment, and improve transparency of the value added over time.

This framework is designed in a way that both water professionals and non-water professionals (i.e., those with a limited knowledge of groundwater hydrology) can assess and understand the groundwater resources and processes of an area. This guidance document proposes flexible assessment methods that account for local conditions and specificities. These management scales can range from a small aquifer to a large groundwater basin in which several aquifers are interconnected, or even to the regional management level.

The methodology framework relies primarily on having access to existing data. Depending on data availability and the characteristics of the aquifer, the user may need to rely on published values for similar regions, global datasets, or interpolation or extrapolation of available data in order to fill data gaps so that the indicators can be calculated.

1.3 This Framework and the Water Funds Project Cycle

The Nature Conservancy and partners have standardized the Water Fund development process around a five-phase project cycle: Feasibility, Design, Creation, Operation and Maturity. Across these five phases there is a science component which builds the case for the appropriate development of the Water Fund.

This Groundwater Resources Assessment Framework (GRAF) aims to support the science work of Water Funds practitioners and can be navigated following the Water Fund project cycle phases (Table 1).

Table 1: The five-phase project cycle of Water Fund projects and the GRAF

Water Fund Project Cycle phase	Key Science Insights	This GRAF
1. **Feasibility**	Eligibility Screening: Summary level description of Water Security challenges Situation Analysis Report: Detailed review of available technical information needed to assess the feasibility of a Water Fund	Chapter 4. Know Your Groundwater System
2. **Design**	Portfolio of Interventions: Evaluation of possible activities that can improve the groundwater resource Business Case: Quantifying the value of investing in NBS in terms of financial benefit Monitoring Plan: Rationale, indicators and strategies to evaluate the impact of Water Fund activities	Chapter 5. Assessing the Water Budget Chapter 6. Indicator-Based Assessment
3. **Creation**	Water Fund Operating Plan: Priorities for on the field interventions, stakeholder engagement and fundraising	Chapter 7. Nature Based Solutions as Interventions
4. **Operation**	Periodic Progress Reports: Measurement of Water Fund impacts toward objectives and adaptive management	Chapter 6.2. Indicators for the Assessment Chapter 7.5. Dynamic Assessment Methodology of NBS Performance
5. **Maturity**	Systematic monitoring of impacts that allows for continual improvement of the Water Fund	Complete integration of the GRAF within Water Fund operating and monitoring plans

1.4 Framework Structure

The framework is structured as follows:

- **Chapter 2:** Definitions
- **Chapter 3:** Framework Overview
- **Chapter 4:** Know your Groundwater System
- **Chapter 5:** Assessing the Water Budget
- **Chapter 6:** Indicator-based assessment and Sustainable Yield
- **Chapter 7:** Nature Based Solutions as Interventions
- **Appendix 1:** Glossary of Terms
- **Appendix 2:** List of Data
- **Appendix 3:** Groundwater Assessment of an Assessment Unit
- **Appendix 4:** Calculations of Components of Water Balance Equation
- **Appendix 5:** Calculation Methods for Environmental Flow

2. Definitions

2.1 Water Funds

For **detailed information on Water Funds** please visit the Water Fund Toolbox website and the Latin America Water Funds Partnership website.

The mission of a Water Fund is to contribute to ecosystem integrity that supports water security in a particular city or river basin. The conceptual framework of the Water Funds is water security, which involves:

- Domestic Water Security: satisfying water consumption and health needs in the homes of rural and urban communities;
- Economic Water Security: supporting productive economic activities such as agriculture, industry and energy;
- Urban Water Security: developing healthy, dynamic and liveable cities with a strong water culture;
- Environmental Water Security: restoring healthy ecosystems, aquifers and rivers;
- Resilience against natural disasters; and
- Building communities that are resilient and adaptive to climate change.

Preserving the integrity of natural ecosystems, i.e., conserving and restoring natural infrastructure, is essential for all dimensions of water security (Calvache et al., 2012).

2.2 Water Security

We consider the definition of water security from UN Water (2013):

"The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."

2.3 DPSIR Framework

The Drivers-Pressures-States-Impacts-Responses (DPSIR) framework allows us to determine and assess the links between human pressures and state-changes in a system (Figure 1). This framework evolved from the stress-response framework developed by Statistics Canada in the late 1970s and was further developed in the 1990s by the OECD and the UN, among others (Pandey & Shrestha, 2016). The causal chain of the framework functions as a tool to integrate knowledge from diverse disciplines and has been widely adopted in environmental assessments (Borji et al., 2018). One of its main advantages is that it captures the key relationships between societal and environmental factors and can, therefore, be used as an effective communication tool between researchers, policy makers, and stakeholders (Pandey & Shrestha, 2016).

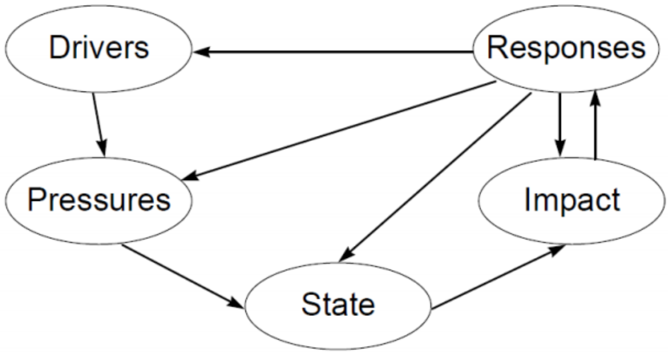

Figure 1: The DPSIR Framework (EEA, 1999)

With regards to groundwater assessment, the components of DPSIR are as follows (Pandey & Shrestha, 2016):

- **Drivers** refer to fundamental processes in a society, which drive activities having a direct impact on the groundwater environment.
- **Pressures** are referred to as direct stress brought about by expansion in an anthropogenic system and associated interventions in the natural environment.
- **State** describes conditions and trends in the groundwater environment induced mainly by human activities.
- **Impacts** deal with effects on the anthropogenic system, which result from changes in the state of the natural environment, contributing to the vulnerability of both natural and social systems.
- **Responses** consist of the actions of society and/or decision makers to modify/substitute drivers, to reduce/prevent pressures, to restore/influence states, and mitigate/reduce impacts.

2.4 Nature-Based Solutions in the Groundwater Context

Nature-based solutions (NBS), also known as "green infrastructure", are defined by Cohen-Shacham et al. (2016) as:

"… actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"

Within the context of groundwater management, we adopt the definition from GRIPP (2018b) for NBS aimed at addressing groundwater as interventions that:

"... intentionally utilize and manage groundwater and subsurface systems and processes in order to increase water storage, retention, water quality and environmental functions or services for the overall benefit of water security, human resilience, and environmental sustainability."

3. Framework Overview

The idea of deploying "Sustainable Yield" to complement groundwater resources assessments has been receiving widespread interest (van der Gun, 2012). The reliable assessment of groundwater resources requires application of a methodological framework that quantifies the different components of the water cycle, links the ecosystem, socio-economic and human spheres and can quantify the impacts of interventions (e.g., NBS). Implementation of **this Groundwater Resources Assessment Framework (GRAF)** over a defined assessment unit leads to an understanding of the system and its water budget. An indicator-based assessment is used to obtain the state of the system itself and characterize the cause and effect relationships among different elements, based on the DPSIR approach. Through the involvement of stakeholders, the sustainable yield for the groundwater basin is determined, and the GRAF promotes NBS as interventions for working towards this desired state. The five steps of the GRAF are illustrated on Figure 2, with these steps described in detail in Chapters 4 to 7. The appendices provide extra information to assist the user in understanding groundwater related terminology, collecting and understanding relevant data, calculating components of the water balance equation, calculating the environmental flow, and generate maps as outputs of their evaluation.

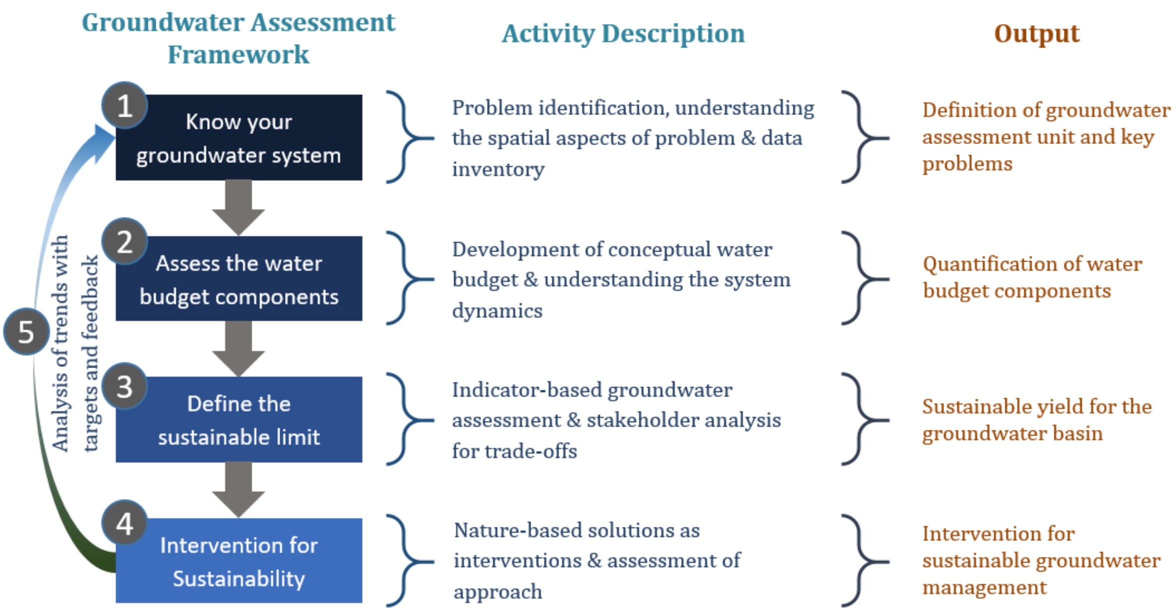

Figure 2: Groundwater Resources Assessment Framework (GRAF), including the sustainable yield concept and the potential to implement nature-based solutions (simplified version)

A more detailed illustration of this five-step process is shown on Figure 3**.**

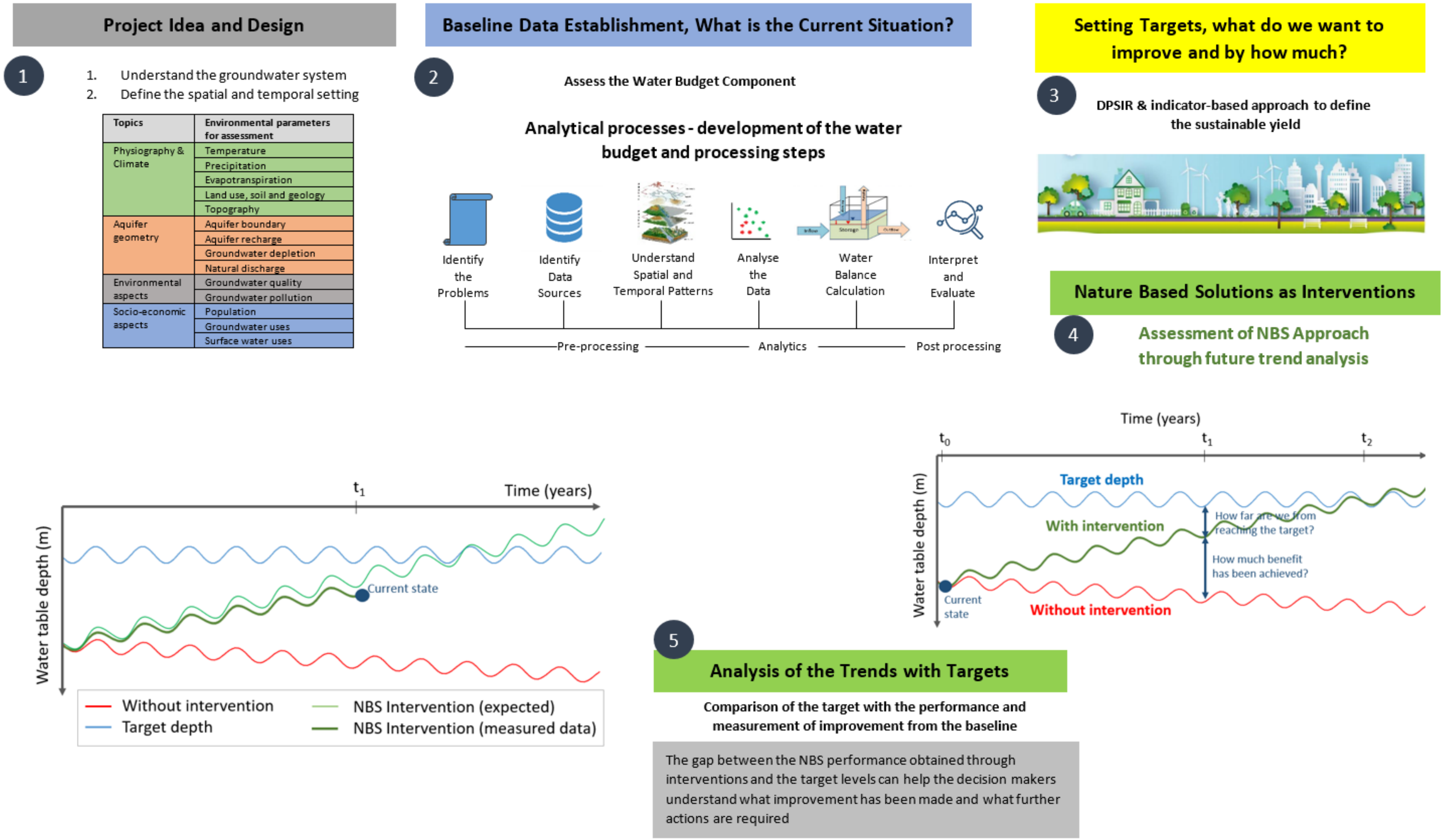

Figure 3: Overview of the steps involved in the Groundwater Resources Assessment Framework, focusing on nature-based solutions as interventions

Step 1: Know your groundwater system

This step defines the purpose and focus of the analysis. Its primary value is to establish an overall strategy for the sustainability of the groundwater system over an area. A broad, initial spatial assessment of the problem can place groundwater concerns into the context of sustainability, environmental protection plans and economic development policies of the region. From there, specific issue identification follows, aimed at zooming in on the priority groundwater concerns for the region. Once the specific issues are identified, the final step of this step is to identify the data available to undertake the groundwater resources assessment.

Step 2: Develop a conceptual water budget

Developing a water budget quantifies the relationships between the natural watershed, groundwater systems and anthropogenic changes to the water cycle. Developing this water budget requires a good understanding of the flow system of the groundwater basin, thus providing the building blocks for the determination of the sustainable yield. Furthermore, separating the components of the water budget assists in organizing data collection and analysis (Maimone, 2004).

Step 3: Define the sustainable limit

To define the sustainable limit, we also need to understand the role of human influences (e.g., groundwater pumping and associated recharge, as well as surface water discharge and withdrawals), including future projections (Maimone, 2004). To achieve this, an indicator-based assessment, as proposed by Vrba and Lipponen (2007), can be used to evaluate the groundwater basin status. This assessment enables the identification of the key areas that require intervention and helps define the sustainable yield of the groundwater basin. For this process, stakeholder feedback is important because the definition of the sustainable yield typically involves a compromise solution regarding aquifer exploitation allowances (i.e., understanding extraction needs but also ensuring that such allowances will not cause unacceptable environmental, economic, or social consequences).

The sustainable limit cannot simply be calculated using the water balance equation; it requires an assessment of the dynamic response of the groundwater basin to the anthropogenic changes to the regime, including its effects on the environment and society. Because of conflicting stakeholder interests, a participative discussion is recommended to manage trade-offs and achieve a groundwater development plan that is agreed upon by all involved parties. Maimone (2004) describes a practical approach to the definition of a sustainable approach that includes considerations of spatial and temporal aspects, conceptual water balance, influence of boundaries, water demand and supply, and stakeholder involvement.

Step 4: Intervention through nature-based solutions (NBS)

The applied DPSIR framework embedded within the indicator-based approach helps define potential interventions (i.e., “responses” in the DPSIR framework) for the groundwater basin. This serves as the entry point for the implementation of NBS to strive for sustainable groundwater management of the area. In an ideal case, the NBS would be implemented in an identified recharge zone where green infrastructure has the potential to enhance recharge processes or to purify the water that enters into the groundwater system.

Indicators can be used to monitor the performance of the NBS interventions. This process provides useful information for scientists, Water Fund managers, and decision makers in their water planning and strategy development activities. A simple way to monitor the effectiveness of the intervention is through using indicators and a time series future trend analysis at the site of a particular NBS intervention compared with baseline data. Typically, the baseline will be the projected groundwater condition at the site of the proposed intervention, but assuming that no intervention is made.

Step 5: Analysis of the trends with targets

To quantify the extent to which the NBS interventions achieve their aim, the fifth step is the comparison of trends with set targets. This step aims to quantify the effectiveness that the NBS intervention has had in reaching the targets, by using time series analyses and indicators. This results of this step help decision makers understand whether the response to the groundwater problem needs to be changed in any way. Application of this framework is a cyclical process, and after Step 5, the user returns to Step 1 to reassess the problem.

4. Know your Groundwater System

Box 3: Water Funds Feasibility phase and this chapter

This chapter provides guidance on the systematic gathering and analysis of information needed for Eligibility Screening and Situation Analysis for Water Funds in areas that depend on groundwater resources.

The purpose of a Feasibility analysis in a Water Fund development process is to understand the current Water Security condition and how a Water Fund can positively contribute to its improvement.

More information on the Water Fund Project Cycle can be found here.

The four steps to know your groundwater system are:

1. Identify the key problems
2. Define the boundary of the system
3. Define the temporal aspects of the problem
4. Collect groundwater data and related information

4.1 Identification of the Key Problems

This step sets the parameters for the assessment by identifying the key issue or issues in the groundwater system. The first step is to identify what is known about the state of groundwater and the groundwater issues specific to the study area. This should include developing a baseline picture of what data are available on the state of groundwater and water uses.

Within this step, the scope of the assessment should be defined (e.g., whether the GRAF is applied as a detailed study that will result in meaningful long term metrics or as a high level study). This will allow early communication of realistic expectations for results. Issue identification aims at defining the groundwater basin area, identifying all useful data, monitoring infrastructure, and evaluation tools and resources.

A significant challenge at the locations of many potential projects, especially those for Water Funds, is the availability of data and information to support the GRAF. We therefore recommend the generation of a comprehensive data inventory, including both current and historical data. Engaging stakeholders early in the evaluation may assist in the identification of various data sources, both from the private sector (utilities, resource companies, etc.) and the public sector (provincial ministries, federal departments, municipalities, etc.).

Box 4: General facts and concepts about groundwater

Adapted from: Alley et al. (1999)

1. Groundwater occurs almost everywhere beneath the land surface.
2. Natural sources of freshwater that becomes groundwater are:
   a. Recharge from precipitation that percolates through the unsaturated zone to the water table (see Figure 4).
   b. The losses of water from streams and other bodies of surface water such as lakes and wetlands.
3. The top of the subsurface groundwater body is called the water table. This surface fluctuates seasonally and from year to year in response to changes in recharge from precipitation and surface water bodies as well as to changes in discharges and groundwater extractions.

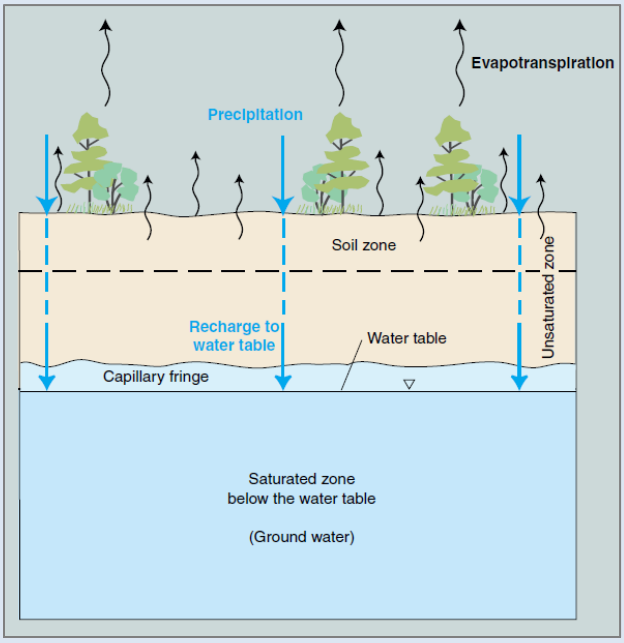

Figure 4: The unsaturated zone, capillary fringe, water table, and saturated zone (Alley et al., 1999)

Water beneath the land surface occurs in two principal zones, the unsaturated zone and the saturated zone. In the unsaturated zone, the spaces between particle grains and the cracks in rocks contain both air and water. Although a considerable amount of water can be present in the unsaturated zone, this water cannot be pumped by wells because capillary forces hold it too tightly.

In contrast to the unsaturated zone, the voids in the saturated zone are completely filled with water. The approximate upper surface of the saturated zone is referred to as the water table. Water in the saturated zone below the water table is referred to as groundwater. Below the water table, the water pressure is high enough to allow water to enter a well as the water level in the well is lowered by pumping, thus permitting groundwater to be withdrawn for use.

Between the unsaturated zone and the water table is a transition zone, the capillary fringe. In this zone, the voids are saturated or almost saturated with water that is held in place by capillary forces.

4. Groundwater is commonly an important source of surface water and serves as a large subsurface water reservoir.
5. Groundwater flow velocities are generally low (orders of magnitude less than the velocities of streamflow).
6. Under natural conditions, groundwater moves along flow paths from areas of recharge to areas of discharge at springs, or along streams, lakes, rivers, wetlands or oceans.
7. The age (time since recharge) of groundwater varies in different parts of groundwater flow systems. The age of groundwater water increases steadily along a particular flow path through the groundwater flow system from an area of recharge to an area of discharge. In shallow, local-scale flow systems, ages of groundwater at areas of discharge can vary from less than a day to a few hundred years. In deep, regional flow systems with long flow paths (e.g., tens of kilometers), ages of groundwater may reach thousands or tens of thousands of years.

Box 4 (Continued)

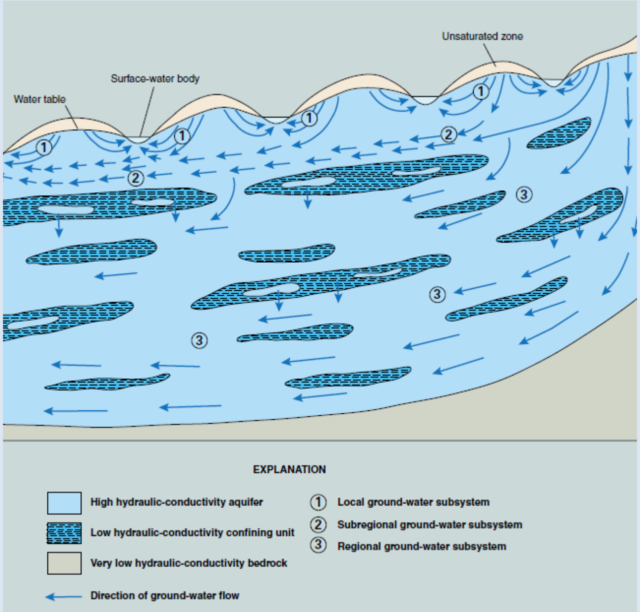

Figure 5: Illustration of a regional scale groundwater flow system comprising of subsystems at different scales and a complex hydrogeological framework (Alley et al., 1999)

Depicted in Figure 5 are: (1) local groundwater subsystems in the upper water table aquifer that discharge to the nearest surface water bodies and are separated by groundwater divides beneath topographically high areas; (2) a subregional groundwater subsystem in the water table aquifer in which flow paths originating at the water table do not discharge into the nearest surface water body but into a more distant one; and (3) a deep, regional groundwater flow subsystem that lies beneath the water table subsystems and is hydraulically connected to them. The horizontal scale of the figure could range from tens to hundreds of kilometers.

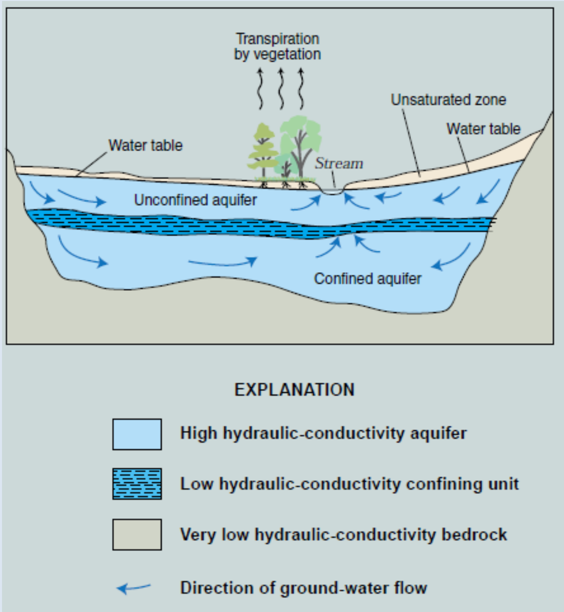

Figure 6: Illustration of a local scale groundwater flow system (Alley et al., 1999)

Figure 6 depicts a local scale groundwater flow system, where inflow of water from precipitation occurs at the water table. Outflow of water occurs as: i) discharge to the atmosphere as groundwater evapotranspiration (transpiration by vegetation rooted at or near the water table or direct evaporation from the water table when it is at or close to the land surface); and ii) discharge of groundwater directly through the streambed. Short, shallow flow paths originate at the water table near the stream. As distance from the stream increases, flow paths to the stream are longer and deeper.

4.2 Definition of the Groundwater Basin

Identifying the spatial domain is helpful in determining the state of the groundwater environment and identifying risk and priority. It provides an opportunity to link groundwater resources with other policies that can influence the system, such as those related to climate change, water quality, land use and economic development. To identify the spatial domain of the assessment, we first need to consider the key problems and how they relate to sustainability. As groundwater problems cover a variety of issues (e.g., water quantity, water quality, ecosystem viability, economic and social well-being and governance, cost, law and policy), the spatial assessment should be conducted by a multidisciplinary team.

Numerous factors contribute to the determination of the sustainable yield of groundwater in the basin of interest. In many cases, not all information will be available; however, a strong assessment can still be made despite missing information. Because a groundwater sustainability assessment initiative is by nature an iterative process, a project that focuses only on a subset of the many components can still produce relevant and useful information or results. The determination of which components are targeted should be made based on the most important issues and the available resources.

4.2.1 Defining the Spatial Limits

For a small aquifer, we can easily bound the area according to the aquifer extent. However, in reality, the groundwater entity could be an aquifer that is partially or wholly bounded by geological boundaries, or it could be a designated groundwater zone defined by surficial property boundaries or topographic limits that leave the groundwater area geologically unbounded (Kalf & Woolley, 2005). In the latter cases, this would mean that there are no physical barriers of low permeability material that laterally constrain inflow, outflow and drawdown propagation.

Under these circumstances (e.g., in very large basins), it may be necessary to define a groundwater entity to apply the water balance approach and to determine the sustainability over that defined zone. In a sense, this is the same premise used in numerical modelling studies in defining a working grid so that the model grid boundaries lie outside the range of influence of the proposed stresses.

Note that a determination of sustainable yield using a defined boundary (which only covers part of the aquifer) may be quite different (and often more conservative) than one determined over a much larger area or for the entire hydrogeological groundwater basin.

4.2.2 Characterization of the Aquifer System

Box 5: Types of aquifers

Adapted from: Sharp (2007)

Aquifer	A consolidated or unconsolidated geologic unit (material, stratum, or formation) or set of connected units that yields water of suitable quality to wells or springs in economically usable amounts.
Confined aquifer (or artesian aquifer)	An aquifer that is immediately overlain by a low-permeability unit (confining layer). A confined aquifer does not have a water table.
Leaky aquifer	An aquifer that receives recharge via cross-formational flow through confining layers.
Perched aquifer	A local, unconfined aquifer at a higher elevation than the regional unconfined aquifer. An unsaturated zone is present between the two unconfined aquifers.
Unconfined aquifer	The upper surface of the aquifer is the water table. Unconfined aquifers are directly overlain by an unsaturated zone or a surface water body.

Aquifer Mapping

To map the groundwater basin, geological, geophysical and hydrological data are required to obtain a preliminary understanding of the aquifer system and its extent. The aquifer is generally classified based on the permeable geologic material (unconsolidated deposits of sand, semi consolidated sand, sandstone, carbonate rocks, inter-bedded sandstone, carbonate rocks and basalts/other types of volcanic rocks, etc.). The aquifer can be classified as a confined aquifer, unconfined aquifer, a combination of both, leaky aquifer or perched aquifer (see Box 4 for definitions and Figure 7 for an illustrative example).

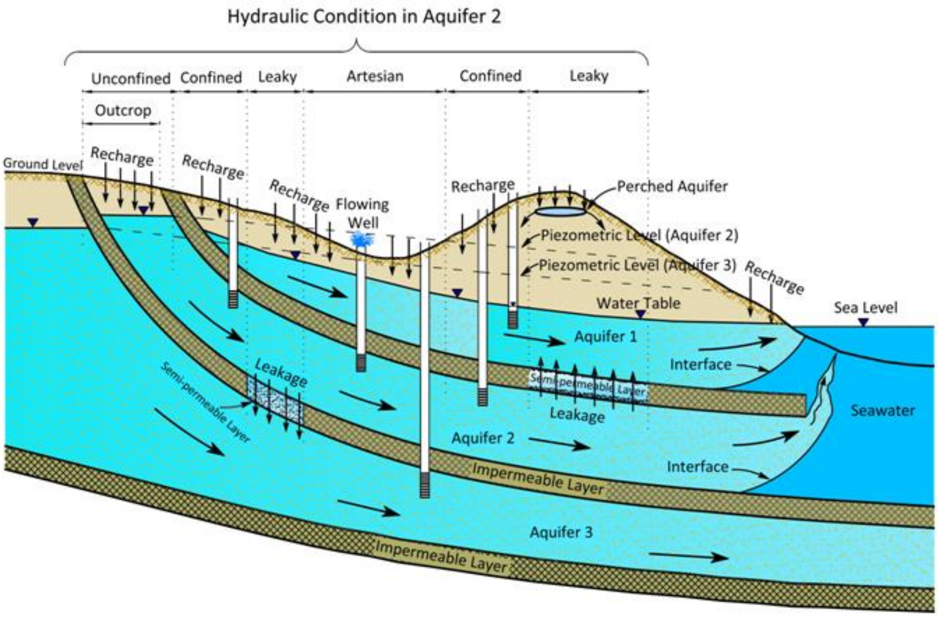

Figure 7: Illustration of different aquifer types (Bear, 1979)

The aquifer mapping approach can help enhance our understanding of groundwater availability, groundwater accessibility and quality aspects. Figure 8 shows the information required (geometry and hydrogeological features) that should be collected and processed to undertake a comprehensive characterization of the aquifer.

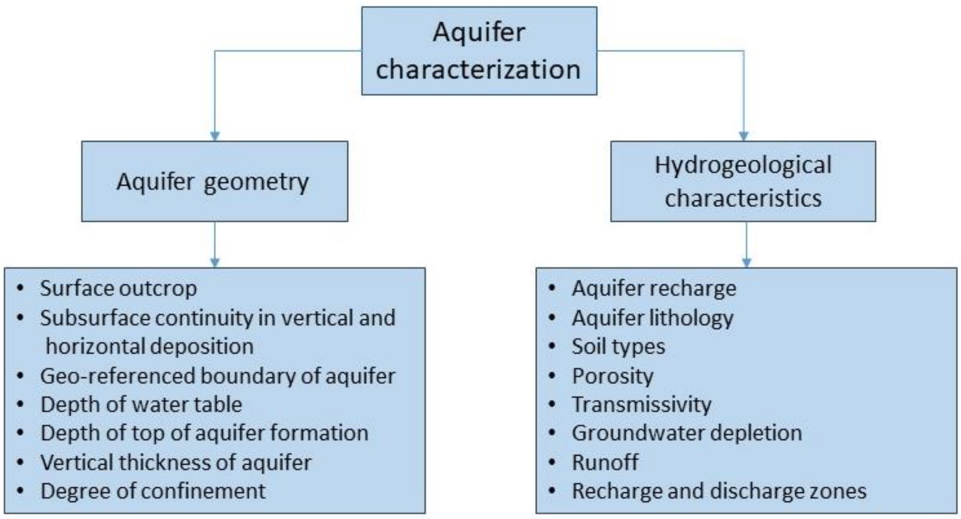

Figure 8: Information required for aquifer characterization

Most aquifer features can be collected and presented in a map format. A map typically consists of the following information (IGRAC & UNESCO-IHP, 2015):

1. Aquifer delineation (mostly based on outcrop and hydrogeological formation).
2. National, federal, local and other jurisdictional boundaries.
3. General direction of groundwater flow. This can be derived from maps of groundwater or piezometric levels.
4. The aquifer systems (i.e., different aquifer layers, which may be presented on separate maps).
5. Where the major recharge areas are located. In the case of an aquifer system, this may need to be depicted by linking each recharge zone with the related aquifer unit.
6. Locations and types (i.e., springs, wetlands, phreatophytes, etc.) of groundwater-dependent ecosystems.
7. Zones of priority, emerging issues and other concerns such as zones of major groundwater pollution and zones of large withdrawals.

Cross Sections

Cross sections (2D) are tools used to visualize sub-surface structures and conceptual models of aquifers (see Figure 9 for an example). Cross sections typically show aquifer features such as the relationships between aquifer layers in aquifer systems, the depth of the aquifer, and vertical flow patterns (IGRAC & UNESCO-IHP, 2015). They allow us to better understand movements of water and pollutants (time spans and pathways).

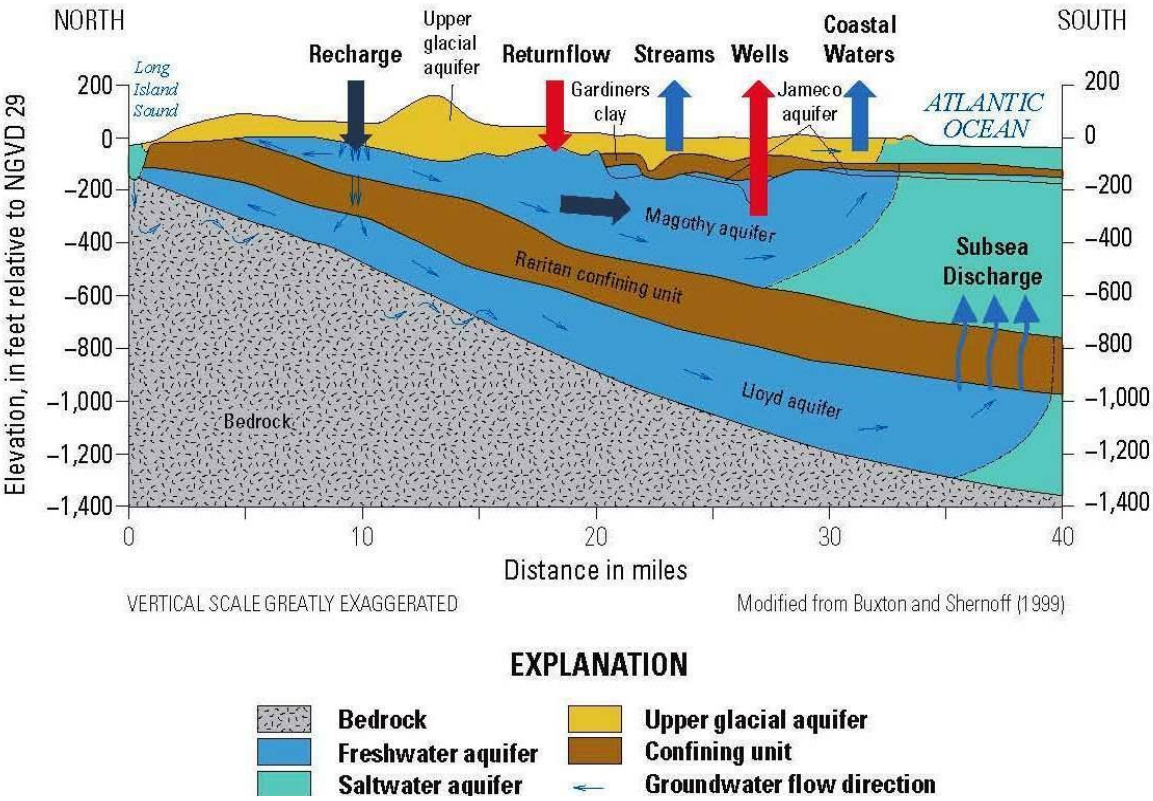

Figure 9: Aquifer cross section example (USGS, 2000)

To improve groundwater management and governance, we should focus on the conceptual links between the aquifer element and processes influencing groundwater quality and quantity (i.e., a diagram showing the relationships between recharge areas, polluted areas, abstraction points, etc.).

We can also use cross sections to provide an overview of the hydrogeology of the aquifer system, with detailed descriptions of each aquifer layer and hydrogeological features. For each layer of the aquifer, cross sections can also show lithological classifications, predominant types of porosity zones, natural salinity, and other characteristics.

The cross sections could include features such as (IGRAC & UNESCO-IHP, 2015):

1. Main aquifer formation and layers.
2. Aquitards and aquicludes (for aquifer systems).
3. Direction of groundwater flow.
4. Main geological features, such as faults.
5. Locations of borders.
6. Relevant hydrological features such as:
    i. Recharge zones.
    ii. Discharge zones.
    iii. Zones of major groundwater abstractions.
    iv. Zones of groundwater pollution.

Block Diagrams

3D hydrogeological conceptual models are a combination of map views and cross sections. They can combine the horizontal spatial distribution of attributes and factors affecting the aquifer with the vertical distribution of the aquifer units (IGRAC & UNESCO-IHP, 2015). Because not all information can be included in such a synthesis exercise, the conceptual model should represent the most relevant and common features of the aquifer dynamic (e.g., water recharge areas, groundwater flow directions, etc.), the current state of the resource (e.g., where water levels are dropping, location of the main polluted areas) and possible future problems (e.g., location of main landfills or large well fields, both existing and proposed). The interactions between the aquifer layers can also be presented in the block diagram in order to provide a better understanding of the dynamics of the hydrogeological system (IGRAC & UNESCO-IHP, 2015).

Figure 10 shows an example of a block diagram for a conceptual model of the Floridan Aquifer System. This example presents mainly hydrogeological dynamics, meaning that in the context of this methodology, it would be missing some additional interpreted features such as pollution sources and recharge areas.

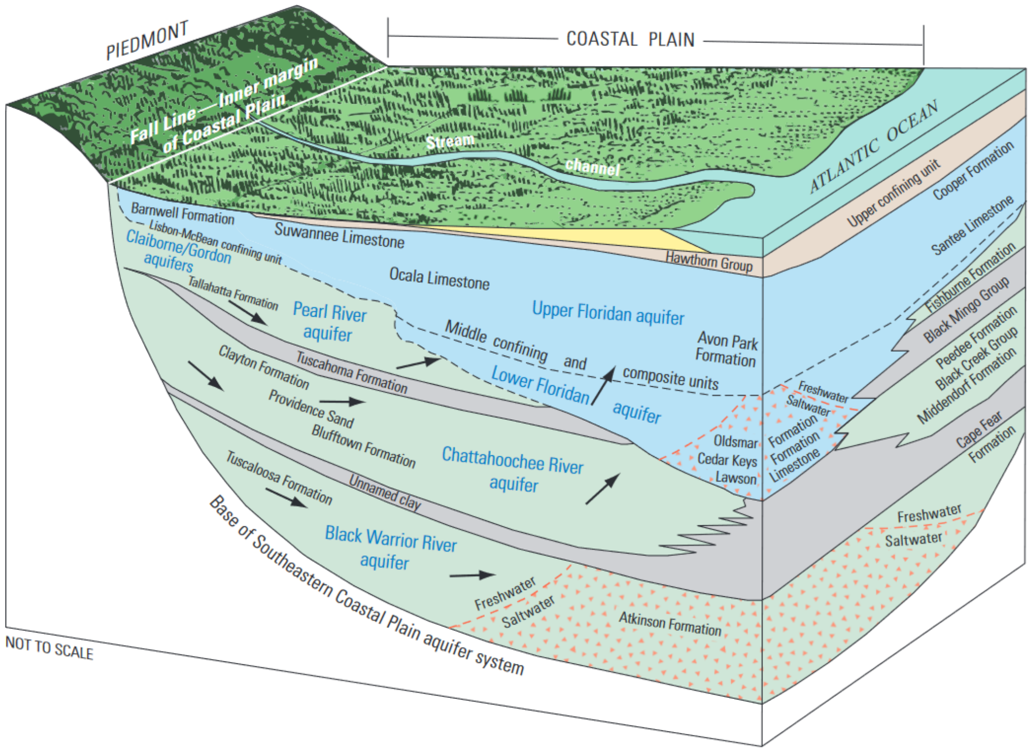

Figure 10. Generalized block diagram of the Floridan aquifer system (USGS, 2015)

4.3 Define the Temporal Scale of the Assessment

A groundwater assessment is generally performed for a sufficiently long time period such as a year that corresponds to a specific cycle (hydrological year, calendar year, wet/dry season, etc.) or over multiple years, if possible. To understand the variability of the key components of the water balance (e.g., rainfall, water demands) both throughout a single year and between years, shorter and longer time scales can also be evaluated. To reflect groundwater recharge processes, longer time scales are typically required.

The time step selected for gaining a better understanding of the functioning of the hydrological cycle within a given year should be carefully selected based on groundwater problems being assessed. Water flows, surface water bodies (e.g., lakes, rivers, and reservoirs) and aquifers considered in water balances do not have the same time response to precipitation events. For example, the effect of reduced precipitation (i.e., during a dry period or drought) is quickly reflected in soil moisture; however, more time is needed for this deficit to be translated into changes in river streamflows, and even more time may be needed to affect the groundwater balance. Figure 11 illustrates the relative general time scales relevant to different flow components of the water balance, demonstrating that changes in groundwater levels are significantly slower (time lagged) and smoother (attenuated) than changes in precipitation.

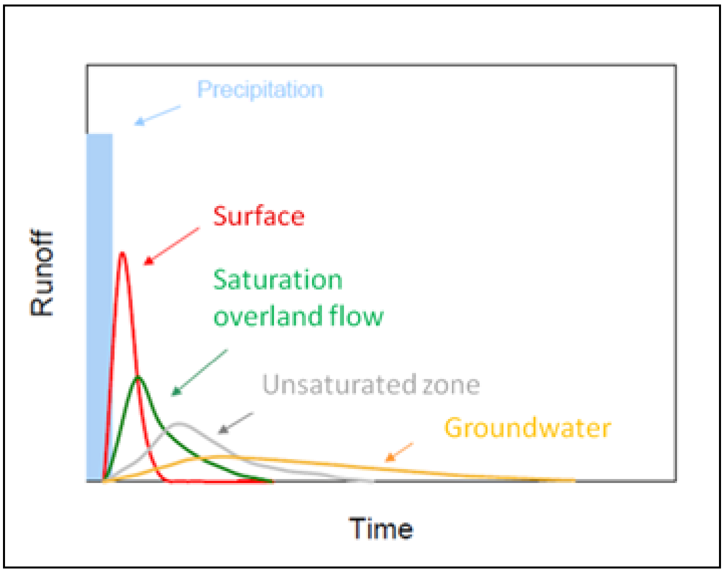

Figure 11: Generalized timescales of different runoff processes. Adapted from TU Delft (2016)

4.4 Information and Data Collection

Data can be collected from many sources, such as ministries, governmental and non-governmental institutions (e.g., geological surveys, water suppliers, or agricultural organizations), universities, secondary literature, etc. These data are available in various formats and different levels of detail (reports, scientific articles, data sheets, database, maps, etc.). Here, we divide the data into six main categories (IGRAC & UNESCO-IHP, 2015):

A. Physiography and climate
B. Aquifer geometry
C. Hydrogeological characteristics
D. Environmental aspects
E. Socio-economic aspects
F. Legal and Institutional aspects

Table 2 presents an overview of the parameters, variables and information to be collected. Descriptions of the calculation or collection of each of these parameters are included in Appendix 2, except for legal and institutional aspects (F), which are typically assessed by questionnaires (IGRAC & UNESCO-IHP, 2015).

Table 2: Data and parameters (Adapted from IGRAC & UNESCO-IHP, 2015)

Field	Parameters, variables and information to be collected
A. Physiography and climate	A.1. Temperature
	A.2. Precipitation
	A.3. Evapotranspiration
	A.4. Land use
	A.4.1. Groundwater-fed agricultural land
	A.4.2. Groundwater-irrigated land
	A.4.3. Groundwater-supported wetlands and ecosystems
	A.4.4. Areas with land subsidence
	A.5. Topography: elevation data
	A.6. Surface water network (rivers, lakes, swamps, reservoirs, canals, etc.)
B. Aquifer geometry	B.1. Hydrogeological map
	B.2. Geo-referenced boundary of the aquifer
	B.3. Depth of water table/piezometric surface
	B.4. Depth of top of aquifer formation
	B.5. Vertical thickness of the aquifer
	B.6. Degree of confinement
	B.7. Aquifer cross section
C. Hydrogeological characteristics	C.1. Aquifer recharge
	C.1.1. Natural recharge
	C.1.2. Return flows from irrigation
	C.1.3. Managed aquifer recharge
	C.1.4. Induced recharge
	C.1.5. Extent of recharge zones
	C.1.6. Sources of recharge
	C.2. Aquifer lithology
	C.3. Soil types
	C.4. Porosity
	C.5. Transmissivity and vertical connectivity
	C.6. Total groundwater volume
	C.7. Groundwater depletion
	C.8. Natural discharge mechanism
	C.9. Discharge by springs

Field	Parameters, variables and information to be collected
D. Environmental aspects	D.1. Groundwater quality (suitability for human consumption)
	D.2. Groundwater pollution
	D.3. Solid waste and wastewater control
	D.3.1. Wastewater being collected in sewerage systems
	D.3.2. Wastewater treated
	D.3.3. Solid waste being stored in controlled fields
	D.4. Shallow groundwater table and groundwater-dependent ecosystems
E. Socio-economic aspects	E.1. Population (total and density)
	E.2. Groundwater use
	E.2.1. Total volume groundwater abstraction
	E.2.2. Groundwater abstraction for domestic use
	E.2.3. Groundwater abstraction for use in agriculture and livestock
	E.2.4. Groundwater abstraction for commercial and industrial use
	E.3. Surface water use
	E.3.1. Total volume of surface water use
	E.3.2. Surface water for domestic use
	E.3.3. Surface water use for agriculture / livestock
	E.3.4. Surface water for commercial and industrial use
	E.4. Dependence of industry and agriculture on groundwater
	E.5. Percentage of population covered by public water supply
	E.6. Percentage of population covered by public sanitation
F. Legal and institutional aspects	F.1. National legal and institutional framework
	F.2. Domestic legal and institutional framework
	F.2.1. Ownership of groundwater
	F.2.2. Water resource planning
	F.2.3. Groundwater resource abstraction and use
	F.2.4. Abatement and control of groundwater pollution
	F.2.5. Other water resource protection measures
	F.2.6. Government and non-government water institutions
	F.2.7. Implementation, administration and enforcement of the legislation

5. Assessing the Water Budget

Box 6: Water Funds Design phase and this chapter

This chapter of the GRAF provides guidance on calculating the key biophysical variables needed to assess groundwater resources condition that are used in Portfolio formulation and Business case studies.

The purpose of Design analysis in the Water Fund development process is to provide the science-based data to convey to stakeholders to improve water security through investing in nature.

More information on the Water Fund Project Cycle can be found here.

Calculating water balances helps combine and structure the key components of the natural hydrological cycle (without human pressures) and the relevant inputs and outputs due to human interventions (e.g., abstractions, returns, etc.) into a coherent framework. This chapter identifies the information required to describe each component and to develop water balances.

5.1 The Water Balance

First, we need to assess the freshwater resources, which is done by quantifying the components of the hydrological cycle (Figure 12).

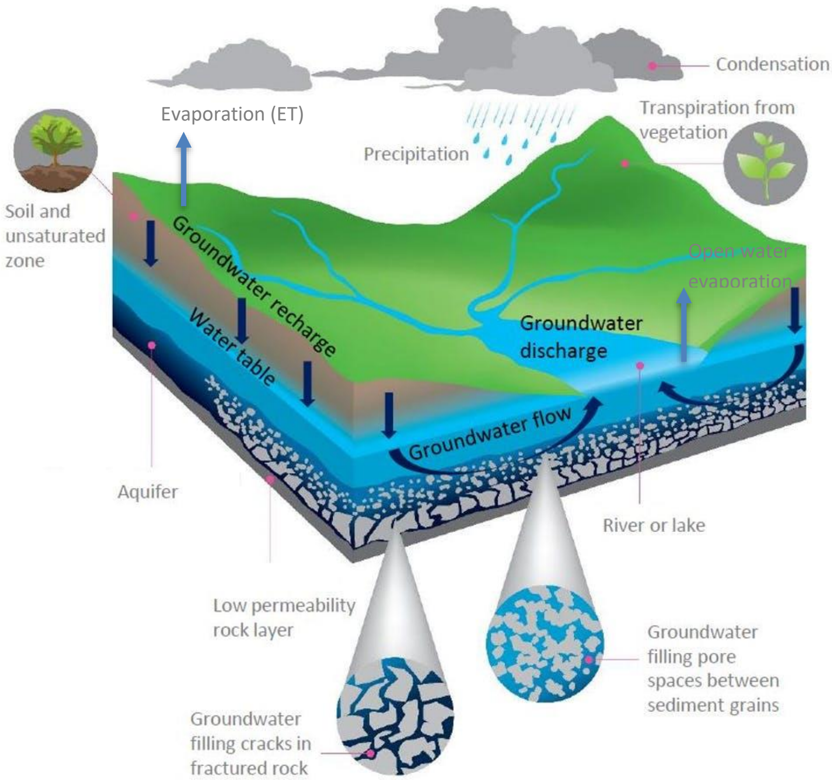

Figure 12: Key hydrological components of a groundwater system. Groundwater stores are 'recharged' by rainfall and they 'discharge' into surface water bodies. (Cuthbert et al., 2019)

Based on the principle of the conservation of mass in a closed system, the simplified hydrological balance of a basin is described as:

$$\mathbf{IN = OUT \pm \Delta}S \qquad \text{Eq. 1}$$

where:

- IN = inflow of water to the groundwater basin
- OUT = outflow from the groundwater basin
- ΔS = change in storage within the groundwater basin

The components of Eq. 1 are typically expressed in units of volume per time unit (m^3/year, m^3/month, etc.) or more commonly as length over time to indicate the response over a unit area (e.g., m/year, mm/year). In this chapter, we use the former. Extending Eq. 1, we derive the following (European Commission, 2015):

$$\mathbf{P = Rs + Rsub + Rgw + Es + Ei + Et \pm \Delta S} \qquad \text{Eq. 2}$$

where:

- P: Precipitation [m^3/ time unit]
- R: Runoff (s: surface, sub: subsurface, gw: groundwater) [m^3/ time unit]
- E: Evaporation (s: surface, i: interception, t: transpiration)[m^3/ time unit]
- ΔS: Change in storage over time [m^3/ time unit]

(P) reaches the soil surface and the vegetation where water can be intercepted and evaporate directly (Ei) or stored (ΔS). Water can also infiltrate the soil or directly runoff (Rs) if the amount of rainfall exceeds the infiltration rate capacity (rainfall excess). The water infiltrating the soil goes to the unsaturated zone (ΔSu) and recharges the groundwater (ΔSgw). Groundwater (Rgw) and unsaturated zone water (Rsub) can also contribute to river flows as subsurface runoff (often called “baseflow”). The roots of vegetation absorb water that is transported to the stomata of the leaves, where it goes back to the atmosphere as transpiration (Et). Water can also evaporate directly from the soil or from the river (Es) (European Commission, 2015).

Please refer to Appendix 3 and Appendix 4 for more specific information and formulae for calculating the components of the water budget for different types of aquifers.

Box 7: Application of the water budget method

The water budget method shown in Eq. 2 is straightforward and relatively easy to apply. Generally, one only requires data from standard sources (e.g., national weather services and stream gauge data) and from open sources (e.g., online open data portals). The key data and information required for this approach are:

1. **Precipitation** (see Appendix 4 for more information on calculation methods over a study area)
2. **Evapotranspiration** (see Appendix 4 for more information on calculation methods over a study area)
3. **Surface flow**: Use stream gauge data where possible. If these data are not available, a common technique for predicting direct runoff is the US Soil Conservation Service curve number method. The dimensionless curve number (CN) is determined on the basis of soil type, land use, and antecedent soil-water content. Direct runoff, R_{off}, in mm, is estimated as (Healy & Scanlon, 2010):

   $$R_{off} = (P - 0.2 * S)^2 / (P + 0.8 * S) \quad \text{Eq. 3}$$

   where P is precipitation (in mm) and:

   $$S = (25400 / CN) - 254 \quad \text{Eq. 4}$$

   Numerous databases for CN values according to soil type appear in literature (e.g., Jaafar et al., 2019). Rainfall-runoff relationships, anther simplified method to estimate surface flow, are described in Appendix 4.

4. **Baseflow**: This refers to the portion of the streamflow that is sustained between precipitation events, fed to streams by delayed pathways (Price, 2011). It should not be confused with groundwater flow. Refer to Appendix 4 for methods of calculation.

5.1.1 Anthropogenic Influences on the Groundwater Balance

Human activities influence components of the water balance, either adding or subtracting water to the system, or by modifying storage capacity. Land use changes, especially those changing the permeability of surfaces, significantly influence the processes of soil storage, infiltration and runoff. Building on Eq. 1 and Eq. 2, we derive the following (European Commission, 2015):

$$P + ExIn + RET = ETa + Outflow + ABS \pm \Delta S \quad \text{Eq. 5}$$

where:

- ExIn = External Inflow is the total volume of actual flow of rivers and groundwater entering the basin of analysis from neighboring territories or other units [m^3/ time unit].
- RET= Returned water is the volume of abstracted water, and/or water produced by economic units, and/or imported, that is discharged to the fresh water resources of the hydrological unit either before use (as losses) or after use (as treated or nontreated effluent)[1]. It includes water

[1] We can further break down returned water into two components: R1 is the amount that is released locally and returned in the system within the time unit and is practically a reduction in the abstraction, while R2 is the

that is directly discharged from a user (e.g. domestic, industrial etc., including cooling water, mining), and water lost from the wastewater collection system (as overflow or leakage). [m^3/time unit]

- ETa = Actual Evapotranspiration [m^3/ time unit].
- Outflow = Total volume of actual outflow of rivers and groundwater (outside the hydrological unit of analysis) [m^3/ time unit].
- ABS = Total volume abstracted from the system, from surface and groundwater resources, intended for any use (consumptive, non-consumptive, transfer etc.) [m^3/time unit].
- ΔS = Change in Storage (both in surface water and groundwater as a lumped sum) [m^3/time unit].

The anthropogenic abstraction component can generally be directly assessed, (e.g., water extractions from point sources[2], or derived from measuring river baseflows, etc.). Eq. 5 can be customized based on the objectives and scale of the analysis. An example of the water balance for Switzerland is presented on Figure 13.

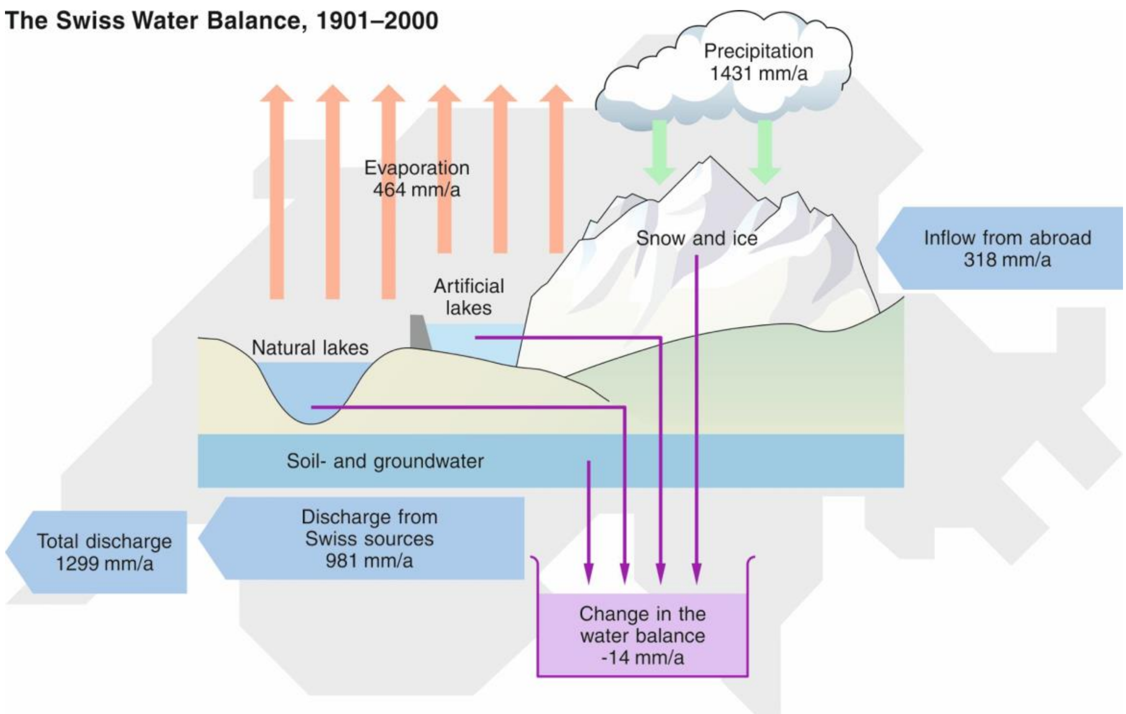

Figure 13: The mean (1901 - 2000) annual water balance of Switzerland (Blanc & Schädler, 2014)

volume that is returned in the system at a later time step or externally (e.g., urban wastewater) and is practically an addition on the resources part (European Commission, 2015).

[2] In many cases, data concerning water extractions will be incomplete or inaccurate. In these instances, we can make assumptions, extrapolate data or attempt to use indirect methods to estimate extractions.

Box 8: Effects of groundwater pumping on streamflow

Adapted from: Alley et al. (1999)

Figure 14 illustrates how groundwater extraction from pumping can affect a water system with a stream. Three conditions are shown:

A. Natural conditions. Recharge at the water table is equal to groundwater discharge to the stream.
B. With a well that pumps at a relatively low rate (Q1). After a new state of dynamic equilibrium is achieved, inflow to the groundwater system from recharge will equal outflow to the stream plus the withdrawal from the well (i.e., some of the groundwater that would have discharged to the stream is intercepted by the well). A groundwater divide, which is a line separating directions of flow, is established locally between the well and the stream.
C. With a well pumped at a higher rate (Q1). An equilibrium is reached where the groundwater divide between the well and the stream is no longer present and withdrawals from the well induce movement of water from the stream into the aquifer. In other words, the high groundwater extraction rate reverses the hydrologic condition of the stream from groundwater discharge to groundwater recharge.

Note that in the illustrated examples (A) and (B), the quality of the stream water generally will have little effect on the quality of groundwater. In example (C), the quality of the stream water can affect the quality of the groundwater between the well and the stream, as well as the quality of the water withdrawn from the well.

Although a stream is used in this example, the general concepts illustrated here apply to all surface water bodies, including lakes, reservoirs, wetlands, and estuaries.

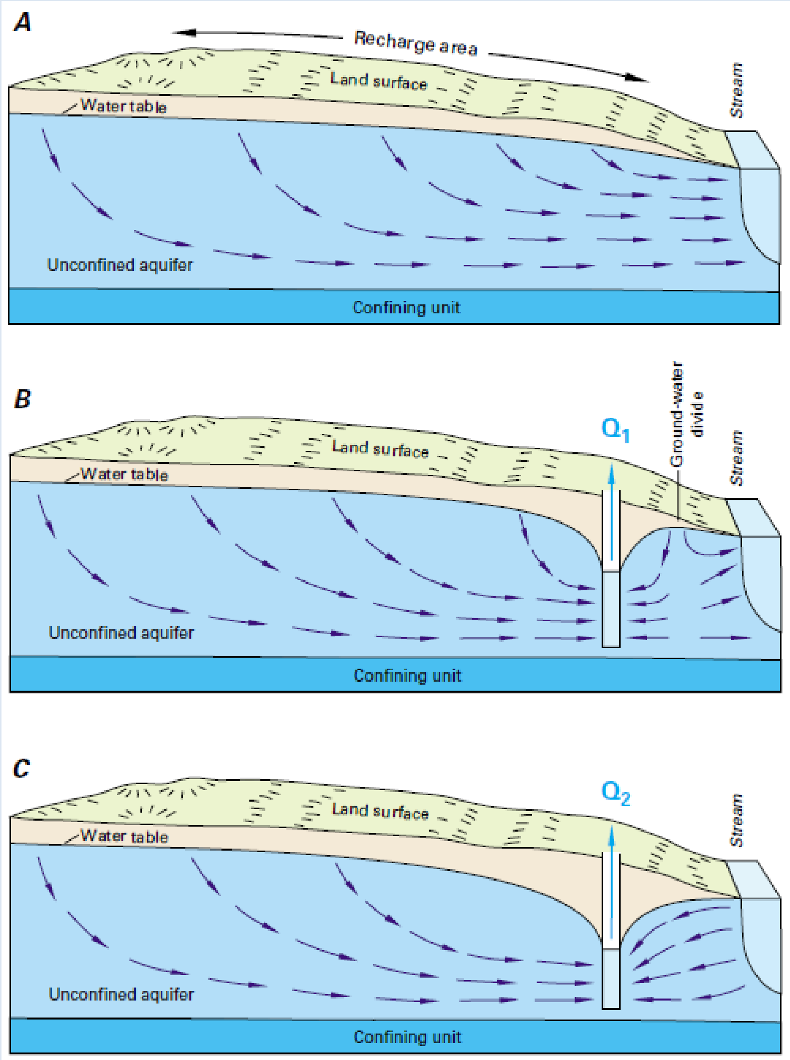

Figure 14: Effects of pumping from a groundwater system that discharges to a stream

Box 9: Groundwater extractions and groundwater budget for the southern High Plains aquifer

The High Plains aquifer (United States of America) has a low natural recharge rate to the groundwater system. Rapid increases in groundwater pumped for irrigation needs has caused substantial drops both in the water table height and the saturated thickness of the aquifer.

Figure 15 displays the effects of groundwater withdrawals on the southern High Plains aquifer. The schematic cross-section (A) illustrates the negligible short-term effect that the groundwater withdrawals (in the middle of the aquifer) have on the discharge at the boundary. The water budgets (B) are for before the development of the area with irrigation and after the development (flows in million cubic feet per day). Note that recharge has increased significantly (a factor of more than 20) because some of the water used for irrigation seeps back into the ground instead of being consumed as evapotranspiration. The southern High Plains is an example of a system that is not in long-term equilibrium.

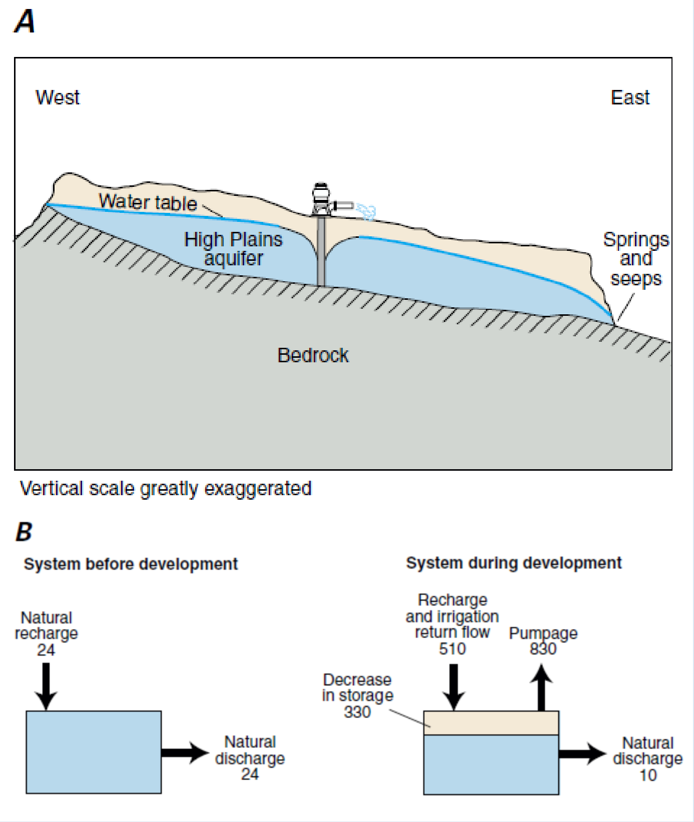

Figure 15: Effects of groundwater withdrawals on the southern High Plains aquifer (Alley et al., 1999)

5.1.2 Time Dependent and Seasonal Water Balance Component

Figure 16 illustrates a hypothetical water budget of a drainage basin and its effects on groundwater storage. In this example drainage basin, in times of heavy rainfall, precipitation is greater than evapotranspiration, thus creating a water surplus. The aquifers fill with more water which means that there is increased surface runoff, and higher discharge from the aquifer. In times where evapotranspiration is greater than precipitation, aquifers deplete, leading to a water deficit.

The temporal variation in groundwater table depth is also important when considering the health of groundwater-dependent ecosystems. The provision of these groundwater-supported ecosystem services is threatened when the groundwater table thresholds are passed (Kath et al., 2018).

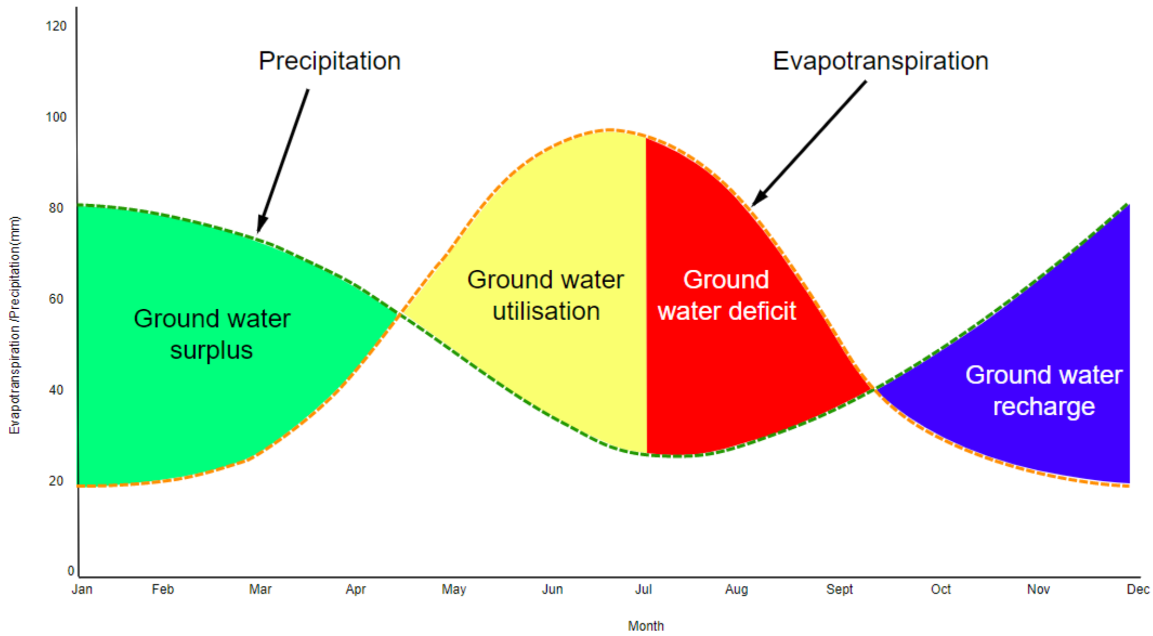

Figure 16: Water budget of a drainage basin and its effects on groundwater storage (Jackson, 2014)

5.1.3 Groundwater Recharge

Changes in groundwater storage involve various recharge and discharge processes. Major recharge sources are rainfall as well as recharge from rivers, ponds, irrigation fields, etc. Discharge processes include evapotranspiration, pumping, baseflow to rivers and springs, etc.

The quantification of recharge is important, yet it can be difficult to determine. Numerous techniques are available for estimation of groundwater recharge (e.g., Simmers, 1988; Scanlon, Healy, & Cook, 2002), and some of these common methods are listed in Figure 17.

Use of physical parameters

- Water budget
- Base flow measurements
- Zero flux plane
- Darcian methods
- Lysimeters

Chemical & Isotopic techniques

- Stable isotopes of hydrogen and oxygen
- Groundwater dating
- Chloride mass balance
    - Concentration method
    - Flux method
- Environmental tritium
    - Peak tritium
    - Total tritium
- Injected tritium

Numerical and empirical methods

- Rainfall runoff models and hydrographs
- Modelling based on unsaturated zone
- Modelling based on saturated zone

Figure 17: Common methods to estimate groundwater recharge

Box 10: Example of calculation of a water budget for the Panther Creek watershed

Adapted from: Healy & Scanlon (2010)

This example shows water budgets for the Panther Creek watershed (Illinois, USA) for the years 1951 and 1952 (Schicht & Walton, 1961). This was achieved by monitoring the precipitation, groundwater levels and discharge. The groundwater budget was calculated through the application of Eq. 2:

$P = ET + R_{off} + \Delta S$

where direct runoff (R_{off}) is determined by subtracting baseflow from measured stream discharge. Baseflow and evaporation from groundwater were determined by developing rating curves for streamflow vs. groundwater level for different times of the year. The net change in saturated zone storage was determined by using water table fluctuation methods (see Appendix 4).

Figure 18 shows cumulative monthly values for all components of the water balance for 1951 and 1952.

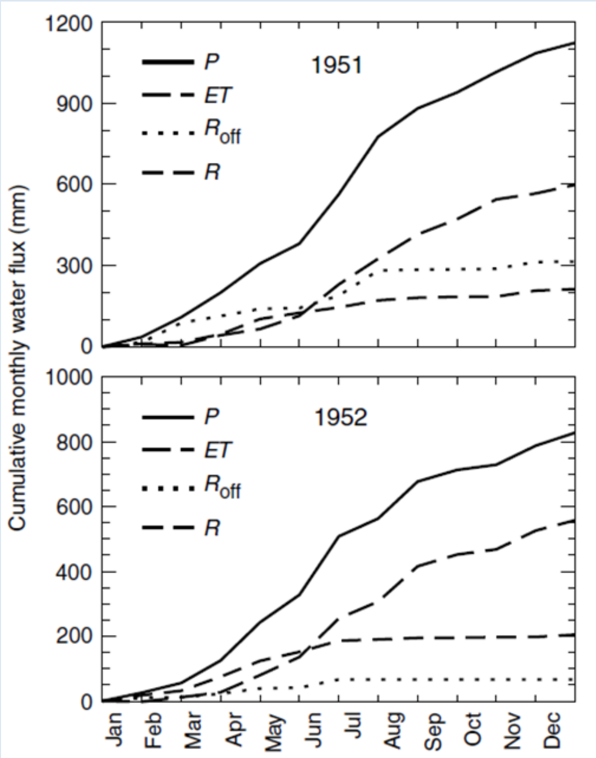

Figure 18: Cumulative monthly values of the water budget components for Panther Creek, 1951 and 1952 (Healy & Scanlon, 2010)

5.2 Norms

There are various norms and predefined values that can be used to calculate the water budget components. **These norms vary according to the local conditions**, and draw on information from previous studies based on the geographical, geological settings of the local area. Before assuming these values we strongly recommend verifying their reliability with local hydrology experts.

Appendix 4 contains information about how to calculate or estimate the following components of the water balance:

- Rainfall recharge
- Other recharge components (from stream channels, surface water irrigation, groundwater irrigation, tanks, ponds and water storage structures)
- Specific Yield
- Hydraulic conductivity
- Lateral flow and inter-aquifer flow
- Evapotranspiration
- Groundwater extractions
- Rainfall-runoff
- Precipitation over an area

6. Indicator-Based Assessment and Sustainable Yield

Box 11: Water Funds Design phase and this chapter

This chapter of the GRAF provides guidance on establishing and calculating the key indicators to assess groundwater resources that can be used in the Monitoring Plan.

Indicators differ according to Water Fund objectives, but at the core of every objective, designed as **S**imple, **M**easurable, **A**chievable, **R**elevant and **T**ime oriented, a good indicator can be found. Objectives are specific to a Water Fund, but can be built around the indicators presented in this chapter.

The purpose of Design analysis in the Water Fund development process is to provide the science-based data that is conveyed to stakeholders to improve water security through investing in nature.

More information on identifying Key Ecological Indicators can be found here. Guidance on selecting indicators and objectives for Water Funds can be found here. More information on the Water Fund Project Cycle can be found here.

6.1 Indicators for the Assessment

Indicators can summarize and represent complex information in a more intuitive and meaningful way, and are particularly useful when comparing different geographical units (IGRAC & UNESCO-IHP, 2015). The level of detail to which indicators for different geographical units can be produced depends on the level of detail and the geographic extent of the available information.

Multi-stakeholder involvement and feedback is an important part of the process of defining sustainable yield. Because of conflicting stakeholder interests, a participative discussion is recommended to manage trade-offs and achieve a groundwater development plan that is agreed upon by all involved parties.

The following points should be considered when using indicators (IGRAC & UNESCO-IHP, 2015):

- Indicators are no more than a tool and should therefore not replace the information and knowledge contained in more detailed reports.
- **Appropriately chosen** indicators can be very strong in passing a message because they can summarize numerous important aspects of the system considered.
- Indicators may help integrate information from different disciplines (e.g., hydrogeological, socio-economic and ecological aspects), thus supporting the development of a holistic view. This holistic view can contribute to a more successful dialogue between the different stakeholders involved.
- Indicators can help differentiate between issues of primary and secondary concern.
- Indicators can demonstrate the importance of properly managing the aquifer.

Table 3 lists the indicators presented in this framework, based on those presented by Vrba & Lipponen (2007). In the last column of the table, core indicators are denoted with the letter 'Y'. The indicators used to calculate the sustainable yield (see Chapter 6.4) are considered as the core indicators.

Table 3: List of indicators to be calculated for the assessment (Adapted from Vrba & Lipponen, 2007)

Indicator	Description	Core indicator (Y/N)
1	Renewable groundwater resources per capita	Y
2	Groundwater abstraction vs. groundwater recharge	Y
3	Dependency on groundwater	Y
4	Abstraction of non-renewable groundwater resources	Y
5	Total groundwater abstraction vs. exploitable groundwater resources	Y
6	Groundwater depletion	N
7	Groundwater vulnerability	N
8	Groundwater pollution	N
9	Groundwater treatment requirement	N

6.2 Calculation Methods for Indicators

Adapted from: Vrba and Lipponen (2007)

This section provides the formulae for the core indicators 1 to 5 from Table 3. For information regarding the calculation of Indicators 6 to 9, refer to Vrba and Lipponen (2007).

Indicator 1: Renewable groundwater resources per capita

The indicator expresses the total annual amount of renewable groundwater resources (m^3 per year) per capita at the spatial scale of analysis. The objective of this indicator is to estimate the amount of good (safe) drinking water, water for agriculture (particularly for irrigation), for industry, and for the ecosystem that exists in a defined area. This amount of available groundwater in relation to the number of people using it becomes an important factor for the social and economic development of a country.

The renewable groundwater resources (in this case at the annual scale) can be calculated as follows:

$$\textbf{Renewable groundwater resources} = R_{RF} + R_{OTH} \pm VF \pm LF - ET - B \qquad \text{Eq. 6}$$

where:

R_{RF} – Recharge from rainfall [m^3/yr]
R_{OTH} – Recharge from other sources (e.g., stream channels, irrigation, tanks, etc.) [m^3/yr]
VF – Vertical inter aquifer flow [m^3/yr]
LF – Lateral flow along the aquifer system (throughflow) [m^3/yr]
ET – Evapotranspiration (from aquifer) [m^3/yr]
B – Baseflow [m^3/yr]

Data regarding the number of inhabitants living within a certain area should be available from government institutions. To calculate the renewable groundwater resources per capita (per year):

$$\textbf{Indicator 1} = \frac{\textbf{Renewable groundwater resources}}{\textbf{Population in area of interest}} \qquad \text{Eq. 7}$$

Indicator 2: Groundwater abstraction vs. groundwater recharge

The total groundwater abstraction as a percentage of the groundwater recharge is calculated as:

$$\textbf{Indicator 2} = \frac{\textbf{Total groundwater abstraction}}{\textbf{Groundwater recharge}} * \textbf{100\%} \qquad \text{Eq. 8}$$

Due to seasonal changes in recharge, this value should be calculated using a minimum time period of one year (and preferably more). For information on calculating the groundwater recharge, see Chapter 5.1.3. Other recharge components (e.g., recharge from streams, irrigation, etc.) should also be included in this calculation (see Appendix 4).

Total groundwater abstraction refers to the total withdrawal of groundwater by means of wells, boreholes, springs and other methods, whether for public water supply, agricultural, industrial or other uses. Data about groundwater abstraction are generally available, because registries exist in many countries. If no estimates are available for irrigation water needs in the study area, we recommend that the FAO paper on crop water requirements is used to derive an estimate (Doorenbos & Pruitt, 1997).

Because data for calculating this indicator are often uncertain, it may be simpler to classify this indicator into the following three scenarios[3]:

- Scenario 1: abstraction ≤ recharge; i.e., < 90%
- Scenario 2: abstraction ≈ recharge; i.e., 90% to 110%
- Scenario 3: abstraction > recharge; i.e., > 110%

If insufficient information is available to estimate this indicator, long-term trends (preferably over multiple years) of water levels measured in wells can serve as a good proxy.

Indicator 3: Dependency on groundwater

This indicator expresses the percentage of people in an area that depend on groundwater. Depending on the setting, there are two ways that we can consider this indicator.

For urban or semi-urban areas, we can calculate the groundwater as a percentage of total use of drinking water:

$$\textbf{Indicator 3} = \frac{\textbf{Groundwater abstractions for drinking water}}{\textbf{Total drinking water supplied}} * \textbf{100\%} \qquad \text{Eq. 9}$$

[3] The ranges for classification of scenarios were changed from the referenced literature of Vrba & Lipponen (2007).

For rural areas, we can calculate the percentage of farmers that depend on groundwater for irrigation (or other) purposes:

$$\textbf{Indicator 3} = \frac{\textbf{Number of farmers dependent on groundwater}}{\textbf{Population of farmers in the area}} * \textbf{100\%} \qquad \text{Eq. 10}$$

Indicator 4: Abstraction of non-renewable groundwater resources

This indicator expresses the percentage of non-renewable groundwater resources that are extracted annually.

$$\textbf{Indicator 4} = \frac{\textbf{Annual abstraction of non-renewable groundwater resources}}{\textbf{Total exploitable non-renewable groundwater resources}} * \textbf{100\%} \qquad \text{Eq. 11}$$

The non-renewable groundwater resources are an effectively finite water resource where no (or very little) recharge occurs. Non-renewable groundwater can be considered as groundwater with mean renewal times surpassing human timescales (e.g., > 100 years) (Bierkens & Wada, 2019).

The total exploitable non-renewable groundwater resource means the calculated total amount of water that can be abstracted from a given aquifer under current socio-economic constraints and ecological conditions. The annual abstraction should be calculated as a mean value over a significant range of years.

Indicator 5: Total groundwater abstraction vs. exploitable groundwater resources

This indicator expresses the percentage of exploitable groundwater resources that are extracted annually.

$$\textbf{Indicator 5} = \frac{\textbf{Annual abstraction of groundwater resources}}{\textbf{Total exploitable groundwater resources}} * \textbf{100\%} \qquad \text{Eq. 12}$$

The annual abstraction of groundwater resources is described in the section for Indicator 2.

The term "exploitable groundwater resources" refers to the amount of water that can be abstracted annually from a given aquifer under prevailing economic, technological and institutional constrains and environmental conditions. **In this framework, this term is considered to be the equivalent of the sustainable yield.** Such estimations are usually based on a combination of hydrological (hydrological budget equation) and hydraulic (finite element aquifer flow models) methods, combined with ecological constraints. Groundwater quality aspects also should be considered, because groundwater quality may affect the overall groundwater exploitability.

Similar to indicator 2, this indicator can be classified into three scenarios[4]:

- Scenario 1: abstraction ≤ recharge; i.e., < 90%
- Scenario 2: abstraction ≈ recharge; i.e., 90% to 110%
- Scenario 3: abstraction > recharge; i.e., > 110%

[4] The ranges for classification of scenarios were changed from the referenced literature of Vrba & Lipponen (2007).

Box 12: Example of Calculation of Indicators for Microbasin Topilejo, Mexico City

Adapted from: ITTrms & UASLP (2020)

Topilejo is a microbasin in the southern part of the Mexico City aquifer (Figure 19). This was selected as one of two pilot case studies to apply the GRAF within Latin America framework. According to the available information, the population has a total dependence on groundwater to ensure its water supply for human use and consumption. Also, hydrogeological, hydrogeochemical, and isotopic evidence suggest that the groundwater in the microbasin flow systems is renewed annually. In this example, the value for Indicator 1 is negative because of the high estimated levels of groundwater discharging out of the study area.

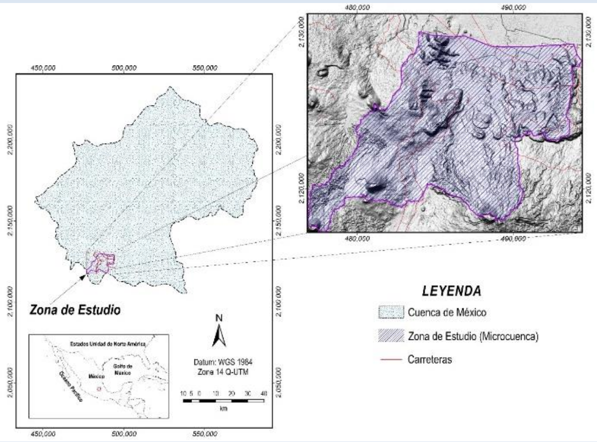

Figure 19: Location of the Topilejo microbasin within the Mexico City basin

Details

- Area of interest: 122.3 km^2
- Population: 49,965
- Mean annual precipitation: 800 mm/yr
- Annual recharge: 250 mm/yr
- Lateral flow (discharge): -77.8 Mm^3/yr
- Groundwater extractions: 33.4 Mm^3 /yr (note that at least 87% of these extractions are to serve users outside for the study area)

Indicator 1:

Renewable groundwater resources/population	=	$((250 * 122.3 * 10^3) - 77.8 * 10^6) / 49,965$
	=	-945 m^3/yr per capita

Indicator 2:

Groundwater abstraction vs. groundwater recharge	=	$(33.4 * 10^6) / (250 * 122.3 * 10^3)$
	=	109%

Indicator 3:

The extracted water is used only for domestic purposes.

Indicator 4:

Hydrogeological, hydrogeochemical, and isotopic evidence suggest that the groundwater in the microbasin flow systems is renewed annually.

Indicator 5:

Based on Eq. 14 (see page 49), the exploitable groundwater resources are calculated as:

Exploitable groundwater resources	=	$20 * 122.3 * 800$
	=	$1.96 * 10^6$ m^3/yr

Therefore, Indicator 5 can be calculated as:

Total groundwater abstraction vs. exploitable groundwater resources	=	$(33.4 * 10^6) / (1.96 * 10^6)$
	=	1705%

6.3 Defining the Sustainable Yield of Groundwater Resources

Box 13: Sustainable Yield of Groundwater

A definition of sustainability from the American Society of Civil Engineers Task Committee for Sustainability Criteria is: "sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity" (ASCE, 1998). This goes beyond the concept of trying to determine a fixed sustainable yield, and instead recognizes that the sustainable yield varies over time as environmental conditions vary.

To define the sustainable yield, we must first understand how water availability and demand varies over time (see Figure 20). Typically, agricultural demands constitute a large portion of the overall demand and have high seasonal fluctuations.

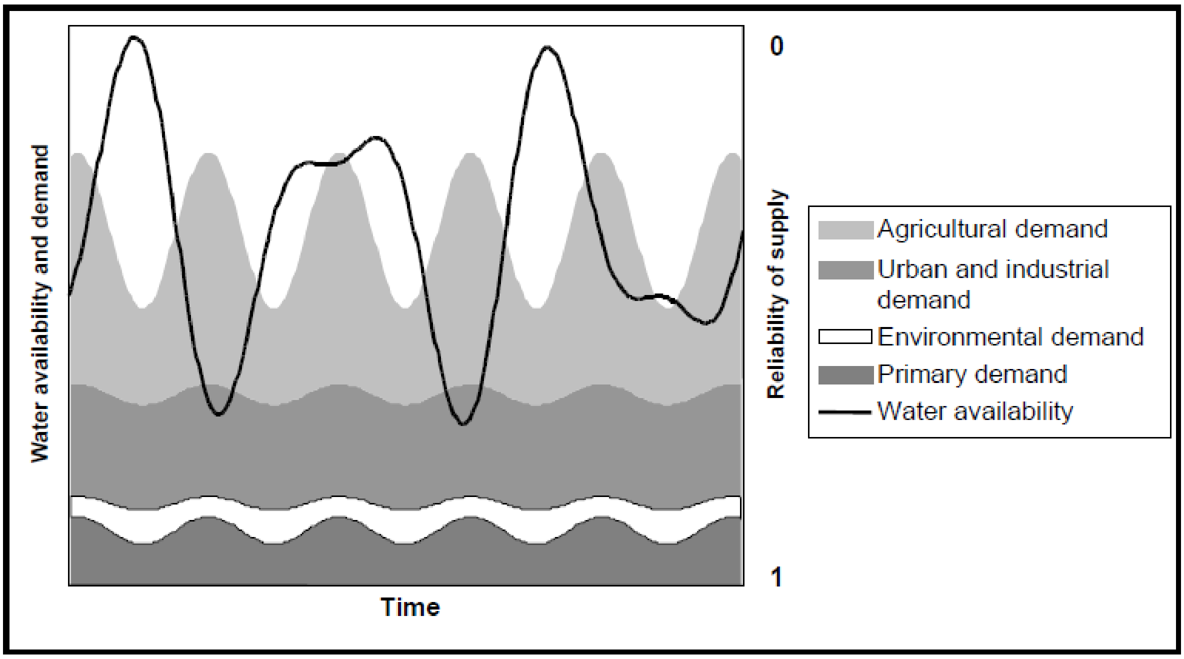

Figure 20: Variation of water availability and demand over time (DFID, 2003)

6.3.1 Defining the Ecological Requirement

Once we determine the ecological requirement (i.e., the environmental demand), we can determine the extractable resources from our water budget. Figure 21 illustrates how much flow is required at different times of the year for ecological maintenance (Postel & Richter, 2003). The light gray is the natural hydrograph while the dark gray indicates amount of water needed in the river at different times of year to maintain healthy ecosystem function. Therefore, the water extraction should be **no higher** than the amount required to bring the hydrograph down to the dark gray curve.

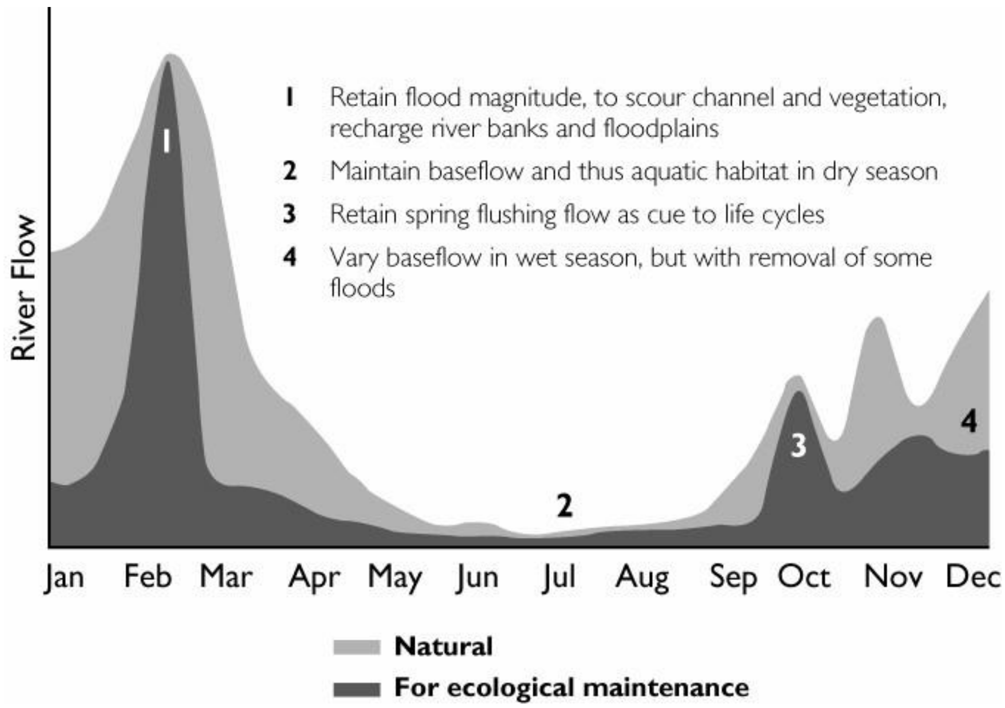

Figure 21: Illustration of the portion of streamflow requited for ecological maintenance (Postel & Richter, 2003)

There are three basic approaches that are often used to set ecological requirements or environmental flow standards: minimum flow thresholds, statistically based standards and Percent-of-Flow (POF) approaches (Richter et al., 2012):

- Minimum flow thresholds are the most widely used approach. An example is the 7Q10, which is defined as the lowest flow for seven consecutive days that occurs every 10 years on average.
- The application of a statistically based standard in regulating water use generally involves using hydrologic models to simulate the cumulative effects of licensed or proposed water withdrawals and dam operations on the flow regime.
- The POF approach explicitly recognizes the importance of natural flow variability and sets protection standards by using allowable departures from natural conditions, expressed as percentage alteration.

For information on the calculation of the groundwater contribution to baseflow, refer to Appendix 4. For information on the calculation of the environmental flow, refer to Appendix 5.

Box 14: Baseflow and its relation with the environmental flow

Adapted from: Gleeson & Richter (2018)

Baseflow can originate from groundwater, lakes, reservoirs, snowpack, or glaciers. Here, we focus on groundwater-derived baseflow (which we call baseflow for simplicity). Baseflow is the most common and volumetrically significant portion of the delayed water sources for almost all rivers.

Groundwater-derived baseflow is driven by groundwater tables that slope and flow towards the river, eventually discharging into the river; this is called a gaining river because the river is gaining flow from groundwater (Figure 18a). Baseflow is generally quantified using baseflow separation (b), where the delayed component of the hydrograph (a graph of measured streamflow through time) is separated from the non-delayed component of the hydrograph using graphical or mathematical algorithms.

Baseflow often dominates the flow of rivers during low-flow periods, which can be seen on the long-term average daily hydrograph of (c). Low-flow statistics and metrics can be derived from a flow duration curve, which shows the relationship between any given streamflow value and the percentage of time that this streamflow is equaled or exceeded (see Appendix 5). In other words, it gives the relationship between magnitude and frequency of streamflow (d).

One common way to characterize low-flow conditions is to assume that Q90 or Q80 (i.e., the streamflow that is exceeding 90% or 80% of the time, respectively), equates to low flow. Some policies consider low-flow metrics a surrogate approximation or equivalent to baseflow. However, note that using flow duration curves to derive baseflow can be problematic because low flow metrics do not distinguish the source of the water (i.e., surface water vs. groundwater).

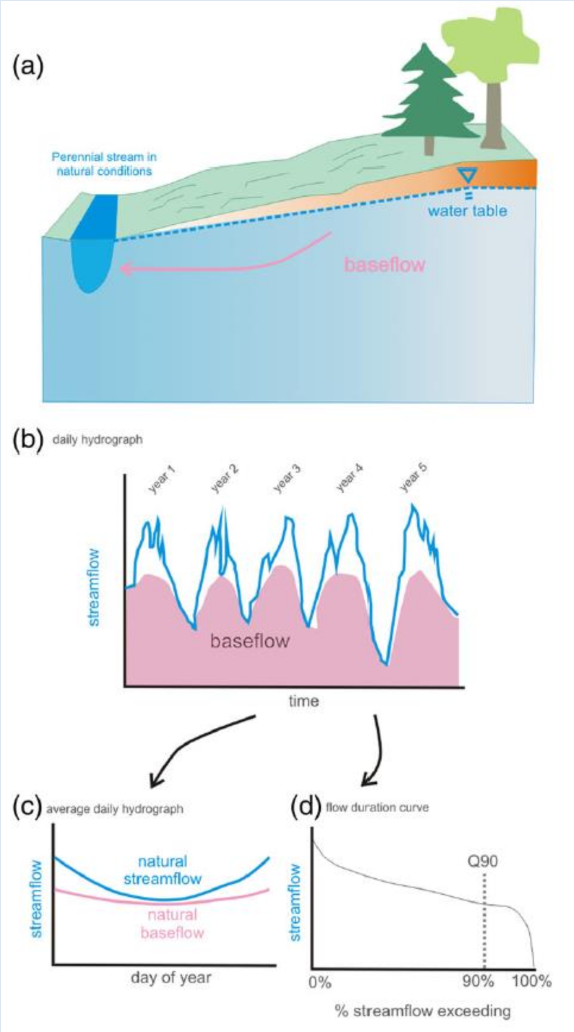

Figure 22: Baseflow and its relation with the environmental flow

6.4 Calculation of Sustainable Yield

The relationships between indicators and sustainable yield describe: i) the conditions and potential of the aquifer or aquifer system; ii) the importance of the interlinkages between groundwater flow systems and various ecosystems; iii) system resilience to changes in groundwater quantity and quality; and iv) changes in groundwater development derived from drivers such as climate change and population increase.

The use of indicators in the estimation of sustainable yield requires the definition of recharge area, annual precipitation and the assessment of the dynamic response of the groundwater basin to anthropogenic changes to the regime, including its effects on the environment and society. The indicators also ensure that the definition of the sustainable yield accounts for the temporal and spatial distribution of water use, by applying the indicators to the zones of interest. Groundwater issues can then be properly managed when they are recognized from regular monitoring, feedback and adjustment. The application of the indicators over a longer temporal scale allows the development of information for an adaptive groundwater management strategy and practices, allowing the implementation of sustainable yield as a changing extraction regime in both time and space.

The expansion of urban areas (with impervious surfaces) will reduce the local recharge areas. Therefore, a projected lower recharge rate linked with an expected water demand increase over time has to be considered in the sustainable yield estimation.

Box 15: Groundwater management examples in Latin America

Latin American countries have diverse groundwater problems and every country requires specific management models. The Central American region currently uses groundwater mainly for drinking water and industrial activities. In some instances this is very unsustainable, for example in Guatemala, where a continuous drawdown in water levels in wells of the metropolitan area of Guatemala City is observed. Groundwater in other Latin American countries such as Brazil and Mexico is extracted mainly for agricultural use. However, the Mexico City aquifer is also used for drinking water and industrial uses (more than 95% of total groundwater extractions). Applying the water budget method, the aquifer is overallocated by a factor of 2 to 3.

6.4.1 Simplified Method to Calculate Sustainable Yield

Adapted from: Ponce (2007)

The sustainable use of groundwater should begin by tapping primarily deep percolation[5], and secondarily shallow percolation. Policy for the exploitation of shallow aquifers should be based on the basin's recharge capacity instead of solely the volume of water that the aquifer holds. Ideally, the effects of such exploitation on the baseflow of neighboring streams and water bodies should be minimal.

[5] Percolation is the gravity flow of groundwater downwards through the unsaturated zone (Sharp, 2007).
- Shallow percolation is the source of shallow groundwater flow, which discharges into surface waters (Ponce, 2007).
- Deep percolation is the fraction of percolation that reaches the deep groundwater (Ponce, 2007).

Detailed hydrological and hydrogeological studies are required to accurately estimate the percolation into the aquifer. **In the absence of basin-specific studies and data**, global values of deep percolation may be used to establish an initial, reference estimate of sustainable yield. This framework suggests the following mechanism to calculate an initial estimate (in the absence of basin-specific data), based on global values published by L'vovich (1979):

$$\mathbf{Y = 0.02 * A * P} \qquad \text{Eq. 13}$$

where:

- Y = Sustainable yield (volume per year)
- A = Recharge surface area (assumed to be the aquifer's surface area)
- P = Annual precipitation (depth per year)

Therefore, if A is measured in square kilometers and P is measured in mm per year, Y (**in cubic meters per year**) will be calculated as:

$$\mathbf{Y = 20 * A * P} \qquad \text{Eq. 14}$$

To account for annual variability in precipitation, it is recommended to use a multiannual mean P which covers enough years to also include drought events in the calculation (see Ponce et al., 2000).

For groundwater extraction quantities that extend beyond the portion of deep percolation and tap into the fractions of shallow percolation, the following should be demonstrated to ensure that the yield is sustainable:

- That surface waters, wetlands and local and regional ecosystems are not affected.
- That no significant drop in the water table is observed.
- That no significant ground subsidence is observed.

6.5 Questions for the Integrated Aquifer Assessment

Table 4 lists questions to help the preparation of the aquifer assessment as well as key variables and indicators that are useful in answering these questions (IGRAC & UNESCO-IHP, 2015). The questions in bold are considered to be the key questions.

Table 4: Questions to help the preparation of the assessment report (Adapted from IGRAC & UNESCO-IHP, 2015)

Questions	Key variables needed to answer questions [a]	Indicators [b]
Drivers and pressures		
What are the main external drivers affecting the aquifer and its users? What are the main pressures on the aquifer and its users?	A1, A2 Annual rainfall and temperature by country and region E1 Population by country and region (total and density) A4 Land use and land cover (growth in incomes)	
Groundwater resources		
What are the boundaries of the aquifer? How much water is in the aquifer? Which direction is water flowing in the aquifer? **How much water can we sustainably take from the aquifer per year)?** At what threshold will further development (rural and urban) be constrained by lack of water? How much does climate change affect the aquifer?	B2 Aquifer boundary B3 - B5 Aquifer size (horizontal and vertical dimensions) C1 Aquifer recharge C6 Total groundwater volume C7 Groundwater depletion (direction of main groundwater flow of aquifer & volume of groundwater)	1, 2, 3, 5, 6
Quality of the groundwater resource		
How clean is the water in the aquifer? **How much water is suitable for different uses (domestic, livestock, irrigation, industry)?** At what threshold will the impacts of urban and rural development on water quality become unacceptable? At what level of groundwater extraction will 'environmental uses' be affected?	D1 Natural groundwater quality and natural groundwater contaminants D2 Groundwater pollution D3 Waste and wastewater control	3, 8, 9
Use of the groundwater resource		
How much water is taken from the aquifer each year? **How much groundwater is taken per person?** **What proportion of groundwater is taken by domestic users, farms and other enterprises** How stressed is the aquifer? **How long can we sustain the current level of extraction?**	E2 Groundwater use by country and by user group o Domestic o Agriculture o Industry o Environment E4 Dependency of user groups on groundwater E5, E6 Percentage of population covered by public water supply and sanitation D4 Shallow groundwater table	1, 3, 4, 7, 9
Impact of the use of the groundwater resources		
How is the groundwater resource being changed by human development? **Is the resource becoming more polluted and what are the impacts?** **What would be the impacts of cutting groundwater use?**	Trends in groundwater level and quality Impacts of groundwater pollution on human use (and environmental assets) Impacts on human communities of increasing, reducing or stopping groundwater use	5, 6, 7, 8

a: Letter-number combinations refer to the data listed in Appendix 2.
b: Numbers refer to the indicators listed in Table 3.

7. Nature Based Solutions (NBS) as Interventions

Box 16: Water Funds Creation phase and this chapter

This chapter of the GRAF provides guidance on identifying the set of NBS that can improve the groundwater resources and will be included in the Operating Plan.

Water Funds requires a roadmap with the priority of interventions to be implemented in the field, as well as the stakeholder engagement and the fundraising needed to achieve this. The foundation for this is identifying the most appropriate set of NBS and understanding what is required to deliver the expected benefits in term of groundwater resources improvement.

More information on the Water Fund Project Cycle can be found here.

7.1 NBS and Groundwater Resources

NBS pay a vital role in water management, including in groundwater management. With regards to aquifer management, the most common aim of NBS is to increase (often to restore original) recharge rates (IGRAC, 2014; WWAP/UN-Water, 2018). Some examples of improving groundwater recharge through NBS are:

- Reforestation in Puebla Tlaxcala Valley, Mexico (Sonneveld et al., 2018)
- Buffer strips, reduced tillage and no-till practices in the Paw Paw River Watershed, USA (Sonneveld et al., 2018)
- Wetland restoration in Persina Nature Park and Kalimok Brushlen Protected Site, Bulgaria (The World Bank, 2009)
- Instream restoration in Humboldt County, United States of America (Formosa, 2013) (Formosa, 2013)
- Flooding of rice fields with a payment for ecosystem services scheme in Kumamoto, Japan (GRIPP, 2018a)

In addition to improving groundwater recharge, these NBS can also generate other ecosystem benefits such as increasing biodiversity, carbon storage and sequestration, and providing recreational value and moderation of extreme events (UNEP, 2014; NWRM, 2019).

7.2 NBS Interventions to Improve Groundwater Recharge

The GRAF is used to help us monitor aquifer health and assess the need for an intervention. After identifying the state of the aquifer and the sustainable yield, the NBS intervention is considered as the “response” in the DPSIR framework (see Figure 23).

Ideally, NBS interventions will cause the recharge to increase to the aquifer and a reevaluation of the aquifer (because GRAF is a cyclical process) should demonstrate that the water budget has been positively altered. The recalculation of the indicators presented in Chapter 6 can be used to demonstrate the effectiveness of the intervention.

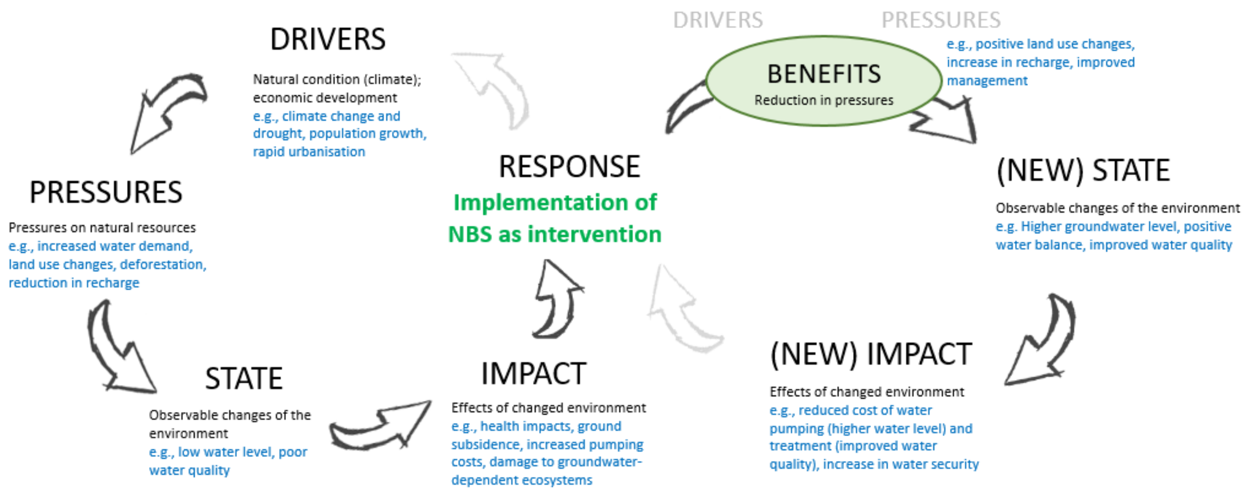

Figure 23: NBS as a response to groundwater problems under the DPSIR framework

7.2.1 Examples of NBS Interventions

Numerous NBS can be used to improve the state of a groundwater body[6]. Here, we present three typical NBS measures that can be used to enable sufficiently high infiltration, thus enabling high levels of aquifer recharge. These measures are:

- Forest protection
- Wetland restoration and management
- Meadows and pastures

Table 5 provides a brief summary of the each of these interventions, including implementation methods, scale, impacts, geographical applicability, expected outcomes and costs. Note that the effectiveness of a particular NBS intervention (or in some cases whether it will even have a positive or negative impact in reaching the stated goal) is dependent on many factors specific to the site of interest (i.e., climate, geology, environment, etc.).

[6] Refer to http://nwrm.eu/measures-catalogue for a comprehensive list of NBS and how they can be applied.

Table 5: Summary of three common NBS interventions to enhance groundwater recharge. Adapted from UNEP (2014) and NWRM (2019)

NBS Intervention	**Forest protection**	**Wetland restoration and management**	**Meadows and pastures**
What is it?	Maintaining forests on lands that would otherwise be handed over for other types of land development. Forest protection can also include reafforestation (i.e., where recent forest cover existed) and afforestation (i.e., where no recent forest cover existed).	Wetlands are defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water".	Meadows are defined as "areas or fields whose main vegetation is grass, or other non-woody plants, used for mowing and haying. Pastures are grassed or wooded areas, moorland or heathland, generally used for grazing".
Implementation / how it works	Forest soils generally have a better infiltration capacity, they act as a sponge and the slower release allows more time for infiltration.	Typically performed to restore wetlands where they have been lost (e.g., in former agricultural lands and forest lands that were drained in the past).	Water retention in the landscape is increased and runoff attenuated. Soil cover is maintained at all times with rooted vegetation, reducing the surface flow of water and allowing greater infiltration to the soil.
Scale	All scales (small to large).	Typically from small to medium scale (0 - 100 km^2).	Small scale (i.e., at the field or farm scale).
Geographical applicability	Best for existing forest and semi-natural areas. Also possible for wetlands and agricultural areas.	Locations where wetlands were drained in the past are desirable.	Agricultural areas.
Expected outcomes	The presence of trees helps increase infiltration. Also, forest soils generally have better infiltration capacity. Surface water flows will also be affected, particularly in reducing the occurrence and intensity of floods.	Some wetlands will resupply aquifers but other wetlands can be fed by groundwater. The slowed/stored runoff also has longer to be able to infiltrate through the soil.	Improved soil structure, for example through grass root systems, can increase infiltration rates.
Potential Problems	Intensive reafforestation and/or afforestation activities may reduce the local total annual runoff and groundwater recharge due to increased water loss through evapotranspiration. For example, a study in the seasonally dry tropics suggests that maximal groundwater recharge is highest for intermediate tree cover (Ilstedt et al., 2016).	Creating larger areas of standing water can form habitats for the spread of vector borne diseases, especially in the tropics.	Meadows and pastures are susceptible to compaction from machinery and livestock; therefore, appropriate management is essential.
Costs	For reforestation/afforestation, the primary costs include the cost of land, purchasing seeds or saplings and tree planting. For managing existing forests, costs are often low.	Costs can be high, consisting of the following: • Land acquisition, especially for former agricultural lands • Investigation and technical design • Physical restoration works Management costs depend on the site and type of activities required.	Costs are typically not too high and mainly consist of: • Maintenance costs • Opportunity costs, particularly when converting arable land to meadows and pastures

7.3 Planning NBS Interventions

After the assessment of groundwater resources, we can now use the information derived by applying this framework to start assessing potential NBS interventions. Table 6 provides a checklist of important considerations for NBS implementations to improve groundwater recharge.

Table 6: Checklist of considerations for NBS implementation to improve aquifer recharge

Data and Core Indicators (see Chapter 6)	• Has the aquifer been mapped and is the groundwater flow regime known? • What information has been obtained from the application of the indicators? Is an intervention necessary?
Planned NBS	• What NBS intervention is planned and why? • What is the planned scale of the intervention?
Location	• Are the geographical conditions appropriate for the proposed NBS intervention? • Is the targeted area effective (i.e., will the aquifer actually be recharged)? • Can the land be used?
Expected outcomes	• Can you model the expected outcomes with regards to groundwater recharge • Can you model the expected outcomes with regards to groundwater quality • What are the uncertainties in your model?
Economic Valuation (adapted from UNEP, 2014)	Costs • Installation and capital costs • Operation and maintenance • Opportunity costs • Transaction costs (e.g., land acquisition) • Negative externalities • Monitoring costs Benefits • Direct benefits (services for which the infrastructure is primarily designed) • Ancillary benefits (positive externalities of infrastructure)
Governance	• Are there any prohibiting governance structures? • Are there any enabling governance structures?
Consider the no intervention scenario	• What will be the consequences if no intervention is taken (i.e. a continuation of the current trajectory)? • What are the future costs of a no intervention scenario?

Box 17: Spatial optimization and NBS

A key premise for scientific analysis in Water Funds is that by adequately understanding the biophysical processes influencing groundwater resources, it is possible to determine the most cost-effective NBS to implement in the field. Based on the amount of data available for a given region, the degree of sophistication to generate a spatially explicit portfolio of NBS for Water Fund use varies.

In the Water Funds context, it is recommended to use spatially explicit GIS based tools that can easily produce visual materials for decision making. A simple but widely used tool for NBS portfolio generation is NatCAP RIOS, which can take advantage of the information produced by following this GRAF.

7.4 Monitoring of NBS

Monitoring allows us both have baseline data about the groundwater system and to assess the impact of an NBS intervention. The parameters to monitor should be selected according to the aim of the intervention (e.g., if the aim of the intervention is to increase the total water stored in the aquifer, then the water table height should be measured). Ideally, the area of interest should be monitored over a long time frame so that information about changes after precipitation events, seasonal changes and even multi-annual changes can be measured.

Despite the importance of monitoring, it is important to note that it may be difficult to isolate the direct impact of an NBS intervention (i.e., because of other changes to the system such as drought, changes in water demand, etc.). For this reason, it is important to define a baseline scenario (see Chapter 7.5).

7.5 Dynamic Assessment Methodology of NBS Performance

Quantitative evidence of the NBS performance using indicators can help monitor the effectiveness of an NBS intervention. This process provides useful information for scientists, Water Fund managers, and decision makers in their water planning and strategy development activities. This framework's dynamic assessment approach contains two stages of analysis:

1. Determination of the benefits that will be achieved by NBS through comparison of NBS performance with a baseline scenario (no NBS).
2. Assessment of the performance of NBS intervention to understand whether performance targets will be met in the designated time frame. The decision maker can then determine whether further interventions are needed to ensure targets are met.

Here, we demonstrate how these steps can be undertaken in the hypothetical case of an NBS intervention to increase aquifer recharge.

1. Determine the benefits

The intervention aims to move towards a defined target, and the results of the intervention will be compared to the estimated trend without an intervention. Figure 24 demonstrates a hypothetical situation based on a green infrastructure project with the aim of increasing groundwater recharge. Three lines are displayed:

- The red "business as usual" situation (i.e., no intervention), which would result in a continual depletion of the groundwater resources.
- The blue line represents the target depth for what is considered to be a healthy groundwater system.
- The green line represents the expected trajectory if the NBS intervention is implemented.

In this example, t_0 refers to the current time (start of intervention), t_1 refers to a certain time after the NBS intervention, and t_2 refers to the time after the intervention at which the target is estimated to be reached. The blue line serves a purpose by setting a target for the intervention, and the NBS should be planned to achieve this target in a defined time frame. Note that the three scenarios shown are not straight lines, but rather demonstrate the seasonal variations that typically occur in groundwater systems (i.e., higher water table depth immediately after the season with the highest precipitation). Furthermore, **many other factors** (e.g., changes in water extractions, climate change, land use changes elsewhere in the watershed, etc.) **will affect the trajectories of these lines**, and Figure 24 therefore presents a simplified conceptual graph.

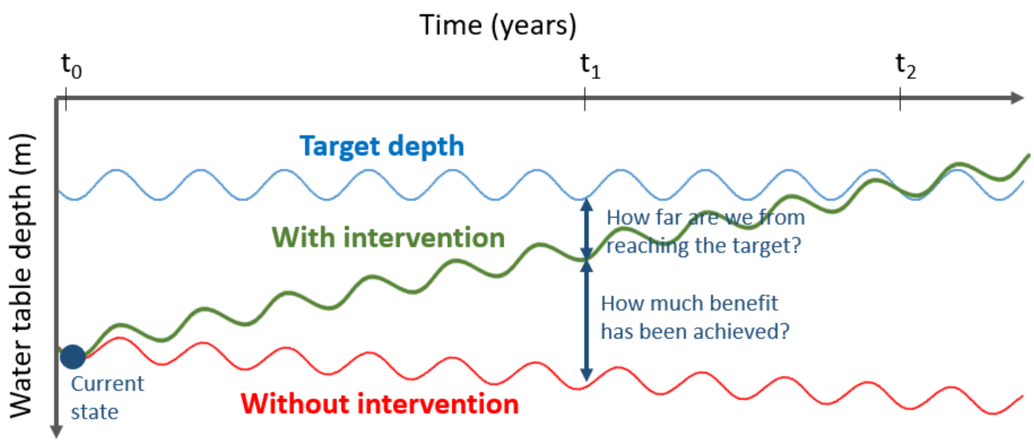

Figure 24: Illustration of NBS planning with a baseline scenario and a target for the NBS

This simplified figure also assumes a constant effectiveness of the NBS intervention, in the extent to which the height of the water table would increase. In reality, this improvement will not be linear. The effectiveness of the intervention can be determined through measuring the water table height at regular intervals (e.g., weekly, monthly, or annual).

Using this assessment methodology and the measurements of water table, the following can be determined:

- The benefit that has been achieved through the intervention
- How far we are away from reaching the target
- In how many years we expect the target to be reached

2. Analysis of trends with target

A considerable period of time after the implementation of the NBS intervention, we can compare the trends with the set targets and analyze any gaps in reaching this target. Note that a "considerable time" is considered to be enough time so that the effectiveness of the NBS can be assessed using the monitoring method[7].

Figure 25 illustrates a point in time (t_1) after the NBS intervention has been implemented. In this example, we can see that the current state has not demonstrated the same quantity of improvement that was expected from the intervention. This information can be used to determine whether further intervention is required.

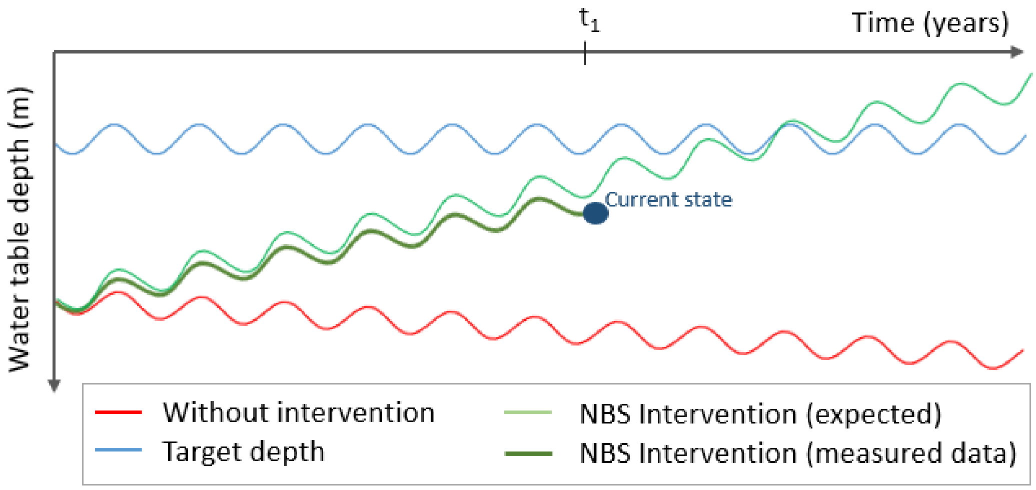

Figure 25: Assessment of intervention scenario

Ideally, the state would be measured continuously to act as a feedback mechanism where a time series is available for the decision maker. Tracking the progress of an intervention with trend analysis allows the decision maker to assess whether the progress matches expectations, accounting for external influences such as drought events. Based on such a data analytics approach, the performance of the intervention can be extrapolated to the future to demonstrate the expected progress. Furthermore, different scenarios to close the gap between the current situation and the target depth can be studied and assessed.

This information provides important feedback to the Water Fund managers regarding the actions that are needed to ensure the success of an ongoing initiative. Understanding the trend analysis together with set targets can assist decision makers significantly to act in a proactive manner to close identified gaps and to succeed in reaching groundwater targets.

The application of the GRAF is a cyclical process. Therefore, a period of time after intervention has been implemented (e.g., t_1 on the above figures), the groundwater body can be reassessed. Most importantly, the water budget, the indicators and the sustainable yield can be reassessed and recalculated at this point in time.

[7] The time needed may change according to the monitoring method. For example, with measurements of the height of the water table, we may need to wait for multiple years to see whether an afforestation programme has had a significant impact. If the monitoring involves direct measurements of infiltration, the impact of the intervention could be assessed almost immediately.

7.6 Considerations and Limitations

We cannot simply assume that any NBS system will generate benefits. Careful planning for NBS interventions to improve aquifer recharge is necessary for the following reasons:

- "The high degree of variation in the impacts of ecosystems on hydrology (depending on ecosystem type or subtype, location and condition, climate and management) cautions to avoid generalized assumptions about NBS. For example, trees can increase or decrease groundwater recharge according to their type, density, location, size and age." (WWAP/UN-Water, 2018).
- The temporal scale of groundwater recharge is very long (TU Delft, 2016), meaning that it may be difficult to convince investors to support such interventions. For this reason, other environmental benefits can also be identified and quantified.
- Sonneveld et al. (2018) attribute failures in NBS implementation to "a lack of understanding of the functioning of ecosystems and ecosystem services as well as a combination of a non-participatory and top-down approach."
- The greater infiltration needs to be balanced against increased rates of evapotranspiration (e.g., from reforestation) and higher water retention in the soils when evaluating the net hydrologic benefit of interventions (NWRM, 2019).
- Quantifying the expected increase in recharge is subject to high uncertainty (de Vries & Simmers, 2002).

In this chapter, we have only introduced selected NBS to improve groundwater infiltration. Numerous other solutions to improve groundwater infiltration are other NBS (e.g., infiltration basins, floodplain restoration, removal of invasive plant species), grey infrastructure (e.g., permeable surfaces, recharge wells) or even a mix of the two (e.g., percolation ponds next to roads).

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Appendix 1: Glossary of Terms

Adapted from: Sharp (2007)

Aquiclude	A geologic material, stratum, or formation that contains water (i.e., has porosity) but does not transmit it (i.e., has zero or negligible permeability).
Aquifer	A consolidated or unconsolidated geologic unit (material, stratum, or formation) or set of connected units that yields water of suitable quality to wells or springs in economically usable amounts.
Confined aquifer (or artesian aquifer)	An aquifer that is immediately overlain by a low-permeability unit (confining layer). A confined aquifer does not have a water table.
Leaky aquifer	An aquifer that receives recharge via cross-formational flow through confining layers
Perched aquifer	A local, unconfined aquifer at a higher elevation than the regional unconfined aquifer. An unsaturated zone is present between the two unconfined aquifers.
Unconfined aquifer	The upper surface of the aquifer is the water table. Water- table aquifers are directly overlain by an unsaturated zone or a surface water body.
Aquitard	A geologic material, stratum, or formation of low permeability (a confining unit) that transmits significant amounts of water on a regional scale or over geologic time.
Baseflow	Groundwater flow to a surface water body (lake, swamp, or stream)
Capillarity	The action by which water is raised (or lowered) relative to the water surface because of interaction between the water molecules and the solids of the porous medium.
Capillary fringe (or zone)	The zone immediately above the water table where the medium is saturated or partially saturated by capillary rise from the phreatic zone.
Cone of depression	The depression in the water table or potentiometric surface cause by pumping from a well.
Drawdown	The drop in head from the initial head caused by pumping from a well or set of wells.
Evaporation	The process by which liquid water at or near the Earth's surface turns into vapor at temperatures less than boiling.
Evapotranspiration	The combination of evaporation and transpiration.
Groundwater	Generally all water beneath the land surface.
Hydraulic conductivity	The volume of fluid that flows through a unit area of porous medium for a unit hydraulic gradient normal to that area.
Hydraulic gradient	The change in hydraulic head with direction
Hydrogeology	The study of subsurface water, including its physical and chemical properties, geologic environment, its role in geologic processes, natural movement, recovery, contamination, and utilization.
Hydrograph	A chart depicting either discharge or water level as a function of time.
Lysimeter	A device for measuring the quantity, quality, or rate of water movement in the soil.
Outcrop	Where a formation is present at the Earth's surface.

Percolation	Gravity flow of groundwater downwards through the unsaturated zone.
Permeability	The ease with which a porous medium can transmit water or other fluids.
Phreatic zone	Water in the zone beneath the water table where the fluid pressure is equal to or greater than atmospheric pressure.
Piezometric surface	A surface of equal hydraulic heads or potentials, typically depicted by a map of equipotentials such as a map of water-table elevations.
Porosity	The volume of the voids divided by the total volume of porous medium.
Recharge	The process by which water enters the groundwater system or, more precisely, enters the phreatic zone.
Recharge zone	The area of an aquifer or aquifer system where water enters the subsurface and, eventually, the phreatic zone
Return flow	That water which is pumped from a stream, an aquifer, or a basin that is not consumptively used and which returns to the stream, aquifer, or basin.
Runoff	Water from precipitation, snowmelt, or irrigation running over the surface of the Earth.
Saturation zone	The zone in the Earth's surface below the water table and the saturated portion of the capillary fringe in which all pore space is generally saturated with liquid water.
Spring	A discharge (or issue) of water from the earth; a natural fountain.
Storativity	The volume of water released per unit area of aquifer for a unit decline in head.
Transmissivity	The discharge through a unit width of the entire saturated thickness of an aquifer for a unit hydraulic gradient normal to the unit width.
Transpiration	The process by which plants (and animals) release water vapor to the atmosphere.
Unsaturated zone	Generically, is considered equivalent to the vadose zone. This is the zone above the water table and the saturated portion of the capillary fringe where the pores are generally filled with both liquid water and air.
Vadose zone	The zone above the water table where the fluid pressure is less than atmospheric pressure.
Water table	A surface at or near the top of the phreatic zone (zone of saturation) where the fluid pressure is equal to atmospheric pressure. In the field, the water table is defined by the level of water in wells that barely penetrate the phreatic (saturated) zone.
Yield	Generically, the amount of water pumped from a well (or bore).

Appendix 2: List of Data

Adapted from IGRAC & UNESCO-IHP (2015)

A – Physiography and Climate

A1 Temperature	
Description	**Format**
Characterization of temperature in the aquifer area, including an overview of the temporal and spatial variation. Use data from meteorological stations in the aquifer area and as close as possible to the aquifer boundaries. When using data from meteorological stations outside the aquifer area, use an interpolation process. Depending on data availability, provide results such as mean annual temperature (mean minimum, mean maximum), graphs of monthly mean values per monitoring station, spatial distribution of mean temperature in the aquifer area (map), etc. If no meteorological stations are available, use global datasets that combine information from weather stations information with remote sensing products.	Numeric values and text: mean values Table + graphs: time series with monthly averages Map: raster or isolines **Unit** [Degrees Celsius] **Global datasets** WorldClim (1970 - 2000, mean values) ERA5 (1979 - present, time series)
Sub-questions / metainformation	**Format**
Description of the method used to interpolate map values (if relevant).	Text

A2 Precipitation	
Description	**Format**
Characterization of precipitation in the aquifer area (or recharge area), including an overview of the temporal and spatial variation. Use data from meteorological stations in the aquifer area and as close as possible to the aquifer boundaries. Include data from meteorological stations outside the aquifer area to use in the interpolation process. Depending on data availability provide results as mean annual precipitation (mean minimum, mean maximum), graphs of monthly mean values per monitoring station, spatial distribution of mean precipitation in the aquifer area (map), etc. Also describe type of precipitation (rainfall, snow) throughout the year.	Numerical values and text: mean values Table + graphs: time series with monthly averages Map: raster or isolines **Unit** [mm/yr], [mm/day], [mm/month] **Global datasets** WorldClim (1970 - 2000, mean values) ERA5 (1979 - present, time series)
Sub-questions / metainformation	**Format**
Describe the method used to interpolate map values (if relevant)	Text

A3 Evapotranspiration	
Description	**Format**
Evapotranspiration is the water lost into the atmosphere through evaporation and plant transpiration. Use data from meteorological stations in the aquifer area and as close as possible to the aquifer boundaries. Include data from stations outside the aquifer area to use in the interpolation process. Depending on data availability provide results as mean annual evapotranspiration (mean minimum, mean maximum), graphs of monthly mean values per monitoring station, spatial distribution of mean evapotranspiration in the aquifer area (map), etc.	Map: raster or isolines and Table: time series with monthly average **Unit** [mm] **Available global datasets** ERA5, SSEBop, MOD16, GLEAM
Sub-questions / metainformation	**Format**
Specify / describe the method used for the calculation of evapotranspiration.	Text
Describe the method used to interpolate map values (if relevant)	Text

A4 Land use / land cover	
Description	**Format**
Land use is characterized by the arrangements, activities and inputs that people undertake in a certain land cover type to produce, change or maintain it. Information on land use in the aquifer area is a key element to understanding the processes and context affecting the aquifer, e.g. to identify the locations of land use with the potential to pollute groundwater. Another example is to know which part of agricultural land is rainwater-fed, or irrigated with groundwater, or irrigated with surface water. Usually land use maps are based on specific classifications at national level. If applicable and if sufficient information is available, make a differentiation in the maps for the following land uses: • A4.1 - Groundwater-fed agricultural land • A.4.2. Groundwater-irrigated land • A.4.3. Groundwater-supported wetlands and ecosystems • A.4.4. Areas with land subsidence	Text: Describing land use including topics such as water needs, potential threats to (ground) water etc. Map: polygon features **Unit** [-] **Available global datasets** ESA, Globcover V2 (2009) EC/JRC, GLC 2000 (2000)

A5 Topography and elevation	
Description	**Format**
A suitable topographical map is needed which can be used as a background map to present thematic maps. In addition, it is useful to have a map of the elevation of the land surface with respect to mean sea level. The map is preferably be available as a digital elevation model for the whole aquifer area and its vicinities.	Map: raster **Unit** [m] above mean sea level **Available global datasets** EAPRS Lab, ACE2 v31 (2009) SRTM, CGIAR

A6 Surface water network	
Description	**Format**
Network of rivers, lakes, swamps and water reservoirs present in the aquifer's area. Often this data is available at national level.	Map: line and polygon features **Unit** [-] **Available global datasets** DIVA GIS

B – Aquifer Geometry

B1 Hydrogeological map	
Description	**Format**
The **hydrogeological map** brings basic geological information together with data on hydraulic and hydro-chemical characteristics of the rocks and their usefulness for groundwater supply Geological and hydrogeological maps are most often produced by national institutions, such as geological surveys.	Map: line and polygon features **Unit** [-] **Available global datasets** [-]

B2 Geo-referenced boundary of aquifer system	
Description	**Format**
Polygon depicting outline of the whole aquifer, possibly including the delineation of each aquifer unit, or national aquifers. **Please note:** this may be considerably different from the delineation of the outcrop of the aquifer. The map should consider the full horizontal extent of the hydrogeological formation. For **aquifer systems** make map layers that depict the delineation of the individual aquifers in the aquifer system. If this is not possible depict the complete aquifer system as if it were one single unit.	Map: polygon feature **Unit** [-] **Available global datasets** [-]
Sub-questions / metainformation	**Format**
B2.1 What type of information is the delineation based on? Common options are: • No-flow boundaries • Lithology / geology • Groundwater quality • Topography • Administrative boundaries	Text – describing how the aquifer was delineated
B2.2 Is the aquifer a single layer aquifer or are you describing an aquifer system consisting of two or more aquifers (layers) that are hydraulically connected?	Text – amount of aquifers in aquifer system and description of their hydraulic connectivity and distribution

B3 Depth of water table / piezometric surface and groundwater flow direction	
Description	**Format**
Distance from ground surface to groundwater table or piezometric level. If enough data are available it may be useful to visualize this information in two different ways: • Depth of groundwater table (distance from ground surface to groundwater table), and • Groundwater table / piezometric level in meters above sea level. Please note: If applicable and if sufficient data are available, create maps for each aquifer / layer.	Map: raster format or isolines **Unit** [m] **Available global datasets** [-]
Sub-questions / metainformation	
Map indicating main directions of groundwater flow. This map can be constructed based on a map of groundwater levels [m above mean sea level], or it can be based on general knowledge.	Map: line features indicating flow direction

B4 Depth to top of aquifer formation [m]	
Description	**Format**
Distance from ground level to the top of the aquifer formation. In unconfined aquifers, this is zero meters. If applicable and if sufficient data are available, create one map for each aquifer / layer.	Map: raster format or isolines (shape-file)
	Unit
	[m]
	Available global datasets
	[-]

B5 Vertical thickness of the aquifer (system) including aquitards / aquicludes	
Description	**Format**
The vertical thickness of the aquifer (system) is the distance between the top and the bottom of the aquifer (system) formation. For aquifer systems, maps should be provided for each aquifer layer and each aquitard / aquiclude.	Map: raster format or isolines
	Unit
	[m]
	Available global datasets
	[-]

B6 Degree of confinement	
Description	**Format**
Indicate for each aquifer the degree of confinement: • Whole aquifer unconfined • Whole aquifer confined • Whole aquifer semi-confined • Aquifer mostly unconfined but some parts confined • Aquifer mostly confined but some parts unconfined • Aquifer mostly semi-confined but some parts unconfined Preferably which part of (each) aquifer is unconfined, confined or semi-confined needs to be clearly indicated on a map.	Text Map: raster format or polygons
	Unit
	[-]
	Available global datasets
	[-]

B7 Representative cross sections	
Description	**Format**
See Chapter 4.2.2.	Graphical files
	Unit
	[-]
	Available global datasets
	[-]

C – Hydrogeological Characteristics

C1 Aquifer recharge	
Description	**Format**
Recharge is the replenishment of groundwater. Total recharge can be split into several categories: • Natural recharge • Return flows from irrigation • Managed aquifer recharge • Induced recharge (i.e., recharge to an aquifer that occurs when a pumping well creates a cone of depression that lowers an adjacent water table below the level of a stream or lake, causing the stream or lake to lose water to the adjacent groundwater aquifer.) Depending on data availability, as much as possible information on the above should be collected and described, preferably in map format and tables. Map information: zones where significant natural recharge occurs; locations where return flows, managed aquifer recharge or induced recharge occurs. If possible, the maps should also indicate the distribution of the recharge values. Please note: for aquifer systems, if relevant, provide different maps for different aquifers (layers) of the aquifer system.	Depending on data availability: Map: polygon recharge zones Map: raster format or isolines of recharge values Tables: recharge values per year and/or per category **Unit** [m^3/yr] or [km^3/yr] **Available global datasets** [-]
Sub-questions / metainformation	
Time variability: Is there significant difference between years in terms of volume and frequency of recharge? If so, describe this variability: • Time interval between extreme events [years] • Average recharge rate for years with extreme events [m^3/yr] • Average recharge rate for years without extreme events [m^3/yr]	Text
Areal extent of area(s) with significant recharge [km^2]	Text
What percentage of total groundwater recharge is natural recharge? [%]	Text
Specify which type(s) of recharge occur. Indicate the most predominant source of recharge. If possible try to indicate how much these sources contribute to total recharge [%]. Choose from the categories listed below: • Precipitation on aquifer area • Runoff into aquifer area • Infiltration from surface water body • Human induced recharge	Text

C2 Aquifer Lithology	
Description	**Format**
Describe each aquifer in terms of lithology. First characterize the aquifer by choosing the most prominent lithology class from the list below: • Sediment - sand • Sediment - gravel • Sediment - silt - clay • Sedimentary rocks - shale • Sedimentary rocks - sandstone • Sedimentary rocks - limestone • Sedimentary rocks - dolostone • Sedimentary rocks - evaporate • Crystalline rocks - granite • Crystalline rocks - basalt • Metamorphic rocks Next, describe the heterogeneity of the aquifer (lateral and vertical variation in lithology). For aquifer systems, describe the lithology of each aquifer and aquitard.	Text describing lithology, including lateral and vertical variations **Unit** [-] **Priority for data collection** 3 (general characterization) **Available global datasets** [-]

C3 Soil types	
Description	**Format**
Soil media refers to the uppermost portion of the vadose zone characterized by significant biological activity. Soil is considered the upper weathered zone of the earth. The type of soil has a big impact on the amount of recharge that can infiltrate and therefore on the ability of pollutants to reach the water table. Classify the soils present in the aquifer area based on the following classification (Aller et al., 1987): A. Confining layer B. Silt/clay C. Shale D. Limestone E. Sandstone F. Bedded limestone, sandstone, shale G. Sand and gravel with significant silt and clay H. Metamorphic/igneous I. Sand and gravel J. Basalt K. Karst limestone	Map: polygon features **Unit** [-] **Available global datasets** [-]

C4 Porosity

Description	Format
Describe the porosity for each aquifer, according to the list below: • Primary porosity (only one answer possible) i. High primary porosity, fine / medium sedimentary deposits ii. Very high primary porosity, gravel / pebbles iii. Low primary porosity, intergranular porosity • Secondary porosity (only one answer possible) i. Dissolution ii. Weathering iii. Fractures iv. No secondary porosity • Connectivity (only one answer possible) i. High horizontal connectivity ii. Low horizontal connectivity Definitions (Margat & van der Gun, 2013): • *Voids (interstices)* are defined as open spaces within subsurface unconsolidated sediments and rock formations, allowing fluids to flow or be stored underground • *Primary porosity*: porosity formed during the deposition of the sediment or from vesicles in igneous rocks • *Secondary porosity*: porosity formed by either dissolution or fracturing after lithification of the rock • *Connectivity:* interconnected porosity that contributes to groundwater flow.	Text **Unit** [-] **Available global datasets** [-]

C5 Transmissivity and vertical connectivity

Description	Format
Describe for each aquifer the transmissivity [m²/day] and/or conductivity [m/d] in terms of average, minimum and maximum and its spatial distribution. If sufficient data are available provide a map of the spatial distribution Definitions**:** • Transmissivity is the rate at which water is transferred through a unit width of an aquifer under a unit hydraulic gradient (World Meteorological Organization, 2012). • Hydraulic conductivity is the capacity of the porous media to transmit water (Margat & van der Gun, 2013)	Text: if sufficient data Map: raster format or isolines **Unit** [m²/d] or [m/d] **Available global datasets** [-]
Sub-questions / metainformation	
For aquifer systems also describe the vertical connectivity between the aquifers (layers) and if sufficient data are available also describe the spatial distribution of the vertical connectivity. It can be qualified in terms such as low, medium or high connectivity. Vertical connectivity can also be expressed as vertical resistance [days].	**Text**: if sufficient data. **Map**: raster format or isolines

C6 Total groundwater volume

Description	Format
Estimate the total volume of water in each aquifer. If sufficient data are available (and if applicable), try to differentiate between water suitable for human consumption and water of inferior quality	**Text** **Unit** [m³] or [km³]

C.7. Groundwater depletion	
Description	**Format**
For each aquifer, estimate or calculate groundwater depletion. Definition: Groundwater depletion is the reduction of the stored volume of groundwater in an aquifer. It is a quantity aggregated over the entire aquifer system. In this case the estimated groundwater depletion will be representative of current conditions and related to a relatively long period (multiple years). It is expressed in m^3/yr. Note that in some cases the 'depletion' may be negative, i.e. accretion or increase of the stored volume. The decrease in groundwater volume in the aquifer is estimated based either on groundwater level observations (taking into account the locally valid storage coefficient) or by using a groundwater simulation model. Also note that groundwater depletion is distinctly different from the cone of depression around a pumping well.	**Text:** based on tabular information **Maps**: raster format or isolines **Unit** [m^3/yr] or [km^3/yr] **Available global datasets** [-]

C8 Natural discharge mechanisms	
Description	**Format**
Describe the discharge mechanisms for each aquifer using general terms, by indicating the most predominant discharge type or by trying to quantify each type [m^3/yr] or [%]. Natural discharge mechanisms can be: • Springs • River baseflow • Outflow into lakes • Submarine outflow • Evapotranspiration • Groundwater flow into another aquifer	**Text** **Unit** [-] or [%] or [m^3/yr] **Available global datasets** [-]

C9 Discharge by spring	
Description	**Format**
Try to quantify the total discharge of all springs originating from the aquifer / aquifer system. Depicting the (major) springs (including annual discharge per spring) in a map can be very useful. Definition: a spring is considered to be any place in the aquifer area where water emerges naturally from rock or soil onto land, or into surface water, i.e. artesian springs, fault springs, joint springs, mineral springs or thermal springs (World Meteorological Organization, 2012).	**Text.** Optional: map with locations of springs and (estimated) discharge per spring. **Unit** [m^3/yr] or [km^3/yr] **Available global datasets** [-]

D – Environmental Aspects

D1 Groundwater quality / suitability for human consumption	
Description	**Format**
In many aquifers not all groundwater is suitable for human consumption, for example, because of high salinity, high arsenic or fluoride concentrations. Try to quantify to what extent the groundwater in each aquifer is unsuitable for human consumption due to natural reasons. In many cases, it is difficult to quantify this exactly, but it is possible to indicate by approximation the areas of the aquifer where groundwater is found of which the natural quality does NOT satisfy local drinking water standards. This means: indicate parts of the aquifer with, for example, high natural arsenic or fluoride concentrations or high natural salinity. Based on this, map estimates can be made of the percentage or volume of the aquifer that is not suitable for human consumption. This includes situations where human activities have mobilized elements that were already naturally present in the aquifer.	Text and maps (polygon or raster) **Unit** [-] **Available global datasets** [-]
Sub-questions / metainformation	
Indicate to what depth natural groundwater quality does NOT satisfy local drinking water standards: • Only superficial layers • Significant part of the aquifer • The whole thickness of the aquifer	
Indicate which are the main pollutants of natural origin affecting natural groundwater quality and provide a map if possible: • Natural salinity • Fluoride • Arsenic • Others, please specify	Text and maps (polygon features indicating occurrence)

D2 Groundwater pollution	
Description	**Format**
Try to quantify to what extent the groundwater in each aquifer is affected by pollution resulting from human activity. In many cases, it is difficult to quantify pollution exactly, but it is possible to indicate by approximation the areas of the aquifer where pollution occurs. Based on this map, estimates can be made of the percentage or volume of the aquifer that is or may be affected by pollution. **Definition:** pollution is considered to be any aspect of water quality (chemical, biological, thermal) which is caused by anthropogenic as well as non-anthropogenic sources (e.g., arsenic and from other geological sources) and which interferes with the intended use of the groundwater. Here we assess pollution by defining the zones with groundwater pollution in the aquifer area. This can be zones with pollution from point sources (e.g. industrial spills) or zones, which suffer from diffuse pollution (for example, from agriculture practices).	Text and maps (polygon indicating major pollution sites / polluted zones) **Unit** [-] **Available global datasets** [-]
Sub-questions / metainformation	
Indicate to what depth groundwater is affected by pollution: • Only superficial layers • Significant part of the aquifer • The whole thickness of the aquifer	
Indicate the most important sources of groundwater pollution in the aquifer: • Landfills / waste disposal sites • Households • Municipalities • Industrial waste disposal • Military sites • Agricultural practices (irrigation, pesticides, fertilizers) • Mining activities • Oil/gas production and / or transport activities • Leakage through boreholes • Other	
Indicate the most important pollutants affecting aquifer's groundwater quality: • Salinization • Nitrogen species • Hydrocarbons • Pathogenic agents • Pesticides • Heavy metals • Industrial organic components • Thermal pollution • Other	

D3 Solid waste and waste water control	
Description	**Format**
Provide an insight into: • The amount of wastewater being collected in sewerage systems • Wastewater being treated in treatment plants before being discharged and location of treatment plants • Solid waste being stored in controlled landfills and location of controlled landfills. Depending on the availability, this can be presented as percentages or just as a number: for example, the amount of wastewater collected in sewage systems as a percentage of total wastewater, or the number of households connected to sewage systems as a percentage of the total number of households. When this level of detail is not feasible it could be presented per municipality if there is a sewage system [yes/no]. Alternatively indicate the amount of sewage treatment plants and landfills. **Definitions:** • **Sewage or wastewater** is the water output of a community after it has been fouled by various uses (World Meteorological Organization, 2012) • **Wastewater treatment plant**: a plant where, through physical-chemical and biological processes, organic matter, bacteria, viruses and solids are removed from residential, commercial and industrial wastewaters before they are discharged into rivers, lakes and seas • **Solid waste** refers to discarded solid materials. Includes agricultural waste, mining waste, industrial waste and municipal waste	Text, table and maps (point features) **Unit** depending on available data] **Available global datasets** WHO/UNICEF, JMP (1990, 1995, 2000, 2005, 2010) AQUASTAT

D4 Shallow groundwater table and groundwater-dependent ecosystems	
Description	**Format**
Shallow groundwater tables can be related to the occurrence of groundwater-dependent ecosystems. Areas with shallow groundwater tables can also be more vulnerable to pollution of the aquifer. Therefore, it is useful to indicate the extent of the aquifer where the depth to the groundwater table is less than 5 m below the soil surface. This can be based on the map of groundwater levels.	Text or map (preferably) **Unit** **Available global datasets**
Sub-questions / metainformation	
Describe the occurrence of groundwater dependent ecosystems. Describe where these ecosystems occur	Text or map (preferably)

E – Socio-Economic Aspects

E1 Population density	
Description	**Format**
Density of population is the amount of people living in the aquifer area per km^2. It is foreseen that in most cases population data is linked to administrative units that most likely does not coincide with the exact areal extent of the aquifer. Alternative sources of information can be available as global datasets, such as the global density population estimates provided by the Socioeconomic Data and Applications Centre (SEDAC) hosted by CIESIN at Columbia University.	Map (raster and/or polygon feature) **Unit** [Inhabitants/km^2] or [Inhabitants] **Available global datasets** CIESIN, GRUMP (2010) IIASA, POP (2000-2010)
Sub-questions / metainformation	
Give the percentage of rural and urban population in the aquifer's area	%
What is the population annual growth rate?	[Inhabitants/yr]
It is possible that people outside the aquifer area are dependent on the (ground) water resources in the aquifer area. If that is the case, please specify/describe.	

E2 Groundwater use	
Description	**Format**
Provide a complete overview of groundwater being abstracted from the aquifer through boreholes and wells, including a breakdown of total volume per water type (fresh, brackish and saline) and per type of water use. Definitions of water types (Margat & van der Gun, 2013): • Freshwater: water with less than 1 000 mg/l dissolved solids. • Brackish water: water containing dissolved solids in a concentration between 1 000 and 10 000 milligram per liter. • Saline water: water containing dissolved solids in concentrations of more than 10 000 milligram per liter. Water use (types of water use to be distinguished): • **Domestic water use:** ○ From private wells/boreholes ○ Public water supply from groundwater • **Agricultural / livestock watering:** ○ Irrigation ○ Livestock ○ Aquaculture • **Commercial and industrial water use:** ○ Mining ○ Industry ○ Energy production ○ Tourism sector (e.g. recreational use) ○ Bottled water, production of soft drinks, breweries. ○ Other • **Environmental use** (e.g. protection of groundwater-dependent ecosystems, providing water for wildlife) Depending on how much information is available, the information should be organized in tables indicating abstraction volumes per year, per type of water use and per water type. Level of detail: Abstraction data may be available for administrative units (e.g. municipalities) rather than per well. Therefore, if data is available at municipality level, please provide a map showing values of total groundwater abstraction per local administrative unit (e.g. municipality) and type of use.	Text Tables: see example below Maps: point data of (major) abstractions, category and yearly volume and polygon features **Unit** [m³/yr] or [km³/yr] **Available global datasets** FAO, AQUASTAT

E3 Surface water use	
Description	**Format**
It is very useful to know how dependent a population is on groundwater. For this purpose, the use of groundwater can be compared to the total water use / use of surface water. Provide information in table format on surface water use, using the same categories of water type and water use as for groundwater use. See E2 above for classifications and further description.	Text Tables Maps: point data of (major) abstractions, category and yearly volume and polygon features **Unit** [m³/yr] or [km³/yr] **Available global datasets** FAO, AQUASTAT

E4 Dependence of industry and agriculture on groundwater	
Description	**Format**
Percentage of the industry and agriculture depending on groundwater supply. To complete the picture of information it is necessary to describe which proportion of industry (or agriculture) is not dependent on surface or groundwater. This parameter can be expressed in the number of industries / businesses or in terms of contribution to GDP ($).	Text , table and diagram/chart **Unit** [-] **Available global datasets** [-]

E5 Percentage of population covered by public water supply	
Description	**Format**
Percentage of total population in the aquifer area covered by public water supply. Water supply data may be linked to administrative units. In this case data can be shown as the percentage of population covered by public water supply per local administrative unit (e.g. municipality). **Public water supply** refers to water withdrawn by public and private water suppliers and delivered to users. Public water suppliers may provide water to domestic, commercial, and industrial users, to facilities generating thermoelectric power, for public use, and occasionally for mining and irrigation (Templin et al., 1980).	Text, table and map: polygon features **Unit** % **Available global datasets** [-]

E6 Percentage of population covered by sanitation	
Description	**Format**
Percentage of total population in aquifer area with access to sanitation. Sanitation data may be linked to administrative units. In this case, data can be shown as the percentage of population covered by public water supply per local administrative unit (e.g. municipality). **Definitions: Sanitation** generally refers to the provision of facilities and services for the safe disposal of human urine and feces. Inadequate sanitation is a major cause of disease worldwide and improving sanitation is known to have a significant beneficial impact on health both in households and across communities. The word 'sanitation' also refers to the maintenance of hygienic conditions, through services such as rubbish collection and wastewater disposal (World Health Organization, 2018).	Text, table and map: polygon features **Unit** % **Available global datasets** [-]

Appendix 3: Groundwater Assessment of an Assessment Unit

The spatial distribution of the piezometric surface and hydraulic head can vary significantly over a groundwater body, both due to natural processes and the cones of influence from groundwater extraction wells (Zhou, 2009). Depending on the particular objectives of a groundwater assessment, these spatial variations may need to be investigated in detail. However, for the simplified assessment presented here, we only consider the water balance of the assessment unit.

Assessment of Annual Replenishment of Dynamic Groundwater Resources

The methodology for groundwater resources estimation is based on the principle of water balance described in Eq. 1. This can be further elaborated as (Adapted from: Ministry of Water Resources, 2017a):

$$\Delta S = R_{RF} + R_{STR} + R_{SWI} + R_{GWI} + R_{TP} + R_{WCS} \pm VF \pm LF - GE - ET - B \qquad \text{Eq. 15}$$

where:

ΔS – Change in storage [m^3/ time unit]
R_{RF} – Rainfall recharge [m^3/ time unit]
R_{STR} – Recharge from stream channels [m^3/ time unit]
R_{SWI} – Recharge from surface water irrigation (lift irrigation) [m^3/ time unit]
R_{GWI} – Recharge from groundwater irrigation [m^3/ time unit]
R_{TP} – Recharge from tanks and ponds [m^3/ time unit]
R_{WCS} – Recharge from water conservation structures [m^3/ time unit]
VF – Vertical inter aquifer flow [m^3/ time unit]
LF – Lateral flow along the aquifer system (throughflow) [m^3/ time unit]
GE – Groundwater extraction [m^3/ time unit]
ET – Evapotranspiration [m^3/ time unit]
B – Baseflow [m^3/ time unit]

Note that the dynamic groundwater resources are also known as the annual replenishable groundwater resources.

The next step is to calculate each of the parameters (if available) to apply Eq. 15 to obtain the overall water balance and ultimately the groundwater recharge. A detailed description of the calculation of the sub-parameters is included in Appendix 4, along with the data requirements.

Assessment of Static Groundwater Resources

Sustainable groundwater exploitation should be restricted to the dynamic resources, with static (i.e., in-storage) resources only exploited in exceptional circumstances. The calculation of static groundwater resources[8] can be calculated as (Ministry of Water Resources, 2017a):

$$\mathbf{SGWR = A * (Z_2 - Z_1) * S_y} \qquad \text{Eq. 16}$$

where:

- SGWR = Static groundwater resources (volume)
- A = Area of the assessment unit (area)
- Z_2 = Bottom of unconfined aquifer (length)
- Z_1 = Water level before rainy season (length)
- S_y = Specific yield in the in-storage zone (unitless) (see Appendix 4 for more information)

The total groundwater volume is therefore the sum of the static groundwater resources and the dynamic groundwater resources.

Assessment a Confined Aquifer

Overexploitation of confined aquifers can have significant negative consequences. If the piezometric surface of a confined aquifer drops below the upper confining layer, the coefficient of storage is no longer related to the elasticity of the aquifer but to its specific yield. Declines in piezometric levels can lead to land subsidence and serious geotectonic problems (Ministry of Water Resources, 2017a).

The storativity (S, otherwise known as the coefficient of storage) is defined as the volume of water released from storage per unit decline in hydraulic head in the aquifer per unit area of the aquifer. To assess the groundwater resources of a confined aquifer, the quantity of water added to or released from the aquifer (ΔV) is related to the storativity and change in head. For a confined aquifer with an aerial extent of A, the total quantity of water added to or released from the aquifer is (Ministry of Water Resources, 2017a):

$$\mathbf{Q = S * A * \Delta h} \qquad \text{Eq. 17}$$

where:

- Q = Quantity of water confined aquifer can release (m^3)
- S = Storativity (unitless)
- A = Areal extent of the confined aquifer (m^2)
- Δh = Change in Piezometric head (m)

[8] Static Groundwater resources of an area are the resources which remain available below the dynamic zone of water table fluctuation. This is not replenished every year and extracting this water is considered to be groundwater mining.

Ensuring that the piezometric does not drop below the top confining bed of the confined aquifer, we can consider the groundwater potential as the resources available under pressure. To calculate the groundwater potential of a confined aquifer (Ministry of Water Resources, 2017a):

$$\mathbf{Q_P = S * A * \Delta h = S * A (h_t - h_0)} \qquad \text{Eq. 18}$$

where:

- Q_P = Groundwater Potential of Confined Aquifer (m^3)
- S = Storativity (unitless)
- A = Areal extent of the confined aquifer (m^2)
- Δh = Change in Piezometric head (m)
- h_t =Piezometric head at any particular time (m)
- h_0 =Bottom of the top Confining Layer (m)

Appendix 4: Calculation Methods for Components of Water Balance Equation

Rainfall Recharge

Here, we present three methods to determine the rainfall recharge:

- Water table fluctuation method
- Using baseflow
- Rainfall infiltration factor method.

Consideration should be given to the seasonal patterns of rainfall in the study area when calculating rainfall recharge. Where possible, we recommend that groundwater recharge should be estimated using a groundwater level fluctuation and specific yield approach. Such a method considers the response of groundwater levels to groundwater input and output components (Ministry of Water Resources, 2017a).

Water Table Fluctuation Method

Ideally, the following data would be available (Ministry of Water Resources, 2017a):

- Water level measurements spatially distributed over the area of interest
- Data over multiple years (at least five years), with corresponding precipitation data
- Water level measurements both before and after the rainy season
    - Ideally, daily groundwater level measurements

The groundwater level fluctuation method can be used to assess rainfall recharge. This method is based on the assumption that rises in groundwater levels **in unconfined aquifers** are due to recharge water arriving at the water table. The change in storage is calculated as (Ministry of Water Resources, 2017a):

$$\mathbf{\Delta S = R_{RF} = \Delta h * A * S_y} \qquad 19$$

where:

ΔS – Change in storage - in this case the recharge from rainfall (R_{RF}) (m^3)
Δh – Rise in water level (m)
A – Area for computation of recharge (m^2)
S_y – Specific yield (unitless) (see section on Specific Yield for calculation methods)

Derivation of Eq. 19 assumes that water arriving at the water table goes immediately into storage and that all other recharge components of Eq. 15 are zero during the period of recharge (or are accounted for and separated from rainfall recharge). A time lag occurs between arrival of water during a recharge event and redistribution of that water to the other non-recharge components of Eq. 19, and if the groundwater level fluctuation method is applied during this time lag, all water recharging the aquifer can be accounted (Healy & Cook, 2002).

Figure 26 presents a groundwater hydrograph, which illustrates the groundwater recharge after a rainfall event (Healy & Scanlon, 2010). In this example:

- The recharge for the water level rise, in terms of depth of water, is calculated as S_y multiplied by Δh, where Δh is the difference between the peak of the rise and low point of the extrapolated antecedent recession curve (dotted line) at the time of the peak.
- The change in subsurface storage between days 85 and 86 is calculated as S_y multiplied by ΔH_n, where ΔH_n is the difference in water level at midnight on days 85 and 86.

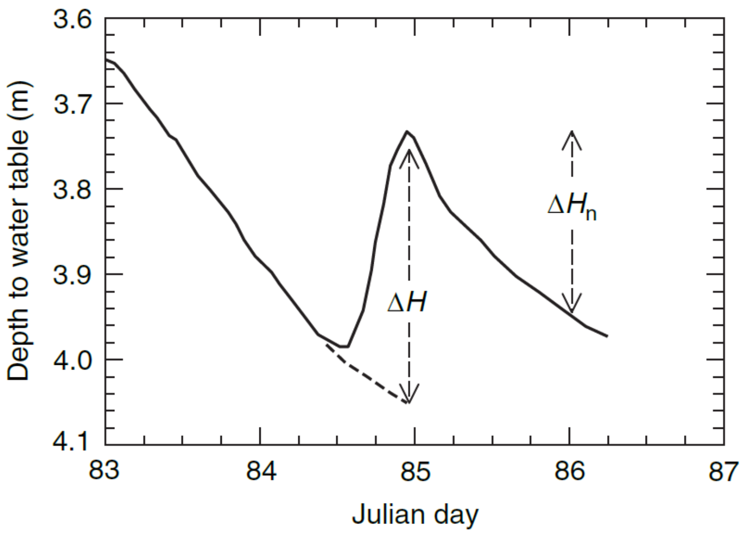

Figure 26: Example of groundwater hydrograph (Healy & Scanlon, 2010)

Calculating Recharge from Baseflow

If stream gauge (i.e., discharge[9]) stations are located in the basin, the baseflow and recharge from streams can be calculated using the stream hydrograph separation method. A single stream gauge at the mouth of the basin can provide the required data for the calculation of baseflow.

Baseflow is considered as the flow from groundwater aquifers (Hewlett & Hibbert, 1967), or as flow from groundwater storage or other delayed sources (Tallaksen, 1995). It is the slowest decaying, longest lasting component of streamflow, meaning that it is usually associated with groundwater processes and therefore cannot be attributed to a single rainfall event (Duncan, 2019). The baseflow phase that is most recognizable and easiest to analyze is the relatively smooth recession observed during extended periods of little or no rain (Duncan, 2019).

The following are characteristic features of baseflow through the course of a runoff event (Nathan & McMahon, 1990; Brodie & Hostetler, 2005; Duncan, 2019):

1. Low flow conditions prior to the start of a runoff event typically consist entirely of baseflow.
2. The baseflow recession will continue for a time after the rise of the total hydrograph.

[9] Note that in this context, "discharge" refers to the streamflow, whereas "groundwater discharge" refers to the release of groundwater from the aquifer via baseflow, evapotranspiration, or springs.

3. Baseflow will peak after the total hydrograph peak, due to the storage-routing effect of the sub-surface stores.
4. The baseflow recession will most likely follow an exponential decay function.
5. The baseflow hydrograph will rejoin the total hydrograph as quickflow ceases.

Baseflow Recessions

Adapted from: Fetter (2001)

The hydrograph of a stream during an extended period with no excess precipitation will decay, following an exponential curve. After a significant (i.e., multiple week) period without significant precipitation (or snow melt), the stream discharge will be composed entirely of groundwater contributions. As the stream drains water from the groundwater reservoir, the water table falls, leaving less and less groundwater to feed the stream. If there were no replenishment of the groundwater reservoir, baseflow to the stream would become zero after an extended period of time. Figure 27 shows a baseflow recession hydrograph for a stream in a climate with a dry summer season.

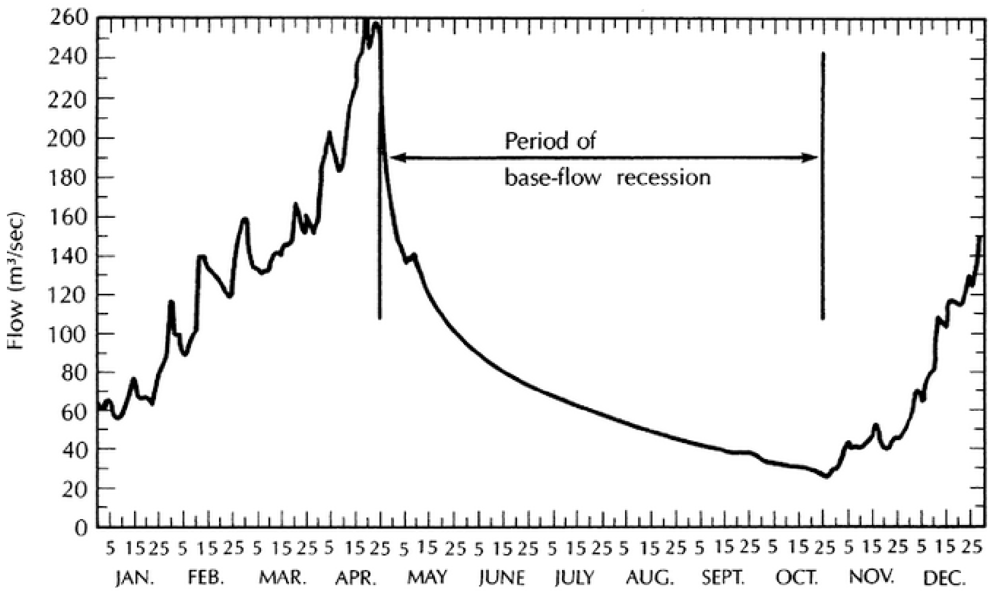

Figure 27: Typical annual hydrograph for a river with a long, dry summer season: Lualaba River, Africa (Wisler & Brater, 1959)

The baseflow recession for a drainage basin is a hydromorphic characteristic. It is a function of the overall topography, drainage pattern, soils, and geology of the watershed. Figure 28 illustrates this by showing the annual summer recession of a river for six consecutive years. In this example, the start of the baseflow recession is considered to be the day when the annual discharge dropped below 3500 ft^3/s. The recession is similar from year to year. The baseflow of the stream decreases during a dry period because as groundwater drains into the stream, the water table falls. A lower water table means that the rate at which groundwater seeps into the stream declines.

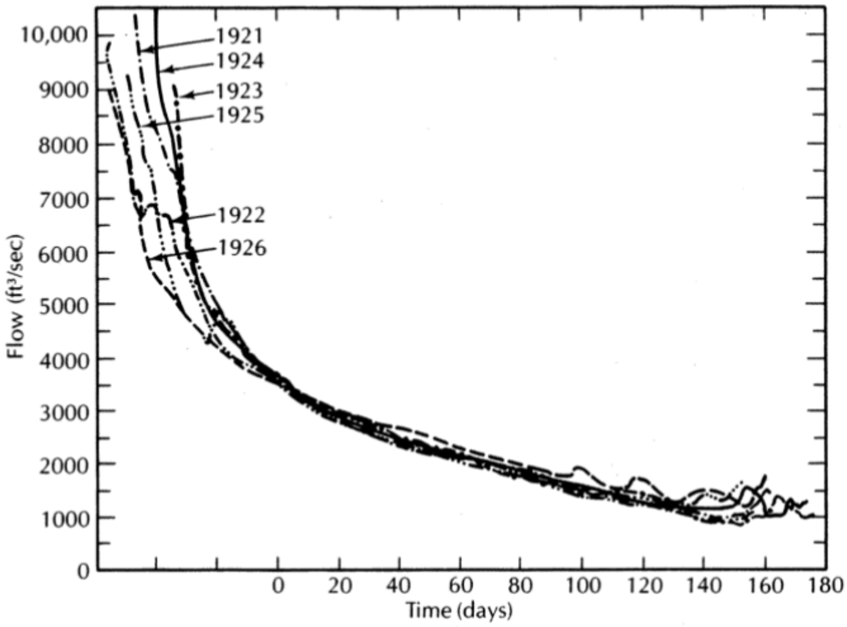

Figure 28: Annual baseflow recessions for six consecutive years for the Lualaba River, Africa (Wisler & Brater, 1959)

Determining Groundwater Recharge from Baseflow

Seasonal Recession Method (Meyboom Method)

Adapted from: Fetter (2001)

The seasonal recession method can be applied if there are discharge data for longer time periods (two or more years). It is also useful for a basin where there is a seasonal recharge event and then a long baseflow recession with little intervening groundwater recharge.

The Meyboom seasonal recession method is a simple method of estimating groundwater recharge in a basin. The underlying assumptions of this method are that the catchment area has no dams or other method of streamflow regulation and that snowmelt contribution to the runoff is negligible. It utilizes stream hydrographs from two or more consecutive years. The baseflow recession relationship indicates that Q varies logarithmically with time, t. A plot of a stream hydrograph with time on an arithmetic scale and discharge on a logarithmic scale will therefore yield a straight line for the baseflow recession. Figure 29 shows a hypothetical stream hydrograph. The baseflow recessions are shown as dashed lines; they were considered to start when the summer stream level dropped below the adjacent water table and to end when the first spring flood occurred.

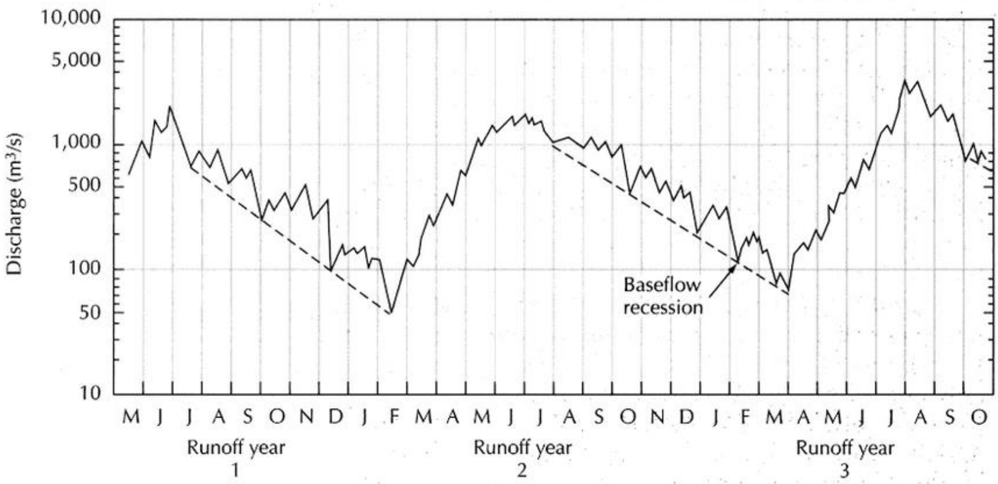

Figure 29: Semi logarithmic stream hydrograph showing the baseflow recessions (Fetter, 2001)

The total potential groundwater discharge is the volume of water that would be discharged during a complete groundwater recession (Meyboom, 1961). Its value can be found from:

$$\mathbf{V_{tp}} = \frac{\mathbf{Q_0\, t_1}}{\mathbf{2.3026}} \qquad 20$$

where:

V_{tp} – Volume of the total potential groundwater discharge (L^3 or m^3)
Q_0 – Baseflow at the start of the recession (L^3/T; ft^3/s or m^3/s)
t_1 – Time that it takes the baseflow to go from Q_0 to 0.1 Q_0 (T; s)

If one determines the remaining potential groundwater discharge at the end of a recession and then the total potential groundwater discharge at the beginning of the next recession, the difference between the two is the groundwater recharge that has taken place between recessions. The amount of potential baseflow, V_i (L^3; ft^3 or m^3), remaining some time, t (T; s), after the start of a baseflow recession is given by:

$$\mathbf{V_t} = \frac{\mathbf{V_{tp}}}{\mathbf{10^{\left(\frac{t}{t_1}\right)}}} \qquad 21$$

This analysis **assumes that there are no consumptive uses of groundwater in the basin**, meaning that all groundwater discharge is by means of baseflow to streams. **If there are such uses** (e.g., pumping, evapotranspiration by plants, springs or seeps), **this use must be added** to the amount determined by the baseflow recession method to obtain total recharge to the groundwater reservoir.

Recession curve displacement method

Adapted from: Fetter (2001)

The recession curve displacement (Rorabaugh) method can be used in situations when a series of groundwater recharge events occur during one runoff season. The recession curve is shifted upward by the recharge event. The amount of groundwater recharge can be determined by the size of the upward shift (Rorabaugh, 1964). This method is applicable to drainage basins where the groundwater recharge is more or less evenly distributed throughout the basin and where all groundwater discharges from the basin via seepage into the stream or springs that feed the stream, and groundwater recharge, can be assumed to be instantaneous.

Figure 30 shows the upward shift of a recession curve after a precipitation event. The first step is to estimate the length of the time following peak discharge over which surface flow continues to contribute to streamflow. A common assumption is that the length of this time interval, D, is constant for all flows and that it can be approximated as (Linsley et al., 1982):

$$\mathbf{D = 0.83\ A^{0.2}} \qquad 22$$

where:

- D is the number of days
- A is the drainage basin area [km^2]

After D days have elapsed, the streamflow can be considered as entirely baseflow, although the volume of discharge in the stream has increased, as has the total potential baseflow, V.

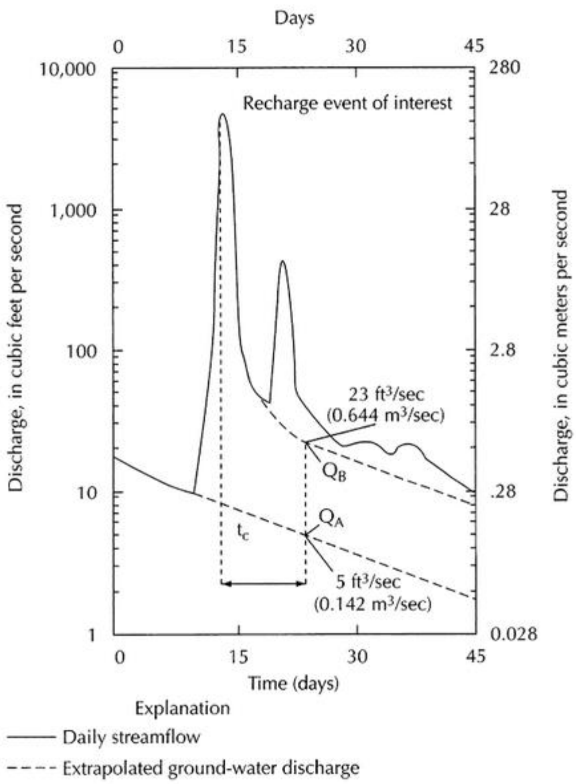

Figure 30: Determining groundwater recharge from baseflow from the incremental recharge method of Rorabaugh (Fetter, 2001; Mau & Winter, 1997)

Rorabaugh (1964) defined a critical time past the hydrograph peak where the total potential groundwater discharge is equal to approximately half of the water that recharged the groundwater system. Therefore, the total recharge for water table rise can be calculated as:

$$\mathbf{R = 2\,(Q^{bf}_2 - Q^{bf}_1)\,K_{RI} / 2.3026} \qquad 23$$

where:

- Q^{bf}_2 and Q^{bf}_1 are groundwater discharge rates at critical time after the peak in surface flow for the post-rise and pre-rise recession curves, respectively [m^3/s].
- K_{RI} is the recession index, which is linked with critical time [unitless].

The estimation of critical time is calculated as:

$$\mathbf{T_c = 0.21 * K_{RI}} \qquad 24$$

where T_c is the critical time and K_{RI} is the recession index, the time required for streamflow to decline through one $\log_{10}$ cycle. This index can be estimated manually (Mau & Winter, 1997).

In summary there are six steps to calculate the recharge using this method (Healy & Scanlon, 2010):

1. Compute the recession index
2. Compute critical time T_c
3. Locate time that is t_c days past the peak
4. Determine Q^{bf}_1 by extrapolation of the pre-rise recession curve
5. Determine Q^{bf}_2 by extrapolation of the post-rise recession curve
6. Apply Eq. 23 to compute recharge.

The recession index and critical time are assumed to be constant for the period of record under analysis. Q^{bf}_1 and Q^{bf}_2 and recharge are calculated for each rise in stream stage.

Rainfall Infiltration Factor Method

If neither groundwater level data nor streamflow data are available, we can estimate the recharge from rainfall by the rainfall infiltration factor method. A common and easy approach for estimating recharge (R) assumes that it is equal to some fraction, a, of annual precipitation (P) (Healy & Scanlon, 2010):

$$\mathbf{R = a * P} \qquad 25$$

Reported ratios of a can vary from about 0.02 to more than 0.5 (Healy & Scanlon, 2010). The relationship between rainfall and groundwater recharge is a complex phenomenon depending on several factors such as runoff coefficient, moisture balance, hydraulic conductivity and storativity / specific yield of the aquifer, vegetation, etc. (Fetter, 2001). Therefore, the use of a rainfall infiltration factor is a simplification based on general assumptions.

The volume of water that seeps to subsurface layers is defined by means of an effective infiltration rate (i.e., “a” from Eq. 25) over the span of several years. The infiltration within a given area can be calculated with the aid of geological or soil maps, with different areas assigned different infiltration classes (Stasko et al., 2012).

Table 7 presents infiltration rates and field water volumes for soils of different protective capacities (Stasko et al., 2012). Note that these values are from a region in Poland and values for infiltration vary from region to region and also depend on the intensity of rainfall, so these factors may not apply in all locations.

Table 7: Example of infiltration rates for soils of different protective capacities (Modified from: Stasko et al., 2012)

Soil category	**Grain Size (according to soil classification)**	**Infiltration rate (%)**
Very light	Sand: fine, silt, loose, slightly clayey,	30 (modified value: 27)
Light	Sand: very fine, light clayey, sandy silt	20
Medium	Loam: light and powdery clay and silt loam	13 (modified value: 20)
Heavy	Loam: medium and silt, heavy loam, clay loam	8

To implement the rainfall infiltration factor method, the average annual rainfall is computed for the study area. The infiltration rate is selected according to soil (or rock) type and the average infiltration rate for the precipitation area is calculated as (Stasko et al., 2012):

$$\boldsymbol{\alpha_r = \frac{\sum_{i=1}^{n} \alpha_{i.} A_i}{\sum_{i=1}^{n} A_i}} \qquad 26$$

where:

- α_r is the average infiltration rate for precipitation area [effective fraction]
- α_i is the infiltration rate for the soil configuration *i* within precipitation area [%]
- A_i is the surface area of the soil configuration *i* within precipitation area [m^2 or km^2]

For larger areas (i.e., with varying precipitation patterns over the area of interest), this area can be subdivided, and Eq. 26 can be used to calculate average infiltration rates over each sub-area.

Other Recharge Components

From Eq. 15, we have five other recharge components:

- Recharge from stream channels
- Recharge from surface water irrigation (lift irrigation)
- Recharge from groundwater irrigation
- Recharge from tanks and ponds
- Recharge from water storage structures

These components are calculated as follows (Adapted from: Ministry of Water Resources, 2017b):

Recharge due to stream channels

$$R_{STR} = WA * SF * Days \quad (27)$$

where:

R_{STR} – Recharge due to stream channels (or canals) [m^3]
WA – Wetted area [m^2] [10]
SF – Seepage factor [m/day][11]
Days – Number of days with water in stream channel (or canal)

Recharge due to surface water irrigation

$$R_{SWI} = AD * RF * Days \quad (28)$$

where:

R_{SWI} – Recharge due to applied surface water irrigation [m^3]
AD – Average discharge [m^3/day]
Days – Number of days water is discharged to the fields
RF – Recharge factor [unitless][12]

Recharge due to applied groundwater irrigation

$$R_{GWI} = GE_{IRR} * RF \quad (29)$$

where:

R_{GWI} – Recharge due to applied groundwater irrigation [m^3]
GD_I – Groundwater extraction for irrigation [m^3]
RF – Recharge factor [unitless]

Recharge due to tanks and ponds:

$$R_{TP} = AWSA * N * RF \quad (30)$$

where:

R_{TP} – Recharge due to tanks and ponds [m^3]
AWSA – Average water spread area [m^2]
N – Number of days water is in the tank or pond
RF – Recharge factor [m/day]

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[10] The wetted area refers to the contact area between the water in the water body and the soil interface.

[11] Seepage is the slow escape of a liquid through porous material or small holes. Seepage generally occurs when the water escapes vertically through the bottom of the pond and horizontal filtration of water through the dykes. More information regarding seepage losses can be found using this link.

[12] The recharge factor is quite dynamic, and depends on numerous factors (e.g., size of the area, amount of water, soil condition, etc.). For examples of estimation approaches, see Islam et al. (2017) and Jafari et.al (2019). Note that there is no universal method to estimate these recharges, as they are specific to the location and site conditions.

Recharge due to water storage structures

$$R_{wss} = WSA * N * RF \quad (31)$$

where:

R_{WSS}	–	Recharge due to water storage structures [m^3]
WSA	–	Water spread area [m^2]
N	–	Number of days
RF	–	Recharge Factor [m/day]

Specific Yield

The specific yield of a rock or soils is defined as the ratio of the volume of water which, after being saturated, will yield by gravity to its own volume (Meinzer, 1923). In simpler words, specific yield is defined as the volume of water released from storage by an aquifer per unit surface area of aquifer per unit decline of the water table.

Specific yield (S_y) can be represented by the formula:

$$S_y = n - S_r \quad (32)$$

where:

- n is porosity (dimensionless)
- S_r is specific retention (the volume of water retained by the rock/soil per unit volume) (dimensionless)

Specific yield is a storage term, independent of time, that accounts for the instantaneous change in water storage upon a change in total head (Healy & Scanlon, 2010). Table 8 summarizes specific yield statistics from 17 studies (Johnson, 1967).

Table 8: Specific Yield of various materials (Johnson, 1967)

Material	Specific Yield (%)		
	Maximum	Minimum	Average
Clay	5	0	2
Sandy clay	12	3	7
Silt	19	3	8
Fine sand	28	10	21
Medium sand	32	15	26
Course sand	35	20	27
Gravelly sand	35	20	25
Fine gravel	35	21	25
Medium gravel	26	13	23
Coarse gravel	26	12	22

Hydraulic Conductivity

Adapted from: Fetter (2001)

Darcy's Law describes the movement of water through porous media. According to Darcy's Law, the discharge Q (volume per time, m^3/s) is proportional to the difference in the height of the water, h (hydraulic head, m), between the ends and inversely proportional to the flow length, L (m). The flow is also proportional to the cross-sectional area of the flow area A (m^2).

$$\mathbf{Q} = -\mathbf{KA}\left(\frac{\mathbf{h_A} - \mathbf{h_g}}{\mathbf{L}}\right) \qquad 33$$

This can be expressed in more general terms as:

$$\mathbf{Q} = -\mathbf{KA}\left(\frac{\mathbf{dh}}{\mathbf{dl}}\right) \qquad 34$$

Where $\frac{dh}{dl}$ is known as the hydraulic gradiant. The quantitiy dh represents the change in head between two points that are very close together, and dl is the small discharge between these points. The negative sign indicates that flow is in the direction of decreasing hydraulic head.

We can rewrite the Eq. 34 as:

$$\mathbf{q} = -\mathbf{K}\,\frac{\mathbf{dh}}{\mathbf{dl}} \qquad 35$$

where q = Q/A. Here, K is the **hydraulic conductivity** (m/s).

Typical values of hydraulic conductivity for different soils are listed in Table 9.

Table 9: Ranges of hydraulic conductivities for unconsolidated sediments (Fetter, 2001)

Material	Hydraulic Conductivity (m/s)
Clay	$10^{-11} – 10^{-8}$
Silt, sandy silts, clayey sands, till	$10^{-8} – 10^{-6}$
Silty sands, fine sands	$10^{-7} – 10^{-5}$
Well-sorted sands, glacial outwash	$10^{-5} – 10^{-3}$
Well-stored gravel	$10^{-4} – 10^{-2}$

Lateral Flow and Inter-aquifer Flow

Lateral flow along the aquifer system (Throughflow)

In Eq. 15, if the area under consideration is a watershed, the lateral flow (LF) across boundaries can be considered as zero, but published estimates should be used if they are available.

If inflow or outflow passes the boundary of the study area, the net lateral flow can be calculated using Darcy's Law (see Eq. 33), through the delineation of the inflow and outflow sections of the boundary (Jain et al., 2007). Such a process requires estimates of transmissivity and hydraulic gradient across the inflow and outflow sections, and computer modeling is recommended for such purposes.

Vertical inter-aquifer flow

The vertical inter-aquifer flow (VF in Eq. 15) can be calculated using Darcy's Law if the hydraulic heads in both aquifers and the hydraulic conductivity and thickness of the aquitard separating both the aquifers are known. Again, groundwater flow modeling is recommended for its calculation. Regional scale modeling may provide useful information to allow appropriate estimates of VF.

Evapotranspiration

Evapotranspiration (ET in Eq. 15) comprises of evaporation and transpiration and can be estimated for the aquifer in the assessment unit if water levels in the aquifer are within the capillary zone.

Note that E from Eq. 2 refers to all evapotranspiration in the watershed while ET from Eq. 15 refers to evapotranspiration from the aquifer.

<u>Evapotranspiration for the aquifer</u>

If the water table is sufficiently deep that vegetation roots do not intersect it, then we can consider that the evapotranspiration is equal to zero. For shallow water tables, direct measurements through field studies or published values should be used.

<u>Evapotranspiration for the watershed</u>

If available, values derived from ground-based measurements should be used. If unavailable, remote sensing techniques (e.g., the Surface Energy Balance Algorithm for Land; SEBAL) or ready-to-use products (e.g., SSEBop, GLEAM, MOD16) can be used to determine evapotranspiration estimates.

Groundwater Extractions

Extractable Groundwater Resources

To adhere to the sustainable yield concept (i.e., fulfilling ecological commitments), the extractable annual groundwater resources cannot be set as high as the total annual groundwater recharge. Therefore, the groundwater baseflow contribution to ecological flow should be identified so that the extractable groundwater resources can be determined (Ministry of Water Resources, 2017b). The minimum ecological flows of rivers should be determined in coordination with the relevant water authorities from the region.

Estimation of Groundwater Extraction

Total groundwater extraction (i.e., draft) is calculated as follows (Ministry of Water Resources, 2017b):

$$\mathbf{GE_{ALL} = GE_{IRR} + GE_{DOM} + GE_{IND}} \quad (36)$$

where:

GE_{ALL} – Groundwater extraction for all uses
GE_{IRR} – Groundwater extraction for irrigation
GE_{DOM} – Groundwater extraction for domestic uses
GE_{IND} – Groundwater extraction for industrial uses

Common methods to determine GE_{IRR} (Ministry of Water Resources, 2017b)[13]:

- Unit Draft Method: Estimation of annual (or monthly) unit draft of each type of well in an assessment unit. The unit draft of is multiplied with the number of wells of that particular type to obtain annual (or monthly) ground water extraction by that particular structure.
- Crop Water Requirement Method: For each crop, the seasonal net irrigation water requirement is determined and then multiplied with the area irrigated by groundwater abstraction structures.
- Power Consumption Method: Groundwater extraction for unit power consumption (electric) is determined. Extraction per unit power consumption is multiplied by the number of power units consumed for agricultural pumps to obtain total groundwater extraction for irrigation.

Common methods to determine GE_{DOM} (Ministry of Water Resources, 2017b):

- Unit Draft Method: The unit draft of each type of well is multiplied by the number of wells used for domestic purposes to obtain the domestic groundwater extraction.
- Consumptive Use Method: Population is multiplied with per capita consumption.

Common methods to determine GE_{IND} (Ministry of Water Resources, 2017b):

- Unit Draft Method: The unit draft of each type of well is multiplied by the number of wells used for industrial purposes to obtain the industrial groundwater extraction.
- Consumptive Use Method: Water consumption of different industrial units is determined. The number of groundwater-dependent industrial units are multiplied by unit water consumption to obtain groundwater extraction for industrial use.

[13] Because this is typically the highest groundwater user in a region, it is recommended that at least two of the three listed methods are employed in each assessment sub unit in order to obtain more robust results.

Rainfall - Runoff Relationships

There are several ways to calculate the amount of runoff that occurs for a particular rainfall event. The rational equation states that if it rains long enough, the peak discharge for the drainage basin will be the average rate of rainfall times the drainage basin area, reduced by a factor to account for infiltration. The time of concentration is the length of time necessary for water to flow from the most distant part of the watershed to the point of discharge. If the period of precipitation exceeds the time of concentration, then the rational equation will apply. The time of concentration is the length of the stream channel divided by the water velocity, plus the estimated time for overland flow to reach the channel (Fetter, 2001).

$$\mathbf{Q = C * I * A} \qquad 37$$

where:

Q – Peak runoff rate (m^3 /s)
C – Runoff coefficient (dimensionless), see Table 10
I – Average rainfall intensity (m/s)
A – Drainage area (m^2)

The runoff coefficient represents the fraction of the rainfall on the watershed that becomes surface runoff, meaning that its value must be between one and zero. Three factors greatly affect its value: i) the soil type; ii) the land use; and iii) the slope (Bengtson, n.d.).

The four main soil groups and their characteristics are (McCuen, 1998):

- Group A: Deep sand; deep loess; aggregated soils
- Group B: Shallow loess; sandy loam
- Group C: Clay loams; shallow sandy loam; soils low in organic content; soils usually high in clay
- Group D: Soils that swell significantly when wet; heavy plastic clays; certain saline soils

Table 10 lists values of C for according to soil group, slope and land use.

Table 10: Runoff factors for the rational equation (Adapted from Bengtson, n.d.)

	Runoff Coefficient, C											
	Soil Group A			**Soil Group B**			**Soil Group C**			**Soil Group D**		
Slope:	**<2%**	**2-6%**	**> 6%**	**<2%**	**2-6%**	**> 6%**	**<2%**	**2-6%**	**> 6%**	**<2%**	**2-6%**	**> 6%**
Forest	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Meadow	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Pasture	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Farmland	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Residential area	0.22 to 0.33	0.26 to 0.37	0.29 to 0.40	0.24 to 0.35	0.28 to 0.39	0.34 to 0.44	0.28 to 0.38	0.32 to 0.42	0.40 to 0.49	0.31 to 0.41	0.35 to 0.45	0.46 to 0.54
Industrial area	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial area	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Street	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Parking area	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97

Precipitation over an Area

Using Rain Gauge Data

Adapted from: Fetter (2001)

When using rain gauge data, the average rainfall over a basin is usually obtained by one of three methods: arithmetic mean, Thiessen polygon or isohyetal. The arithmetic mean is a simple average whereas the other two derive weighted averages.

For the arithmetic mean, the average rainfall is computed as:

$$\mathbf{P = (P_1 + P_2 + P_3 + \ldots + P_n)/\ n} \qquad 38$$

where:

P	–	Average rainfall (mm)
n	–	Number of stations
P_1, P_2, P_3 … P_n	–	Precipitations measured at stations 1, 2, 3 … n (mm)

In the Thiessen Polygon Method, weights are assigned to each rain gauge depending on its relative location. This method involves constructing polygons around each gauge, which are a result of perpendicular bisectors of lines joining two adjacent rain gauges. The polygons form the boundary of the effective area assumed to be controlled by the gauge, or in other words, the area closer to the gauge than to any other gauge. The ratio of the area of each polygon to the total area is the weight. The average or weighted rainfall is the sum of the product of the rainfall and weight of each gauge. Figure 31 illustrates the derivation of Thiessen polygons.

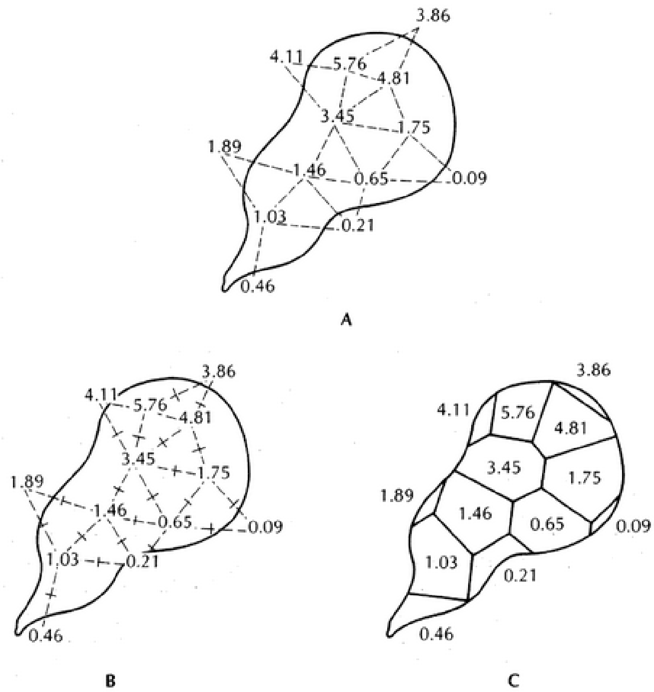

Figure 31: Construction of Thiessen polygons based on a rain gauge network (Fetter, 2001)

In the isohyetal method, isohyets are drawn connecting points of equal rainfall (Figure 32). This method is based on interpolation and can account for factors such as topography (which has a marked influence on precipitation patterns). The weighted average is given by the sum of the products of weights and average contour value of corresponding isohyets.

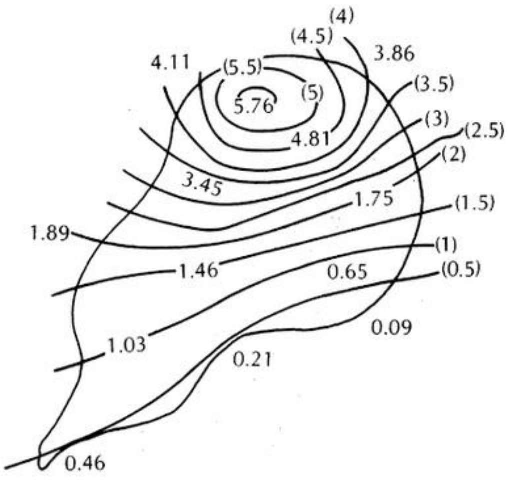

Figure 32: Isohyetal lines for the rain gauge network (Fetter, 2001)

Gridded Precipitation Products

In data-scarce areas, global or semi-global gridded precipitation products, i.e., gauge-based, satellite-related and reanalysis datasets, can be highly valuable to estimate the spatio-temporal patterns of precipitation (Sun et al., 2018). To select the most appropriate dataset for the catchment of interest, refer to literature that compares the performance of different products over the study region or a similar nearby region. Some products that have shown good performance over most global regions include CHIRPS (Funk et al., 2015), ERA-Interim (Dee et al., 2011) and CMORPH (Joyce et al., 2004; Xie et al., 2017).

If rain gauge data are available (and the network is sufficiently dense), we suggest using it. The gridded precipitation products can provide added value as they can be used to spatially interpolate precipitation values or fill data gaps.

Appendix 5: Calculation Methods for Environmental Flow

Adapted from: DFID (2003)

The quantity of water to be allocated to the environment is a decision made by society. This quantity will always be less than in the ideal case, that is, the natural and undisturbed flow regime of a river. The potential costs and benefits of allocating certain amounts of water to different users and the environment are weighed up, and in doing so, society accepts a certain modification of the natural environment. This accepted level may differ from river to river. Table 11 lists some common environmental flow assessment methods.

Table 11: Selected environmental flow assessment methods (Adapted from: DFID, 2003)

Methodology Type	**Examples of Methods**
Hydrological index methodologies	- Tennant method - Texas method - Flow duration curve method - Aquatic baseflow method - Presumptive standards - Range of variability approach
Hydraulic rating methodologies	- Wetted perimeter method
Habitat simulation methodologies	- Building block method
Holistic methodologies	- Instream flow incremental method
Framework approach	- Ecological limits of hydrologic alteration (ELOHA)

A selection of these methods are described below. For more information on all methods, refer to either DFID (2003) or the original literature sources.

Hydrological Index Methods

Hydrological index methods use historical hydrological data, typically long-term historical daily or monthly discharge records, for making environmental flow recommendations.

The Tennant Method

Adapted from: DFID (2003)

In the Tennant Method (Tennant, 1976), the minimum flow requirement for a watercourse is expressed as a percentage of the mean annual naturalised flow at a specified site (accounting for low-flow or high-flow seasons). The states range from poor (10%) to excellent (30% to 50%) to optimal (60% to 100%). These values were determined for Mid-Western USA, and therefore, the transferability of such numbers need to be considered if applying this approaches in other areas.

Flow duration curve analysis

Adapted from: DFID (2003)

This method involves analyzing naturalized or historical flow records to produce curves displaying the percentage of time that a particular discharge is equalled or exceeded. Figure 33 shows an example of using a flow duration curve where the Q_{90} (the flow that is exceeded 90% of the time) is used to determine the minimum environmental flow.

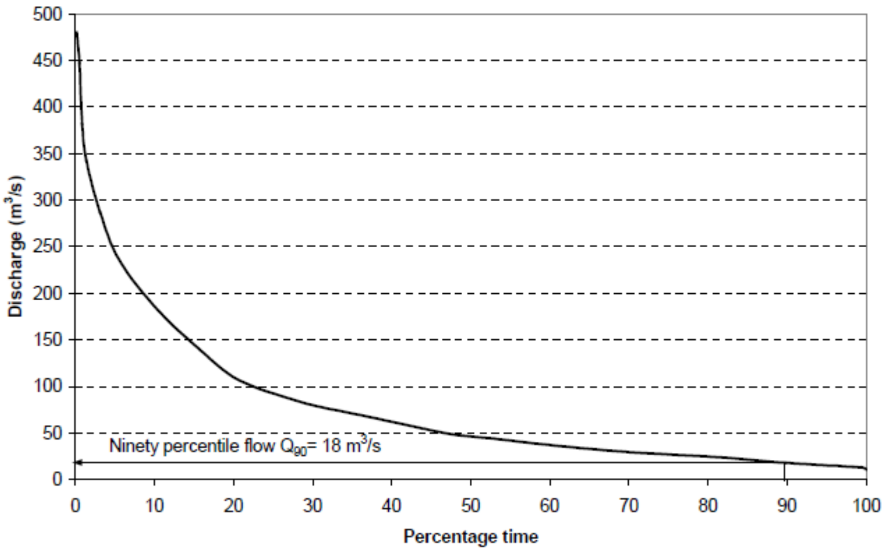

Figure 33: Example of the flow duration curve method (DFID, 2003)

Presumptive Standards

Adapted from: Gleeson & Richter (2018)

Richter et al. (2012) proposed "presumptive standards" that restrict hydrologic alterations to within a percentage-based range around natural or historic flow variability. Figure 34a illustrates this idea, with bands of allowable alteration called "sustainability boundaries" that are placed around the natural flow conditions as a means of expressing environmental flow needs. Gleeson & Richter (2018) expanded on this idea, with the groundwater presumptive standard (Figure 34b). They argued that high levels of ecological protection will be provided as long as groundwater pumping does not decrease the monthly natural baseflow by more than 10%. These standards are proposed as critical placeholders only where detailed scientific assessments of environmental flow needs cannot be undertaken.

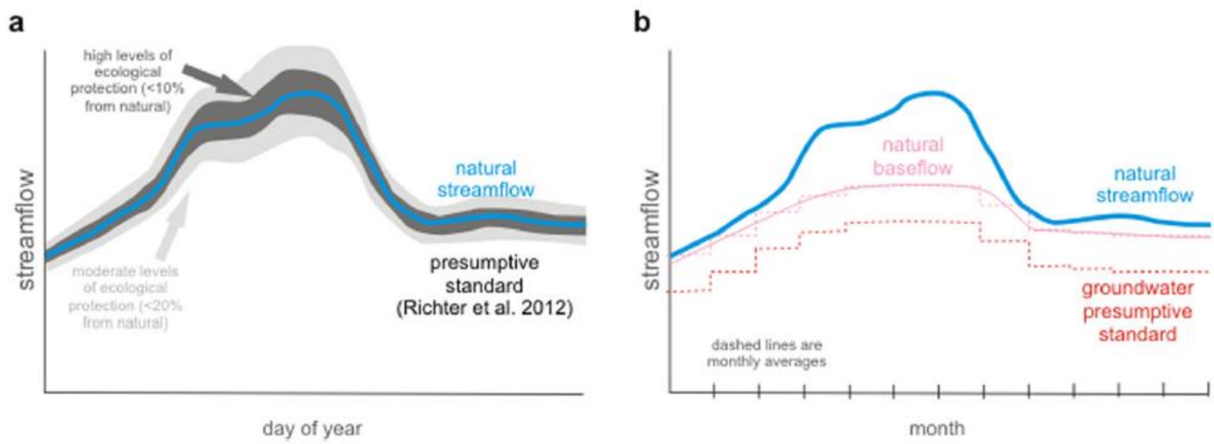

Figure 34: The presumptive standard for protecting streamflow; and (b) the groundwater presumptive standard for protecting baseflow from the impact of groundwater pumping (Gleeson & Richter, 2018)

Range of Variability Approach (RVA)

The Range of Variability Approach (Richter et al., 1997) is the most sophisticated of the hydrological index methodologies. It involves a comprehensive statistical characterization of the ecologically relevant features of the flow regime, while recognizing the importance of hydrological variability. The methodology comprises six basic steps:

1. Characterization of the natural range of streamflow variation using the Indicators of Hydrologic Alteration (IHA) method (Richter et al., 1996)
2. Selection of management targets, one for each of the IHA parameters
3. Designing of a set of management rules or a management system that enables attainment of the targeted flow conditions in most (or all) years
4. Monitoring to assess the ecological effects of the (new) management system
5. At the end of the year, the actual streamflow variation can be assessed using the same hydrological parameters and target values
6. Repeat Steps 2 to 5, incorporating the results of the management interventions from previous years

Framework Approaches

Ecological Limits of Hydrologic Alteration (ELOHA)

The ELOHA framework (Poff et al., 2010) can be used to assess regional relationships between hydrologic alterations and ecological responses. The ELOHA framework is illustrated on Figure 35, comprising of both a scientific and social process. The hydrologic analysis and classification (blue) are developed in parallel with flow alteration–ecological response relationships (green), providing scientific input into a social process (orange). Hence, the information hydrologic and ecologic information is balanced with societal values and goals to set environmental flow standards. This framework has been applied in numerous settings around the world (TNC, 2018), but it can be timeconsuming and expensive to implement as it requires significant data gathering, analysis, and community involvement.

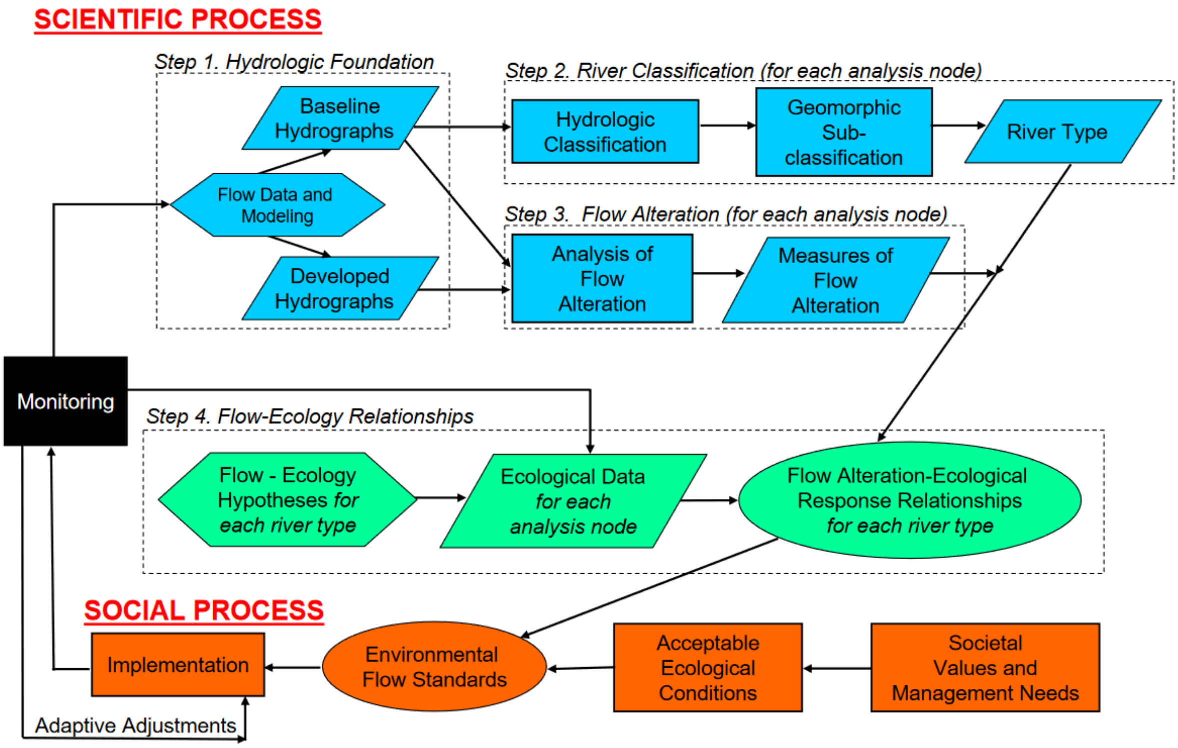

Figure 35: The Ecological Limits of Hydrological Alteration Framework method (Poff et al., 2010)