Hydrological Impacts of Watershed Management

Training Manual

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Contents

Introduction

Despite the millions of dollars in investments and country wide mobilization of communities for watershed management, empirical evidence of the hydrological benefits of these investments is still lacking. Three factors are identified for lack of quantitative evidence of hydrological benefits of watershed interventions in Ethiopia: (i) lack of attention to impact evaluation, (ii) absence of hydro-meteorological monitoring, and (iii) knowledge gaps about tools for hydrological impact evaluation.

Aim: The main aim of this course is to enhance the understanding of local experts regarding the potential hydrological impacts of changes in watershed characteristics and interventions, and data requirement and monitoring for impact evaluation.

Structure: Participants of this course are expected to come from different backgrounds and levels of hydrological knowledge. It is therefore important to introduce key concepts of hydrology to prepare participants for the subsequent modules. Hence, the aim in Module 1 is to introduce the hydrologic cycle, runoff generation mechanisms, and shallow groundwater resources. The hydrology of most small watersheds remains unmonitored in Ethiopia. It is therefore important to investigate novel and affordable approaches for monitoring. In Module 2, the process of setting up citizen science-based hydrological monitoring is presented so that trainees can translate this to their district/woreda. In Module 3, the focus is to describe common changes in watersheds and their impact on hydrology. Finally, methods for quantifying hydrological impacts of watershed management are introduced in Module 4. At the end of the course, the trainees are expected to acknowledge the importance of evaluating hydrological impacts of watershed management, and its data needs.

Training tools: The training includes a series of presentations to introduce the contents of each Module. The presentations will be interactive by providing the opportunity for trainees to participate by interpreting figures, responding to questions, and sharing their experience. Trainees will be encouraged to share experience on watershed management and hydrological impacts in their districts. There are also group discussion sessions on pre-defined topics or exercises.

Target audience: This training manual is prepared for watershed experts at local level (district and zone).

Module 1

Introduction to key concepts

1.1. Water balance

In this section, first, the global hydrological cycle is described. This is followed by a brief discussion onthe definition and characteristics of a watershed. Then,the storage of water on the land surface and subsurface is presented. Next, equations are presented that are used to estimate the water balance of selected watershed domains. Understanding runoff generation mechanisms is essential for evaluating hydrological impacts. Therefore, the key runoff generation mechanisms are briefly discussed here. The shallow groundwater resource is also described since it can beaffected by watershed interventions.

1.1.1. The Hydrological cycle

The hydrological cycle describes the perpetual flux and exchange of water between different global reservoirs: the oceans, atmosphere, land surface, soils, groundwater systems, and the solid Earth (Marshall 2013).Water evaporates from water bodies (lakes, oceans). The evaporated water undergoes condensation at high altitude with colder temperatures in the atmosphere leading to formation of clouds (Figure 1). When the condensed water vapour has enough weight to overcome gravity, precipitation (rainfall and snowfall) will occur over the land surface. Part of the precipitation will satisfy evaporation, transpiration, surface storage and percolation demand. Vegetation plays a significant role in maintaining the hydrologic cycle through transpiration, interception, and retention of moisture. The remaining precipitation will travel to water bodies to sustain the next cycle. Note that the sub-surface water (aquifers) contributes to the hydrologic cycle through losing or gaining water to/from water bodies (e.g. oceans and rivers).

Figure 1 *The hydrological cycle. (Source: Science direct, from hutterstock.com/Image ID:236708653)*

Oceans store 96.3% of the global water reserves with most of the remining water stored as groundwater or ice (Figure 2). Only 0.02% of the global water reserve is stored as surface water. Most of the surface water is either stored in lakes, wetlands, atmosphere, biosphere or as soil water. Only 1.6% of the tiny reserve of surface water is conveyed by rivers. Interesting facts about the global hydrological cycle is summarized in Box 1.

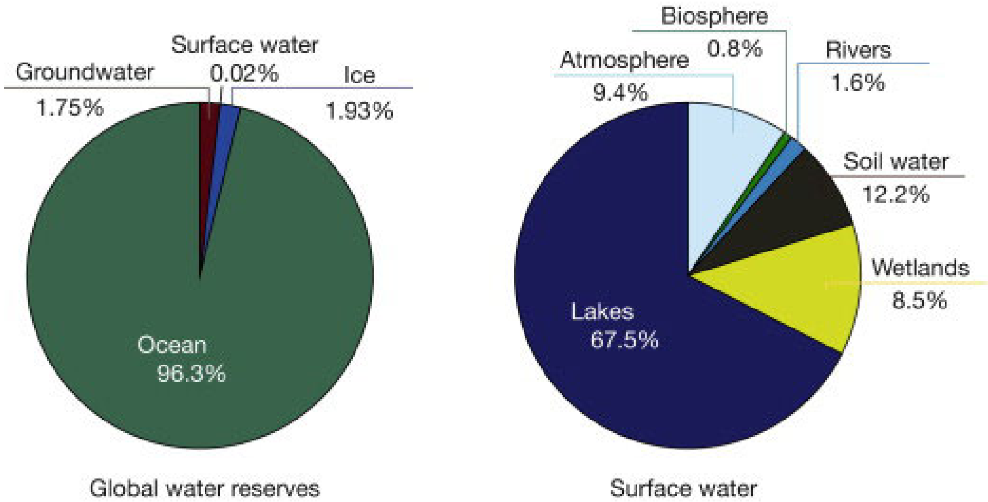


Figure 2 *The global water inventory (Source: Marshal, 2013).*

Box 1. Interesting Facts about the Global Hydrological Cycle

- Around 78% of the global precipitation falls back on the oceans.
- Evaporation would have led to a drop in sea level by 1.2 m yr−1 if rivers did not return water to the ocean.
- The United Nations Environmental Program (UNEP) estimates the global, accessible freshwater supply to be about 200 000 km3. This equates to about 29 million liters of water for each person on the planet.
- The hydrologic cycle affects the economy, environment, and society.
- “Life, it appears, is simultaneously a product of the hydrological cycle and its cause”.

Trees and forests play important roles in the hydrologic cycle, by e.g. altering the release of water into the atmosphere, influencing soil moisture, and improving soil infiltration and groundwater recharge (Figure 3). Forest-related changes in land usesuch as deforestation, reforestation andafforestation can affect both nearby anddistant water supplies:for example, a decrease in evapotranspirationfollowing deforestation in one areamay reduce rainfall in downwind areas(Ellison et al., 2017). Climate change andan increase in extreme weather events aredisturbing water cycles and threateningthe stability of water flows (IPCC, 2019).Meanwhile, water supplies are affected byan increase in human water consumption tomeet domestic, agricultural, and industrialneeds (Rockström et al., 2009). Increasingdemand for water is reducing freshwaterflows and groundwater levels, often withnegative effects on biodiversity, ecosystems,and ecosystem services (Power, 2010).Water, forests, and climate, therefore, areintrinsically interlinked at multiple levelsin what has been termed the forest–waternexus. Forests and water are linked through their multiple functions, such as the regulation of basin flows, the reduction of floods and droughts, and the impacts of forests on water yield and quality (Gustafsson et al., 2019).

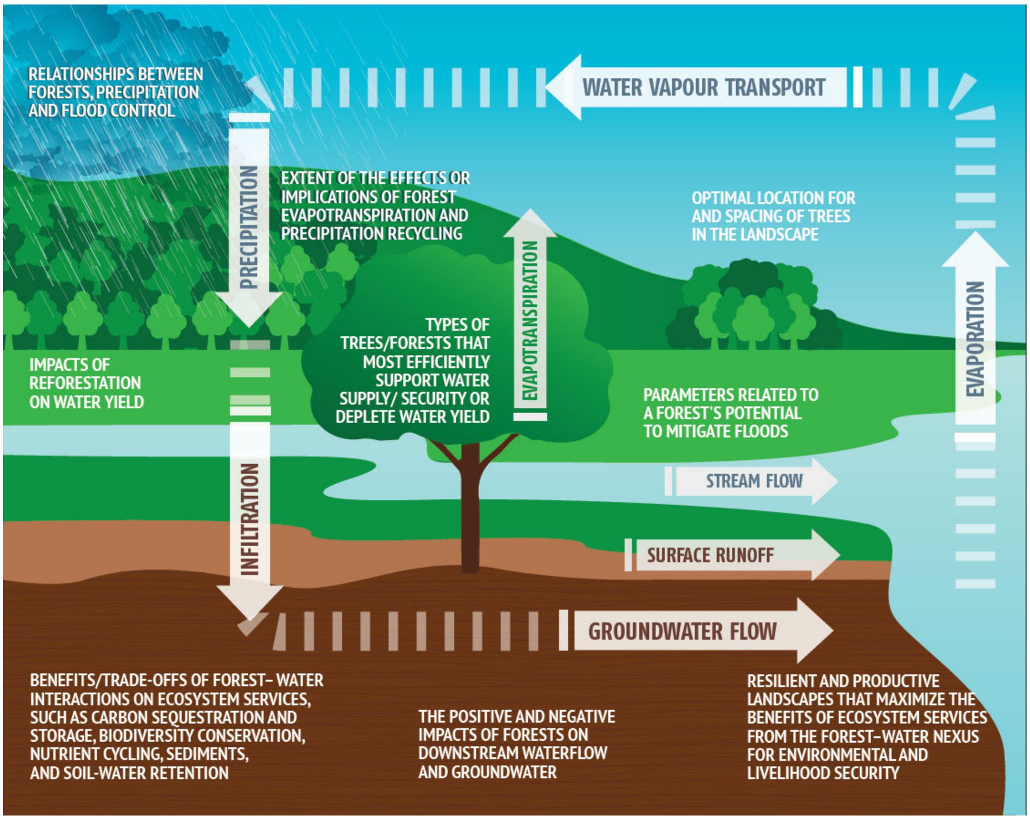


Figure 3 *The Forest water nexus (from Gustafsson et al., 2019).*

1.1.2. Watershed

A watershed is defined as **any surface area** from which runoff resulting from rainfall is collected and drained through a common confluence point (MoARD, 2006).Figure 4 shows a simple schematization of a watershed.

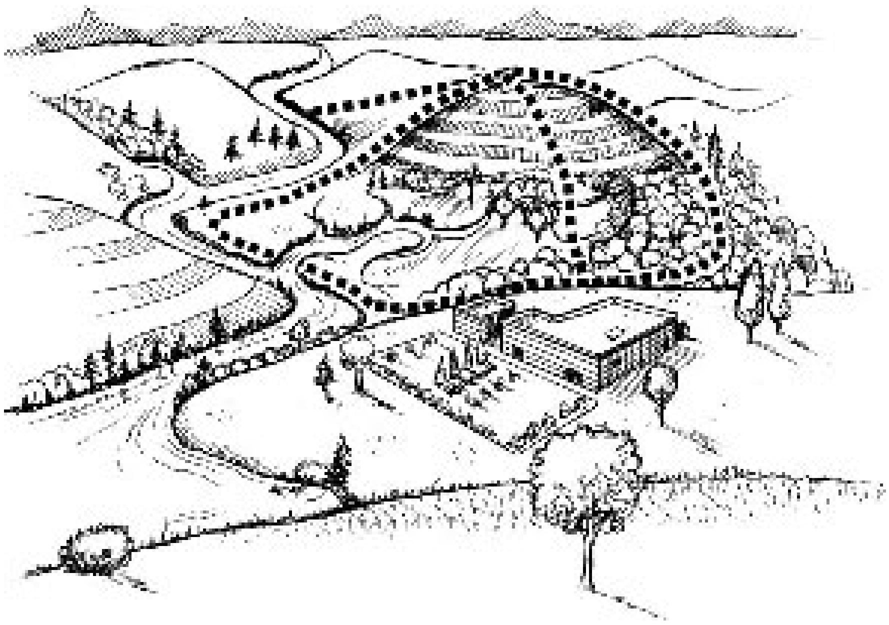


Figure 4 *Schematic illustration of watersheds with the broken line representing watershed boundary.*
Source:http://www.ctic.purdue.edu/Know%20Your%20Watershed/What%20is%20a%20Watershed?/

A watershed is an “area of land that drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel” (Dunne and Leopold, 1978). This definition indicates that the watershed drains not only water but also sediment and dissolved materials.

The definition provided in FAO Conservation Guide 16 is as follows: “A watershed is a topographically delineated area that is drained by a stream system, i.e., the total land area that drains to some point on a stream or a river. The watershed is a hydrologic unit that has been described and used as a physical-biological unit and a socio-economic-political unit for planning and management of natural resources”. This definition indicates that a watershed is “topographically delineated” which means its boundary is defined by ridges, and encompasses both social, economic, and political dimensions.

The biophysical & social elements of watersheds include:

- Climate, soil, geology
- A stream system
- Infiltration, runoff, stream flow, groundwater
- Water quality
- Plant and animal communities
- Land use
- Social and economic systems
- Valued features and activities.

The difference between basin, catchment, and watershed is often not very clear in the literature. However, Table 1 provides some indicative drainage area (size)that helps to distinguish the use of the terms.

Table 1 *Typical terms used for various sizes of drainage area.*

Drainage area (km2)	Unit
50,000 – 5,000,000	Water resources region
5,000 – 50,000	River basin
500 – 5,000	River sub-basin
50 - 500	Watershed/catchment
5 - 50	Sub-watershed
2.5 - 5	Mini watershed
< 2.5	Micro watershed

Note that size matters in watershed management since it involves community participation.

Watershed size can also be inferred from drainage order (Figure 5), which is used to classify (order) the hierarchy of natural channels within a watershed. No other stream flows intothe first order streams whereas first order streams flow into second order streams.

Watershed interventions are commonly effective when applied in watersheds with low drainage order. There are several methods for drainage ordering. However, the most widely used method is Strahler stream ordering system (Box 2).

Box 2. Drainage Ordering in a Watersehd

- Strahler's stream ordering system is a well-known classification based on stream/tributary relationships. The uppermost channels in a drainage network (i.e. headwater channels with no upstream tributaries) are designated as first-order streams down to their first confluence. A second-order stream is formed below the confluence of two first-order channels. Third-order streams are created when two second-order channels join, and so on. Note in the Figure 5 that the intersection of a channel with another channel of lower order does not raise the order of the stream below the intersection (e.g. a fourth-order stream intersecting with a second-order stream is still a fourth-order stream below the intersection)." Source: EPA: Watershed Academy Web.

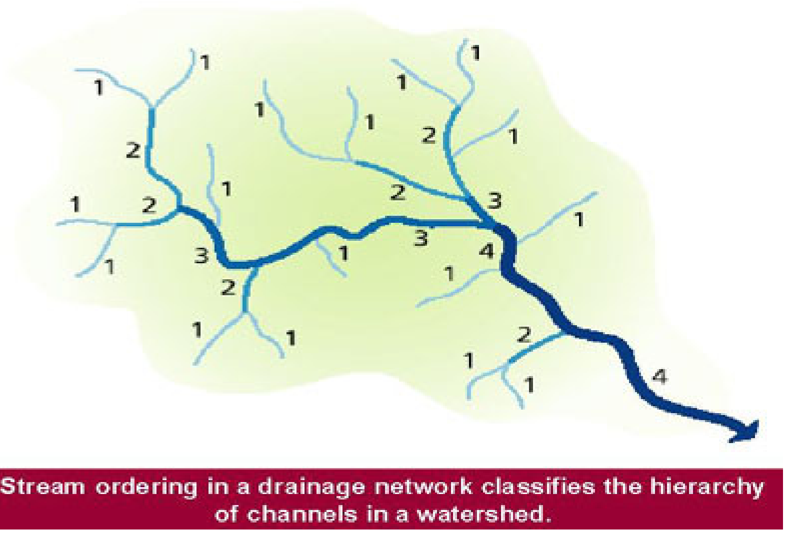


Figure 5 *Illustration of Strahler's stream ordering system. Source:https://cfpub.epa.gov/watertrain/moduleFrame.cfm?parent_object_id=657&object_id=661#661*

Morphometric characteristics or patterns refer to the form and structure of drainage basins and their associated drainage networks. These characteristics can be estimated from various drainage parameters of a watershed. These characteristics can be extracted from readily available data sources (e.g. Digital Elevation Model - DEM, Figure 6). These characteristics can be used to study the nature of the stream network which reveals the hydrological behavior of the watershed.Morphometric characteristics of multiple watersheds can be estimated to prioritize watersheds forthe implementation of soil and water conservation (SWC) measures.

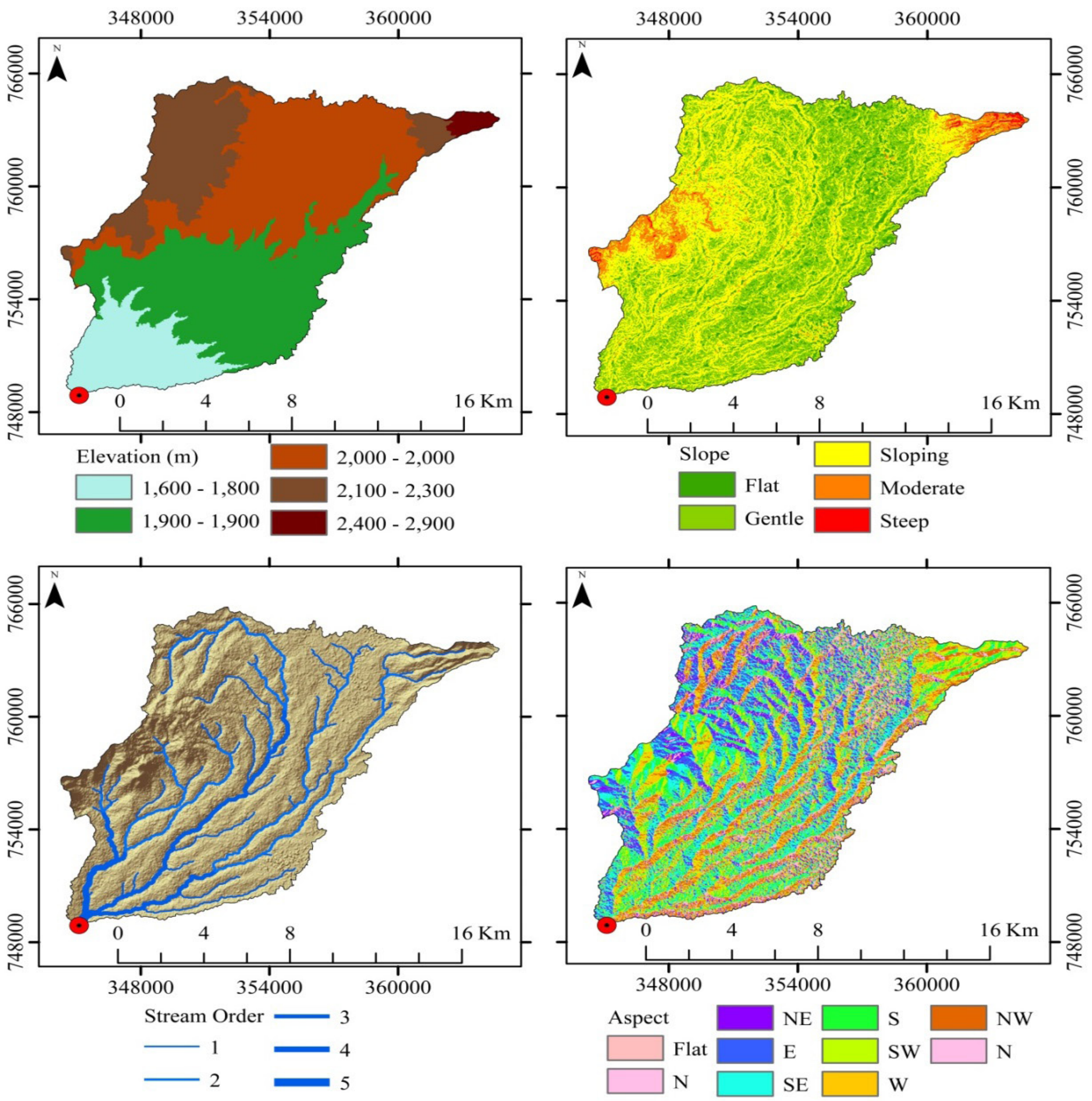


Figure 6 *Maps showing a) elevation, b) slope, c) stream order and d) aspect of Menissa Watershed in southern Ethiopia (Source: IWMI unpublished report).*

1.1.3. Watershed storage

In a watershed, water can be stored over the land surface, soil matrix and aquifer (Figure 7). Overland surface depressions and vegetation canopies store water for a few minutes to several days. In the soil matrix, water can be stored for weeks depending on soil type. Both confined and unconfined aquifers store water for several years. Water is also stored underground in rock cracks or pores.

The factors that affect catchment storage during storms are catchment resistance to flow (slopes, land use, surface roughness, travel distance), and sub-surface and rainfall characteristics. The factors that affect catchment storage at the onset of a rainless period are history of the catchment, amount of storage relative to the total capacity, and magnitude of recent precipitation.

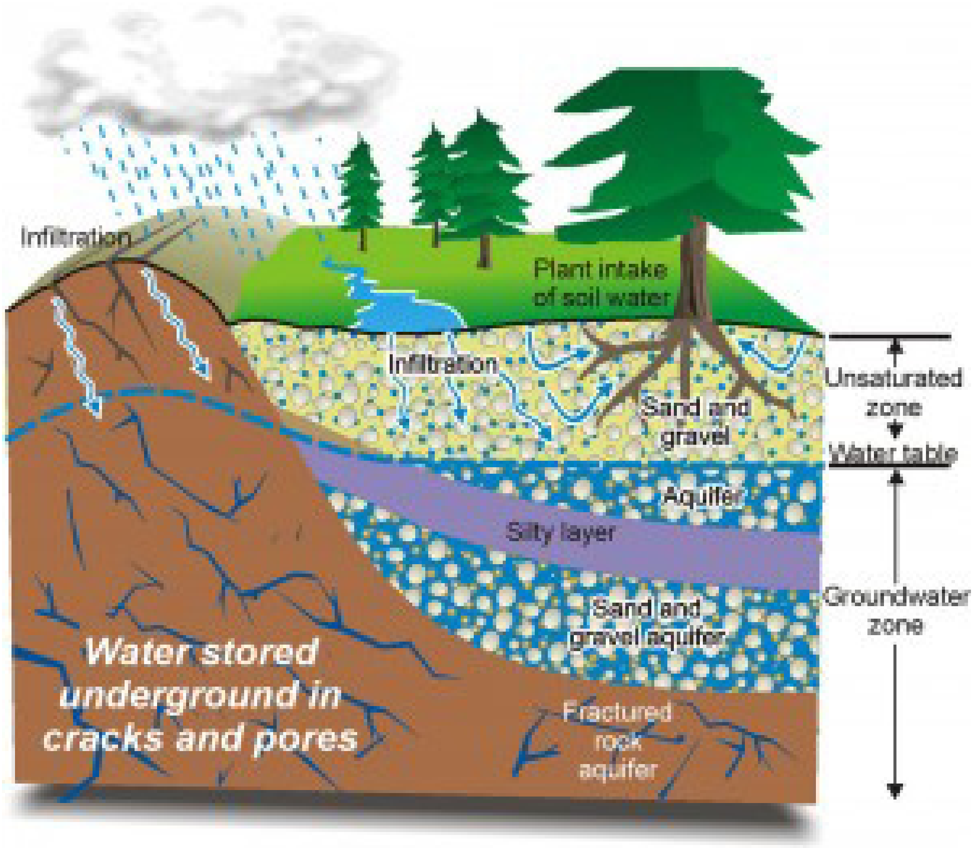


Figure 7 *Water storage over land surface, soil matrix and aquifers.Source: https://ozarksliving.com*

Storage in soils is determined by the porosity of soils. Porosity can be defined as the gap between solid particles. It excludes fluid pockets that are totally enclosed within solid material. In simple terms, porosity can be defined as the percent of volume that is void space (Figure 8). In sediment, porosity is determined by how tightly packed and how clean (silt and clay) it is. Usually porosity is between 20 and 40%. In crystalline and volcanic bedrock, porosity is determined by size and number of fractures (most oftenporosity is very low, <5%).

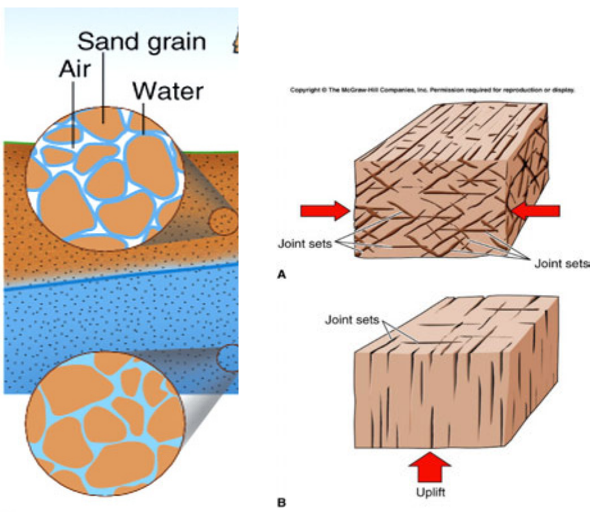


Figure 8 *pore spaces in different soils and crystalline and volcanic bedrock.*

Permeability is the ease with which water will flow through a porous material. In soils, permeability is affected by texture. Gravel can be rated as excellent while clay is rated poor in terms of ease with which water flows through them. Permeability of sand and silt is good and moderate, respectively. Permeability of crystalline and volcanic bedrock is proportional to fracture size and number. It can be poor to excellent.

1.1.3. Water balance equations

For planning and management, we are often interested in the water budget at local scales: watersheds, basins, or country. Hence water budgets are commonly computed for agricultural fields, watersheds, lakes or reservoirs, river basins, or administrative units (e.g. woreda). For water resources planning purposes, the interest is often estimation of water balance on seasonal, annual, or decadal time scales. However, operational purposes (crop growth, river flows, flood events) require estimation of the water budget at short time scales ranging from hourly to monthly. Data required for accurate estimation of water budgets is summarized in Box 3.

Box 3. Data for Estimating Water Budgeting

- Water budgeting requires accurate estimation of water inputs, outputs and storage. Inputs are often in the form of precipitation and water entering from adjacent areas (e.g. rivers, groundwater, springs). Outputs occur in the form of evaporation, transpiration, surface water flow, groundwater flows leaving the region or domain of interest. Water abstraction by humans is also considered an output.
- Storage represents the water stored over the land surface, soil matrix, or aquifer. Water can also be stored either for short periods (e.g. forest canopy or depressions on the land surface) to extended periods of several years (large lakes, reservoirs and groundwater aquifer).

The equation for a water budget within a specific space and time domain can be written as follows:

$$\Delta S = I - O \qquad (1)$$

Where: S refers to the total volume of water stored per unit time, I represents the inflow in terms of volume of water per unit time, and O represents the outflow in terms of volume of water per unit time, and indicates change per unit time.

Forthe land surface, the storage takes place by including interception and depression storage;the main inflow is rainfall (P) whereas the outflows are evaporation (E), surface runoff (S), and Infiltration (I). Hence, the water budget for the land surface can be written as follows:

$$\Delta S = P - E - S - I \qquad (2)$$

Note that ΔS refers to change in storage over the land surface.

Similarly, the water budget in soil is computed by differentiating between its inputs and outputs. The inputs to the soil matrix include Infiltration (I) and Capillary rise (C) whereas the outputs are

Interflow (R), Evaporation (E), Transpiration (T) and Percolation (Pe).

The equation for the water budget of the soil matrix reads:

$$\Delta S = I + C - E - T - R - Pe \quad (3)$$

Note that in the above equation refers to change in moisture storage in the soil. Lateral inflows are ignored for the soil but should be considered if significant lateral sub-surface inflow is expected (Figure 9).

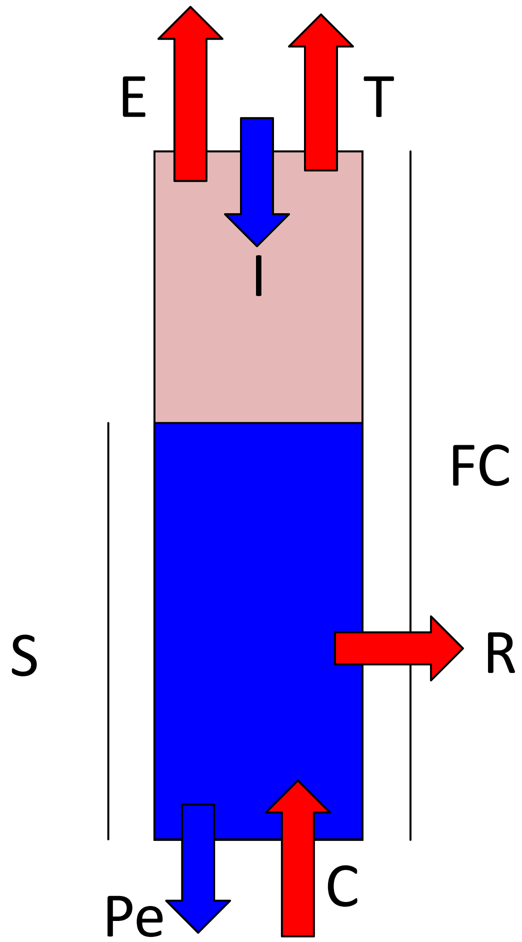


Figure 9 *Schematic illustration of the water budget in soils.*

For the groundwater system (aquifer) with impermeable bottom layer, the main input is Recharge (Re) and Groundwater inflow (GWi), and outflows areCapillary rise (C) and Groundwater outflow (GWo): The equation reads as follows:

$$\Delta S = Re + GWi - C - GWo \quad (4)$$

Note that in the above equation refers to change in storage in the groundwater system. Transpiration (I) from the groundwater system can sometimes occur when tree roots are deep enough to reach the groundwater table.Water is stored in different parts (also called "reservoirs") of a watershed. These reservoirs include the land surface, soil and groundwater. The water balance components for the different "reservoirs" of a watershed are shown in Figure 10.

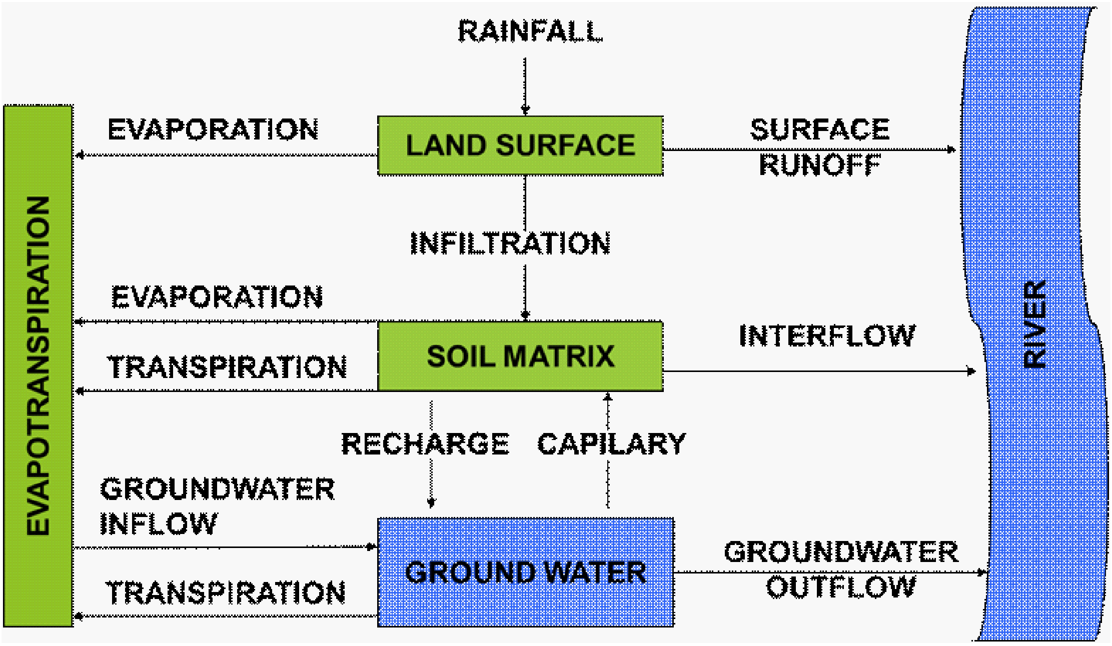


Figure 10 *Illustration of water budget components for land surface, soil matrix and groundwater system.Note: recharge is defined here as percolation minus sub-surface lateral flow.*

In the long term (e.g. decades), the water balance of a watershed (Figure 11) can be written as follows:

$$\Delta S = P - ET - Q \quad (5)$$

where: *Q* refers to discharge, *ET* represents the combined evaporation and transpiration in a watershed and *P* is as defined before. Here, ΔS represents the change in watershed storage.

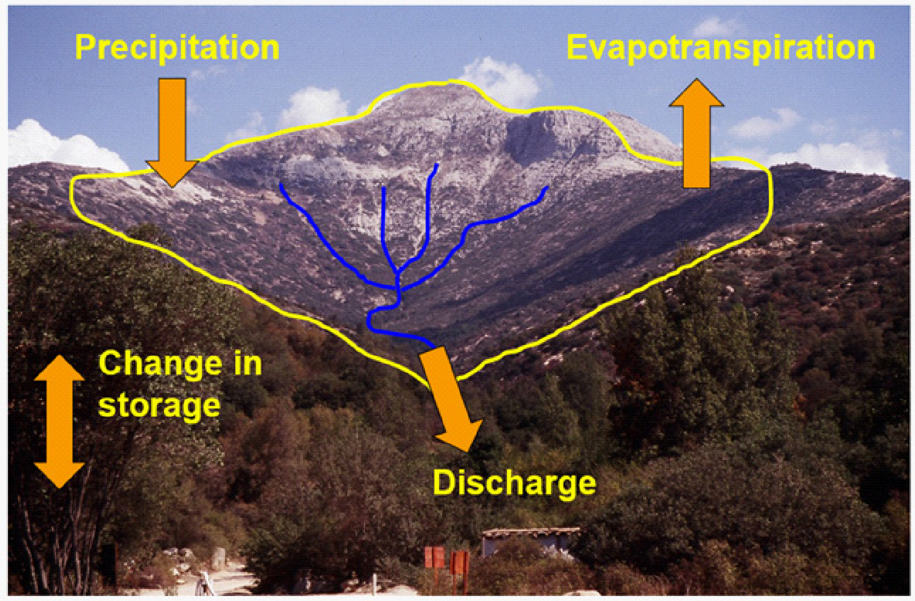


Figure 11 Illustration of water balance in watersheds. Source Presentation by David Walker

1.2. Runoff generation mechanism

The aim of many watershed interventions is to reduce runoff and soil erosion. To understand the hydrological benefits of these interventions, it is important to clearly understand mechanisms by which runoff is generated in a watershed. Accordingly, this session introduces runoff generation mechanisms to participants of the training. We first address the question "what happens to the rain during rainfall events?" Next, dominant runoff generation mechanisms in watershedsare discussed followed by factors affecting runoff generations.

1.2.1. What happens during a rainfall event?

During a rainfall event, most of the rain falls directly on the ground as throughfall (this can reach upto 70% of the total rainfall amount).Part of the rain is intercepted by the vegetation canopy. Only a tiny fraction of the intercepted rainfall will reach the ground surface since most of the intercepted water is evaporated back to the atmosphere.A small part of the rainfall amount runs down the branches, trunks and stems as stemflow (Figure 12). About 10% or more of the incident rainfall may reach the ground as stemflow. Since the stemflow results in local concentrations of water, it has a much higher intensity than the incident rainfall. Some plants, such as maize, have a structure designed to channel water to their roots in this way.In many places, particularly on vegetated surfaces, rainfall rarely exceeds the infiltration rate of the soil unless the soil becomes completely saturated.

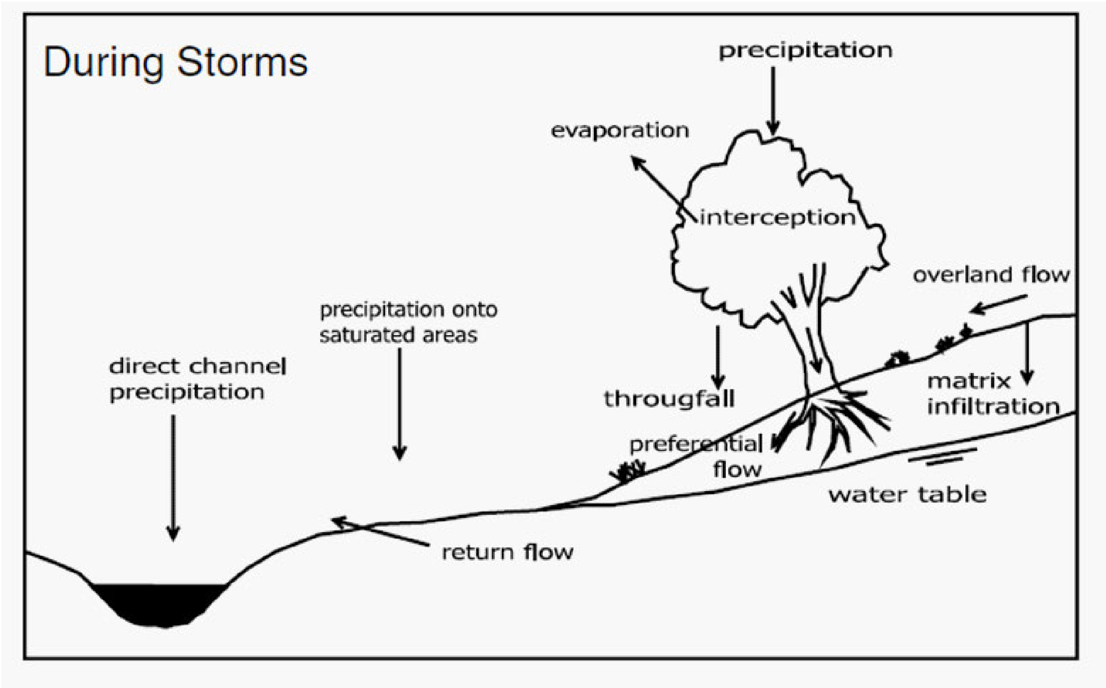


Figure 12 *Processes in a perceptual model of hillslope hydrology (Beven, 1991).*

1.2.2. Runoff generation mechanisms

Infiltration excess overland flow (Hortonian overland flow):assumes runoff is generated by an infiltration excess mechanism all over the hillslope. It occurs when water enters a soil system faster than the soil can absorb or move it. Bare soil areas will be particularly favourable to such infiltration excess runoff generation, since the energy of the raindrops can rearrange the soil particles at the surface and form a surface crust, effectively sealing the larger pores.

The y-axis of Figure 13 represents the rainfall amount and infiltration capacity of the soil whereas the x-axis represents time elapsed since start of the rainfall event. Infiltration capacity represents a maximum limiting rate at which a soil in each condition can absorb surface water input.Infiltration capacity of the soil declines as time elapses since rainfall initiation as the soil moisture increases. After sufficiently long enough time has elapsed, the infiltration rate reaches a constant rate, which is named as "basic rate of infiltration".

As shown in Figure 13, the rainfall rate was initially smaller than the infiltration capacity for the first two-time steps. As a result, all the rain infiltrated without generating runoff. In the third time step, the rainfall rate exceeded the infiltration capacity. Hence, part of the rainfall will satisfy the infiltration demand and the excess rainfall will generate runoff.There is commonly some water ponding in depressions of the land surface before runoff is generated.

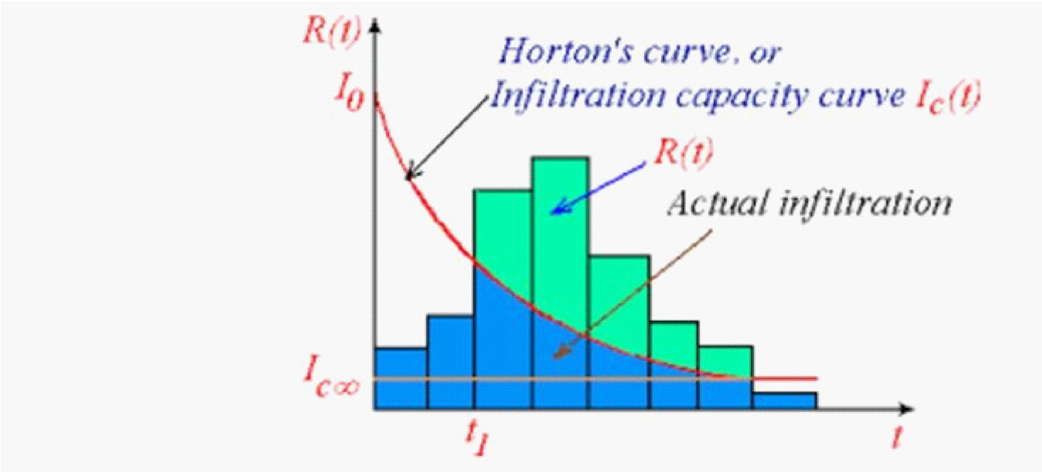


Figure 13 *Infiltration capacity curve and hyetograph of rainfall event demonstrating the infiltration excess runoff generation mechanism.*

Partial area infiltration excess overland flow:It is known that "the area contributing to infiltration excessrunoff may only be a small portion of the watershed", which led to the concept of partial area infiltration excess overland flow. The variation in overland flowvelocities and the heterogeneities of soil characteristics and infiltration rates are important in controlling partial area responses. Runoff can be generated in one part of the hillslope by infiltration excess mechanisms. When the generated runoff flows downslope, it will infiltrate as it encounters higher infiltration capacity of soil further downslope. If the high intensity rainfall producing the overland flow is of short duration, then it is also possible that the water will infiltrate before it reaches the channel.

Saturation excess overland flow (Dune flow):This can occur either as 'direct precipitation on saturated areas' or as 'return flow'. Saturated soil tends to occur first where the antecedent soil moisture deficit is smallest. This occurs for instance where there is convergence of flow typically invalley bottom areas; thin soils where storage capacity is limited; and low permeability and low slope areas. Return flow occurs when subsurface flow returns to the surface.Examples of catchment characteristics (Figure 14) that control runoff generation mechanisms are summarized in Box 4.

Box 4. Catchment Charactrstics Controlling Runoff Generation Mechanisms

- Watersheds in arid to sub-humid climates are often characterized by sparse vegetation. Rainfall in these areas has high intensity which often exceeds the infiltration capacity of soils. Hence, infiltration excess runoff (Horton overland flow) dominates the hydrograph of arid to sub-humid watersheds.
- Watersheds in humid climates often have dense vegetation which resist overland flow but encourage infiltration. Hence, Horton overland flow is not dominant in these watersheds. When the topography is steep with permeable soils in narrow valley bottoms, subsurface stormflow dominates the hydrograph; otherwise, direct precipitation and return flow dominates the hydrographs of watersheds in humid climates.

It is important to note that infiltration excess, saturation excess or purely subsurface responses might all occur in the same catchment at different times or different places due to different antecedent conditions, soil characteristics or rainfall intensities.

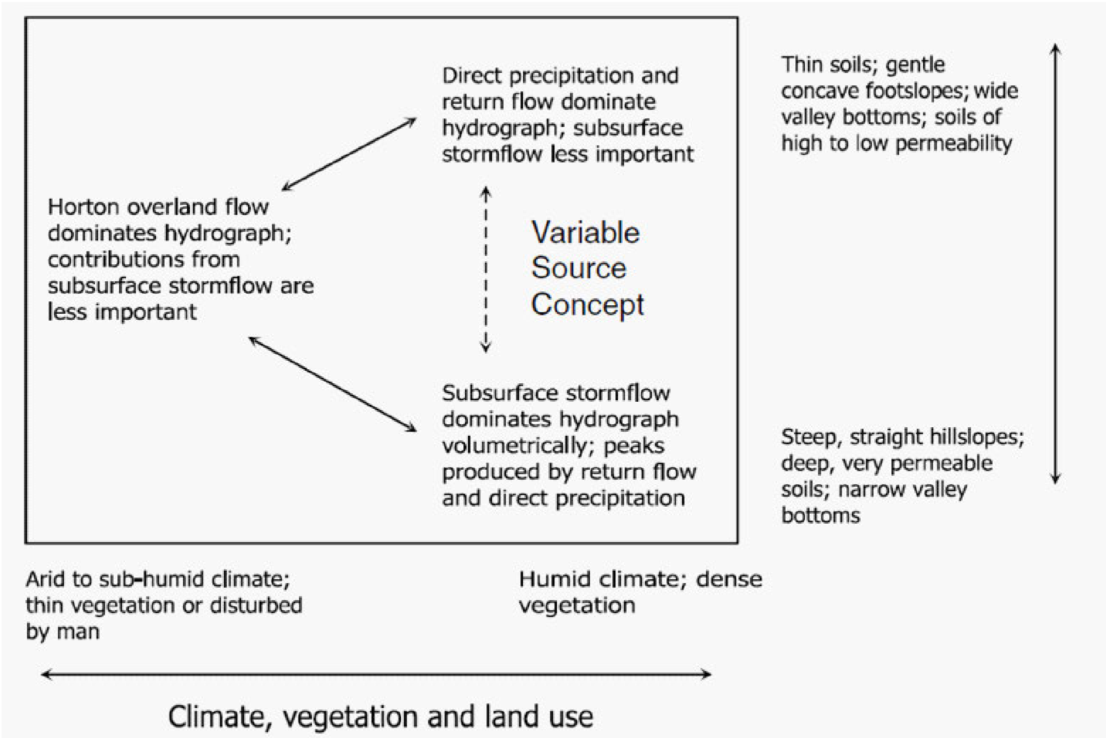


Figure 14 *Control of climate, vegetation, land use, soil, and topography on the dominant runoff generation mechanism in a watershed (Dunne, 1978).*

A significant amount of the measured streamflow can be an old water or pre-event water. Hence, we can divide the streamflow arriving at a watershed outlet into new and old based on the time it takes for the water to reach the watershed outlet. This is shown in Figure 15 which is commonly called hydrograph or discharge vs. time plot. The old water mostly comes from the groundwater which responds slowly. The new water is mostly generated from the land surface which immediately responds to the most recent rainfall event. The hydrograph can also be further partitioned to saturation excess, macro pore, perched sub surface and delayed groundwater with the chronological order of arriving at the watershed outlet. For additional partitioning of the hydrograph, please refer to Figure 15.

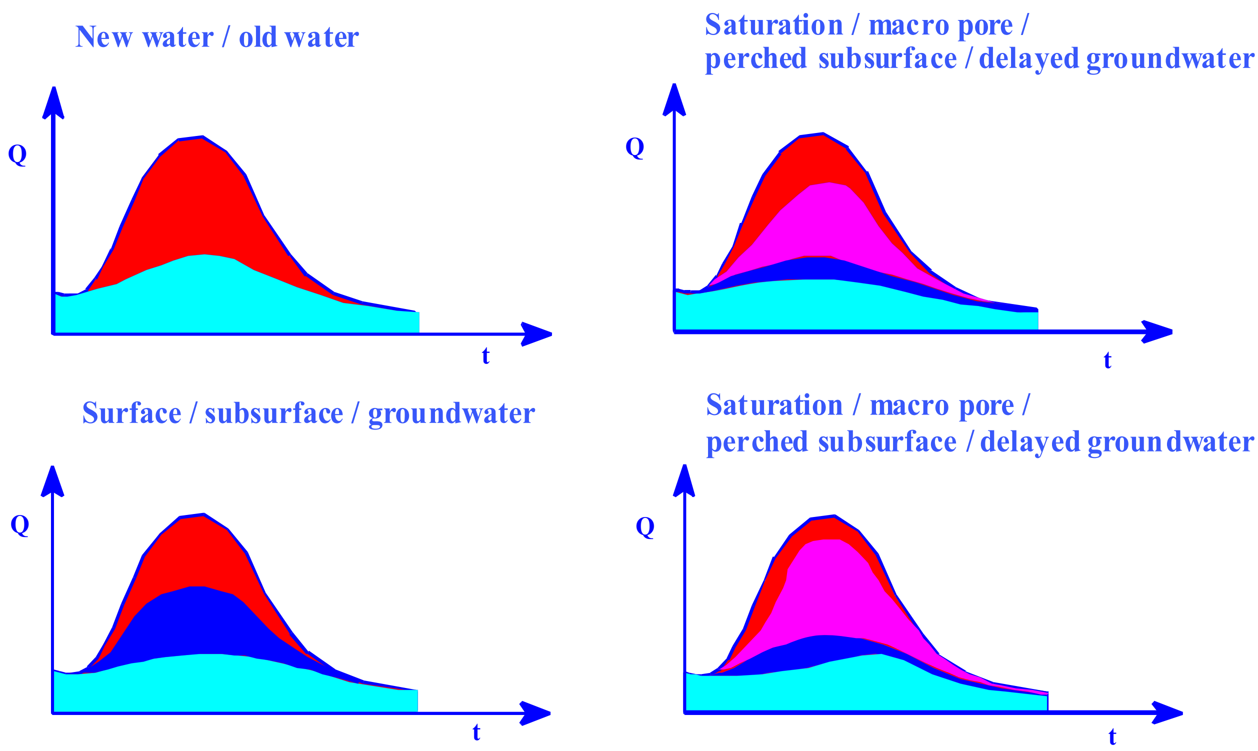


Figure 15 *Partitioning the hydrograph into components based on source of water (Source: Tom Rientjes, personal communication).*

Group Exercise One

Note: Before closing this session, please fill in Table 2 based your current understanding of the two runoff generation mechanisms. The following questions can provide hints to fill in the table.

- Which of the two runoff generations are more affected by rainfall intensity?
- When does infiltration capacity or sub-surface transmissibility become more important?
- How does soil moisture control runoff initiation?
- Which watershed characteristics result in the specified overland flow types?
- Which runoff generation results in flashy hydrograph?

Table 2 *Principal differences between overland flow types (To be filled by participants).*

Characteristic	Horton overland flow	Saturation excess overland flow
Rainfall		
Infiltration		
Overland flow initiate		
Watershed characteristics		
Hydrograph shape		

1.3. Shallow groundwater

Here, shallow groundwater (SGW) is first defined, and confined and unconfined aquifers are thereafter distinguished. This will be followed by presentation of factors which affect shallow groundwater availability, and why SGW are often preferred by farmers and factors affecting the SGW resources. The sub-section also covers the differences between the various recharge types which are commonly reported in the literature (minimum, actual, and potential).Finally, some experiences of SGW in different parts of Ethiopia is shared to enable the course participants to identify issues pertinent to SGW availability and use in their woreda.

1.3.1. Definition

Hydrological processes also occur beneath the land surface though these processes are invisible to us. If we dig a well deep enough, we may encounter an aquifer, which is defined as a water-bearing materialthat readily transmits water.

> *"A geologic unit that is highly permeable and can store and transmit a significant amount of groundwater is called an aquifer." In Ge and Gorelick (2015)*

Aquifers may have hundreds and thousands of square kilometres of lateral extent and tens to hundreds of meters thickness.As shown in Figure 16, an aquifer can be confined or unconfined. There is an unsaturated zone above the water table of unconfined aquifers. The unsaturated zone still contains water to be extracted by plants but also contains air and hence is not saturated. Trees facilitate infiltration to increase water stored in the unsaturated zone. They also facilitate loss of water from the unsaturated zone through transpiration.

There are impermeable materials below and above a confinedaquifer. These impermeable materials do not allow vertical movement or percolation of water. If a well is drilled into a confined aquifer, the internal pressure in the aquifer can lift the water above the top impermeable layer and even to the ground surface in some cases.

Aquifers release water to streams within days or years of receiving new water depending on distance and depth from the stream bed. Aquifers can also gain water from streams. Water exchange between confined aquifers and streams can take centuries and even longer.

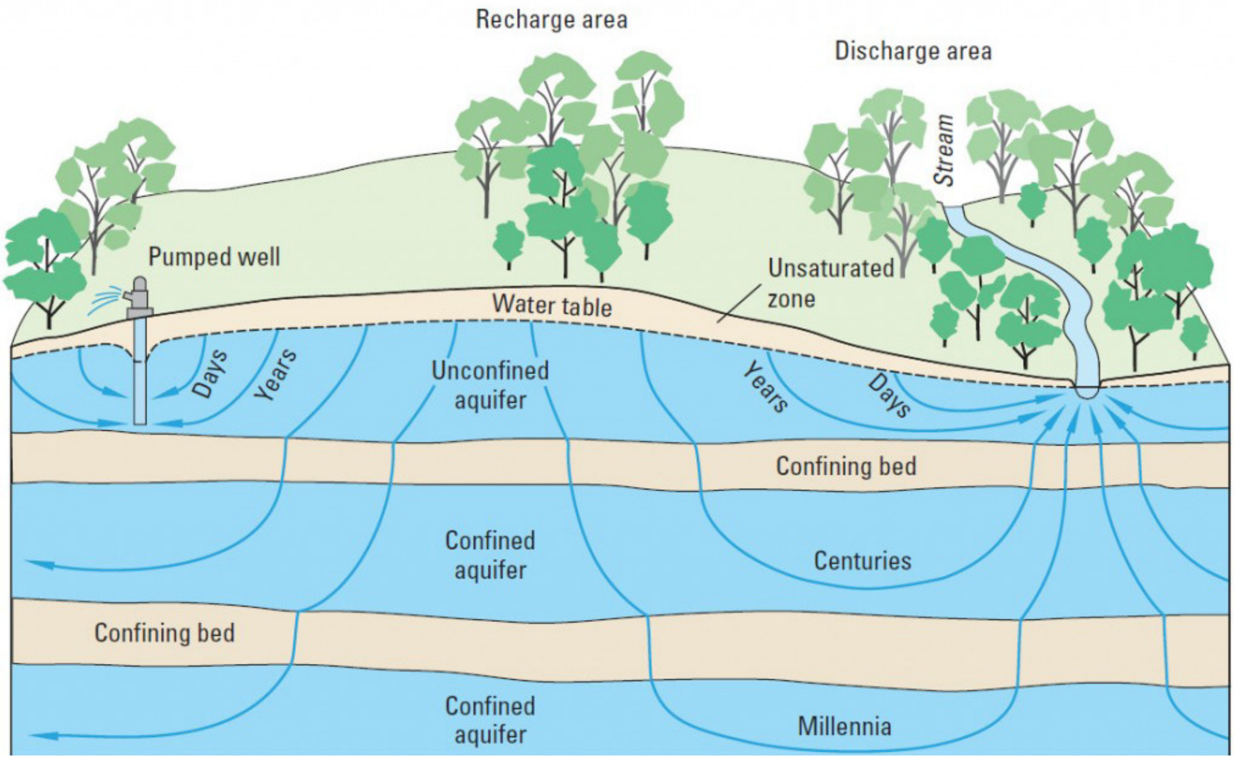


Figure 16 *Unconfined and confined aquifers and possible water flow pathways.*

Shallow groundwater (SGW) refers to any aquifer within a depth of 50 to 60m. This definition can work when machineryis used to drill wells as is often the case for domestic water supply by government and non-government organizations. However, the applicability of the above definition for backyard irrigation by farmers is questionable. Farmers in Ethiopia cannot easily access water deeper than 20 m due to technological and power (fuel) related constraints to dig wells and lift water from wells.Therefore, a working definition of SGWfor irrigation in the rural Ethiopia context can be any aquifer with less than 20m depth below the ground level.Some regions in Ethiopia have adopted their own definitions for SGW (e.g. Table 3).

The amount and quality of water that can be extracted from a SGW aquifer determines its usability for various purposes. In Ethiopia we can extract 1 to 5 l/s from volcanic and consolidated sedimentary aquifers, but the amount is less than 0.5 l/s for crystalline basement rocks.

__Table 3__ Classification of groundwater wells as defined and used by the Amhara Regional State Bureau of Water Resource Development as of 2014.

	Depth below ground surface (m)	Current Use	Remark
Hand dug wells	< 25	Irrigation and Domestic water supply	Well digging is by human labour
Shallow wells	25-75	Domestic water supply	Well drilling is by complicated and expensive drill rig under the supervision of the Water Bureau
Deep wells	>75	Domestic water supply	Well drilling is by heavy machinery under the supervision of the Water Bureau who hires contractors for drilling

***Questions**: Is the definition in Table 3 applicable for your district?*

1.3.2. Why is SGW preferred by farmers?

SGW is a "highly decentralized resource" as groundwater wells are often owned by individuals. Farmers prefer shallow groundwater since it offers an individual mode of access to users and can be readily available on demand. As a result of the individual mode of access, farmers are involved in less conflict with other users of the resource. SGW also offersflexibility in timing and amount of water application. To utilize groundwater for irrigation, farmers do not necessarily need to have farmland close to a river.

Compared to surface water sources, groundwater is less sensitive to effects of climate variability and change. It is known to be a reliable source of water in both dry and wet seasons. As a result, SGW irrigation helps to cope with current vulnerabilities of rain-fed agriculture and enhance adaptive capacity of smallholder farmers.

1.3.3. Factors affecting SGW availability

SGW availability can vary for several reasons including:

- **Rainfall**: The water table will rise to the surface during the rainy season and it falls during the dry season.
- **Topographic factors**: We expect higher abundance of SGW in valleys than onhillsides, but exceptions occur (e.g. Esheto watershed in Zigity near Arba Minch). Gentle slope areas provide the opportunity for rainwater to infiltrate and be stored in aquifers.
- **Surface geology** (upto 30 m depth below the ground surface): Rocks are very good indicators of groundwater. Types and orientations of joints and/ or other fractures can also serve as indicators. The aquifer must have good porosity (small spaces between grains) and permeability (connections between pores),see Figures 17 and 18.

- **Water bodies**: Presence of springs, swamps, or lakes indicate presence of shallow groundwater.
- **Presence of "water-loving" plants** (phreatophytes) such as salt cedar and cottonwood trees indicate presence of SGW.
- **Geomorphology**: low drainage density facilitates recharge and hence indicate presence of SGW.

Questions

- Do you know any indigenous knowledge in use to identify shallow groundwater resource in your district?

- What are the impacts of poor management and planning of shallow groundwater resource?

Recharge is an important variable that determines SGW resources and how much of such a resource can be sustainably utilized. There are several recharge estimation methods in the literature. The methods may provide estimates of actual, potential, or minimum recharge (Table 4). Experiences of SGW for selected sites is presented in Boxes 5 to 7.

***Table 4** Recharge types as adopted from Walker et al. (2020).*

Terminology	Description	Estimation
Actual recharge	The downward flow of water reaching the water table, forming an addition to the groundwater reservoir	Physically based modelling
Potential Recharge	Water passing downward through the unsaturated zone that could potentially contribute to the aquifer	Computed from unsaturated zone methods as this infiltrated water may be subject to losses (e.g., root zone uptake, interflow then surface discharge) before contributing to the aquifer
Minimum recharge	Groundwater discharge to rivers or springs	Other losses (e.g., evaporation from the saturated zone, seepage to deeper aquifers) may have occurred since the water was recharged

Box 5. Shallow groundwater in Branti watershed of Dangila woreda, Ethiopia

- Figure 17 shows the conceptualization of the SGW aquifer of Branti watershed, Ethiopia. The water table is found at a deeper depth from the ground surface at upper catchment areas. The slope of the water table follows along the topographic slope downhill. Wetlands and springs are common in valleys since the groundwater table intersects with the land surface.
- Households in Dangila have a rich experience of using hand dug wells particularly for domestic water supply with some using it for irrigation. Digging of wells commonly takes place during the driest months to avoid false alarms which commonly occur when construction takes place during the wet season. Women and sometimes children are involved in manual digging. The total depth of the dug wells is about one meter below the water level of the driest months to allow a buffer for water level fluctuation. Typical top covers for SGW well in Branti Are shown in Figure 19.
- In 2014, the total number of hand dug wells in Dangila rural kebeles was 2281 which suggests one well per 11 households on average. Not all households have equal access to the shallow groundwater resource due to its fragmented availability. Some villages have a massive rock near the ground surface which resulted in minimal or no access to groundwater. As a consequence of this and many other factors, the number of existing hand dug wells show a considerable spatial variation from 18 to 198 wells per kebele with an average of 84 wells.

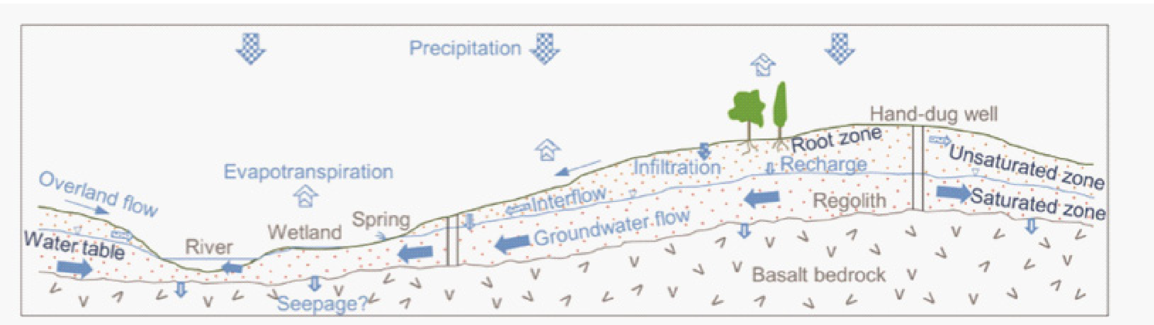


***Figure 17** Conceptual model of Branti watershed, Dengeshta kebele of Dangial woreda.*
(Source: Newcastle University & International Water Management Institute, IWMI).

Group Exercise Two

- Interpret the conceptualization of groundwater systems around Hawassa (Figure 18)
- Share the actual and potential shallow groundwater use in your district.

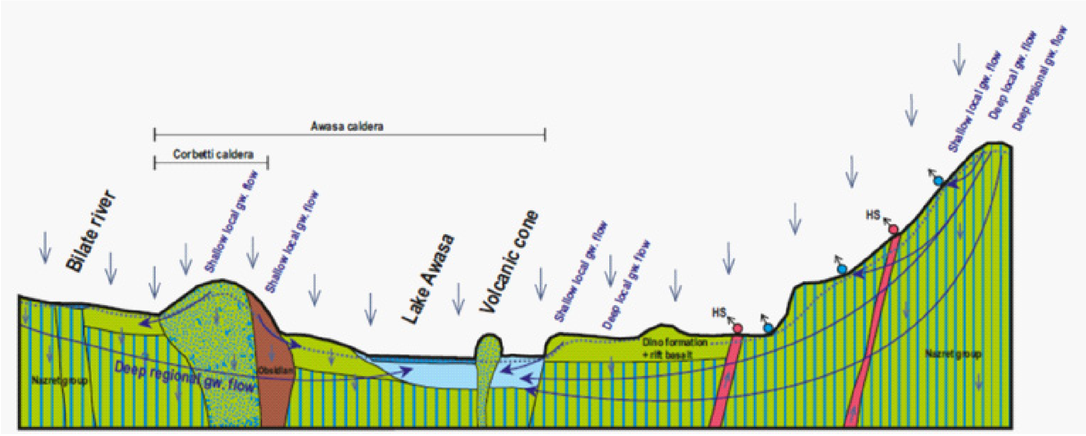


Figure 18 *Conceptual model of the groundwater system around Lake Hawassa (Source: presentation by Jiri Sima).*

Figure 19 *Top cover of hand-dug wells in Dengeshta kebele. The wells have been used for backyard irrigation and domestic water use. Photo credit: Alemseged Tamiru Haile.*

Box 6. Shallow groundwater in Wuatame watershed in Bolosso Bombe woreda, Ethiopia. Source: Haile et al. (2019).

- Many houses are built on landscapes in Wutame watershed which have low SGW potential. Some residents encountered massive rocks after digging to about 5m depth while those who did not encounter rocks gave up after digging to more than 10–15m depth without striking the water table.
- Many of the existing wells were not dug during the driest month and as such their water level drops below the well bottom several weeks before the next rainy season. Such an inappropriate digging time has sent the wrong message to residents, and they have started to doubt the reliability of wells during periods of critical water shortage. The owners use these wells only for a few months but mostly rely on public fountains, rivers, or springs.

Box 7. Shallow groundwater in Zigity woreda, Ethiopia. Source: Ferede (2018)

- Groundwater is the major water source for irrigation practices in Zigity in addition to river diversions. Many farmers use SGW for backyard crop production. Based on informal discussions with smallholders, the maximum and minimum well depth in this area is 10m and 2m, respectively. The average groundwater table varies between 1m and 9m throughout the year. During the rainy season, the groundwater level rises and reaches the ground surface causing saturated overland flow.
- The potential of groundwater for irrigation in Zigity Woreda is about 0.25 ha per household. However, the actual minimum command area in Zigity varies between 0.001 ha and 0.145ha. Hence, land is the constraint to expanding SGW irrigation.
- Farmers in this area dig their groundwater wells manually and traditionally measure the depth of wells using their arm (considered to be equivalent to 0.5m). The aquifer system of the area is mainly characterized by two classes. The first (top) aquifer system is comprised of high yielding quaternary deposits having a thickness of 40 to 90m. The second aquifer system is comprised of fractured, and highly weathered trap basalt of the Rift Valley escarpment. Some farmers use rope and washer-water lifting technology for water lifting in Zigity but most of these technologies are not working properly.

Module 2

Hydrological data collection and interpretation

2. Community participation in hydrological data collection

In this section, the key terms in community-based (citizen science) monitoring are defined first. This will be followed by the process of setting-up citizen science programs. Although the process can vary from site to site, the general issues to be considered in community engagement remain the same. The steps and precautions to be taken while training citizen scientistsare also shared in this section. Finally, trainees will have an opportunity to learn from examples of citizen science applications in selected watersheds in Ethiopia. This sub-section will help participants to understand that they can set up a citizen science program in their watersheds to fill hydrological data gaps.

2.1.1. Definitions

Definition of key terms relevant to this module are provided below (Walker et al., 2019a,b).

Participatory approaches: "Involve participants collaboratively in the study or research with an aim to create change in the study community".

Community-based participatory research (CBPR): "Stakeholder participation to the fullest extent, i.e., involving stakeholders in initial conception of the study, study design, implementation, data analysis, and evaluation of the program, and dissemination". It involves mutual learning between researchers and the community.

Citizen science**:** "Citizen science refers to the participation of the general public (i.e. non-scientists) in the generation of new scientific knowledge"

Citizen scientist**:** "a member of the general public who engages in scientific work, often in collaboration with or under the direction of professional scientists and scientific institutions; an amateur scientist".

Crowdsourcing: "a form of citizen science, where data is provided by "the crowd". Anyone can participate!" For instance, citizen scientists can send river water level data via text message to a server.

Para-hydrologist: "an expert with local knowledge, being largely trained on the job in hydrological monitoring and processes."

In many instances, definitions in literature are less clear to distinguish citizen science from community-based approach.

Figure 20 shows classification of citizen science based on engagement of the public. Most of the time, the target can be to achieve "Extreme citizen Science" by engaging the public at all levels of collaborative science. However, it may be good to start simple when investigatingthe scope for citizen science in new sites.

Figure 20 *Classification of citizen science*

Source: http://ec.europa.eu/environment/integration/research/newsalert/multimedia/infographics/CS_Infog_02.pdf

2.1.2. The process of setting up community-based monitoring

Setting-up community-based monitoring (citizen science project) requires properly outlining and following a series of steps. The steps that were followed by IWMI and Newcastle university (Figure 21) are presented below:

Define purpose: The purpose of the citizen science program can be linked to the national development agenda or specific projects, for instance, the Sustainable Land Management Program (SLMP) in Ethiopia.

Expert consultation: this step helps to obtain feedback from local experts aboutthe scope of applying citizen science in the local context. At this level, it is important to learn from similar participatory projects, explore synergies with existing projects (e.g. SLMP), and to identify appropriate incentives in the local context. The expert consultation can be organized at the beginning, middle and end of the project.

Consultation of local leaders: In many parts of the developing world, it is expected to talk to local leaders before engaging the public. The project objectives should be clearly described to the local leaders. Any questions or concerns which are raised by the leaders require satisfactory responses. The main purpose here can be to be granted access to the community, facilitate community engagement, and prioritize watersheds in the district. It is also important to identify the para-hydrologist during the consultation with local leaders. The local leaders can assign an expert to facilitate community consultation.

Community consultation: It is always preferred to start the consultation meeting with a discussion on the community perception of the hydrologic cycle. Typical questions for the consultations can also include (1) What are the rainy seasons in the watershed? (2) Where does the groundwater in the wells come from? and (3) What is the perception of the water resource in the watershed, its use, barriers for use and actions for the future? The objective of the citizen science project needs to be described in the local language and, where possible, the measuring equipment should be demonstrated. This can be followed by explaining the criteria for selection of citizen scientists and monitoring sites. Community members can (i) share lists of monitoring sites that meet agreed criteria, and (ii) volunteer to engage as citizen scientists.

Installation: The candidate monitoring sites can be visited and checked against technical criteria for monitoring to complete the site selection. Installation of the monitoring instruments can be done in a participatory manner by engaging citizen scientists and other community members.

Training: Citizen scientists will receive practical training on data collection, recording and proper use of the data recording book. The para-hydrologist can receive a separate training on how to supervise citizen scientists and check data quality.

Data management: Data management is often underestimated but can be complicated particularly when multiple citizen scientists are involved. It may require a dedicated person to apply standard data quality assessment on a continuous basis and provide timely feedback to the para-hydrologists.

Figure 21 *Process followed to introduce citizen science in Dangila woreda, Ethiopia.*

2.1.3. Training citizen scientists and use of citizen science data

It is mandatory to provide proper training to citizen scientists since the quality and extent of the training highly determine the data quality. The training can be conducted during installation of instruments, continuously for the first few days of measurement with a close follow up by the para-hydrologist, and then on an annual basis as refresher training.

The contents of the training depend on the type of hydrological variables to be measured. Here we discuss river water level as an example, but the discussion also applies to monitoring of other variables such rainfall, groundwater level, spring flow, etc. In the case of river water level, the observers should be trained to read the markers accurately and consistently on the staff board (Figure 22). Reading these markers (usually at one-centimeter intervals) may seem simple initially. However, experience shows that citizen scientists can be confused with the centimeter markers. As a result, the data reading can be a source of error. Regular training and supervision of the observers can help to minimize the error in the long term.

***Figure 22** River staff gauges at Branti River in Dangila woreda, Ethiopia*. (Photo credit: Alemseged Tamiru Haile).

A data recording book is prepared prior to the installation campaign. It is recommended that commonly used formats should be followed in preparing these books. The header of each recording sheet of the book often includes names of observer, district, river, and station. Geographic coordinates of the station are also displayed in the header of each data recording sheet. Hence, training the citizen scientists includes explaining the content of the header.

The first column of the data recording sheet is commonly reserved for writing the date. The second column can be reserved for the days (Monday, Tuesday, etc.) so that citizen scientists will use the weekdays to remember the dates. If the data collection interval is twice per day, then the morning and afternoon water level data can be recorded in the third and fourth columns. It is important to explain the importance of tidy handwriting for the citizen scientists. Also, experience shows that inspecting the handwriting of citizen scientists and providing feedback to improve ambiguous writing of numbers helps to improve data recording. The last column is for writing remarks including overflow riverbanks, damage to instruments, and reason for missing recording if any. The remark column is very important but often overlooked. Hence, citizen scientists should receive proper instruction on how and when to write remarks. The data recording book is presented in Figure 34.

Refresher training always benefits the data collection program since it motivates citizen scientists. The refresher training provides an opportunity to discuss common mistakes and how to minimize these mistakes, exchange experience among citizen scientists, and plan. It is good practice to plot the recorded data to present it back to the citizen scientists. For instance, joint plot of streamflow hydrographs and rainfall hyetographs can be used to discuss rainfall-runoff relationships in the watershed (See Figure 23).

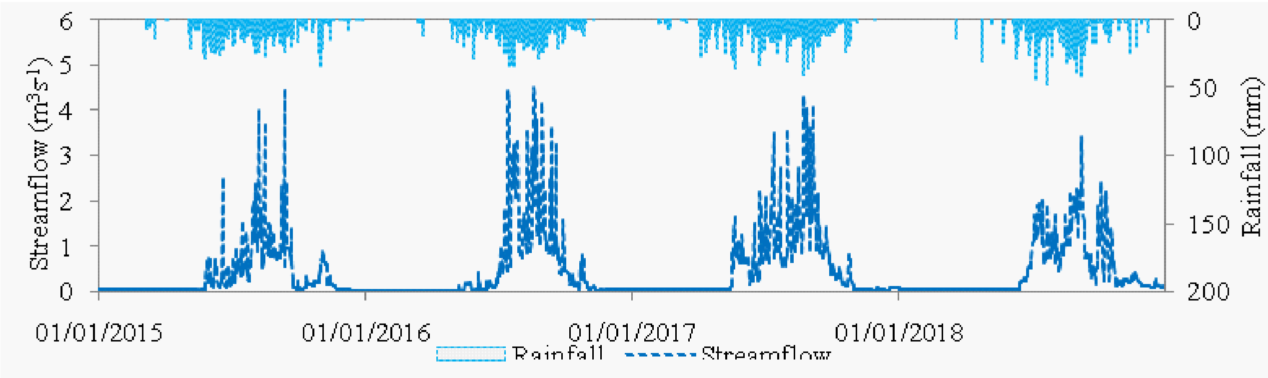


Figure 23 *Rainfall and streamflow data that is collected by citizen scientists in Branti watershed, Dangila.*

2.2. Role of para-hydrologists

In this section, we will provide the definition for "para-hydrologist", and then share IWMI's experience in training and engaging para-hydrologists.

Responsibility of para-hydrologists

The para-hydrologist is an intermediary who is a person based in the community and who receives on-the-job training on hydrological data collection, supervision, and interpretation. The following are the main responsibilities of a para-hydrologist:

Facilitate meetings: Community meetings are facilitated by a para-hydrologist, who speaks the local language.

Visit monitoring sites and citizen scientists on a bi-weekly base: The purpose of bi-weekly site visits is to (i) inspect the gauging site and assess the need for maintenance, (ii) provide feedback to citizen scientists by evaluating the data collection and recording process. The frequency of the site visits can be adjusted when needed, for instance, during frequent and heavy rainfall events, and when the number of citizen scientists is large.

Velocity measurement (mostly low flows): A para-hydrologist can be trained to measure flow velocity, which can be used to develop stage-discharge relationship. However, velocity measurement can have high risks for high flows. It is therefore advised to involve the para-hydrologist only for low flow measurements (<0.75m water depth). Necessary precautions and procedures should also be followed to avoid injury. Para-hydrologists can be equipped with safety closes and hand tools such as hammer, pliers, screwdriver, measuring tape, shovel, spirit level and measuring tape.

Digitizing data: Citizen scientists record data on hard copy which is collected by the para-hydrologist at the end of each month. The hard copy of the data can be archived both at the woreda office and with the para-hydrologist. It is the responsibility of the para-hydrologist to enter the data to a computer and transfer the soft copy of the data to a central database if there is any. For digitizing the data, access to computer should be provided to the para-hydrologist. Tablets can be preferred since these can be taken to the field to take pictures.

Take pictures: The bi-monthly field visit creates an opportunity for the para-hydrologist to take pictures of salient features in the catchment (land cover classes and sustainable land management activities) on a regular basis. The pictures can be geocoded and imported to a GIS environment for further analysis.

Contact person at the woreda office: It is always preferred if the para-hydrologist is a staff member at the woreda agricultural, water or natural resources office. This has twin benefits: the citizen science program can be integrated with existing initiatives, and the woreda can receive timely information on each citizen science activity, progress, and findings.

2.2.2. Criteria for selection of a para-hydrologist

A para-hydrologist is selected by consulting the woreda administration. The selection criteria should be clearly communicated beforehand. Below are some common criteria that can guide the selection of the para-hydrologist:

Education level: Priority should be given to a college graduate. However, the person is not necessarily trained as a hydrologist.

Skills: Since the para-hydrologist will continuously work with the local community, a person who speaks the local language is preferred. Knowledge of basic computer skills is mandatory to handle data entry and management.

Experience: Agriculture, natural resources or irrigation extension workers are preferred choices to serve as para-hydrologist. An extension worker who has worked with farmers for multiple years is expected to have good knowledge of temporal changes, interventions, and problems in the watershed. Priority should be given to an extension worker who is currently involved with advising farmers or facilitating natural resource management campaigns.

Other personal attributes: The work requires personal dedication and hence the selected person should express willingness to volunteer as a para-hydrologist. An extension worker who is less likely to change his/her job and move outside the woreda is a preferred choice to ensure continuity of engagement.

2.2.3. Training para-hydrologists

Training 1 (Data record and supervision): The para-hydrologist takes the responsibility of facilitating installation of instruments. This enables him to join the training session for citizen scientists and understand how data is read and recorded. The total duration of the training is determined by the number of variables and stations to be monitored. One-day trainings can be organized separately for the para-hydrologist on supervision of observers. This includes understanding the data recoding books, communicating with citizen scientists, checking data quality, providing regular feedback to citizen scientists, digitizing and archiving the data citizen science data, undertaking minor maintenance of stations, and communicating with researchers or experts.

Training 2 (Velocity measurement): The training on velocity measurement of streamflow is organized in the field on a quarterlybases. This requires appropriate equipment such as a current meter and data recording book. One day per three months can be allocated for the actual training in the field.

Training 3: Development of rating curves using velocity that is collected by the para-hydrologist and experts. The content of the training includes theoretical description of the various techniques for velocity measurement. It also covers estimation of discharge from velocity measurements, developing stage-discharge curves and conversion of stage (water level) measurements to streamflow discharge. Two days can be allocated for training 3.

Training 4: Data quality assessment. Simple techniques for checking accuracy, consistency and mistakes in data recording are discussed here. The para-hydrologist need to be familiarized with simple visualization and interpretation techniques of hydrological data (e.g. scatter plots, bar graphs, hydrograph, hyetograph, etc.) with the aid of hands-on exercises. Catchment water balance is described in this training. Two days can be allocated for training 4. Note that Training 3 and 4 can be offered in the same week.

Refresher training: The objective is to review and reinforce the knowledge and skills acquired in other trainings. This can also be organized for multiple para-hydrologists so that they share experiences. Two days can be allocated for the refresher training on an annual basis.

Attend workshops on citizen science and hydrological data: to share experiences and learn from others. This also helps to understand common issues, advances, and applications of citizen science.

Group Exercise Three: Discuss scope for setting-up citizen science program in your district

- What are the existing monitoring activities in the woreda?

•- Discuss how experience of community participation supports establishment of a citizen science program in your woreda

•- What could be the purpose of citizen science in your woreda: Support sustainable land management, shallow groundwater irrigation, etc.?

•- What can be monitored? In which watershed?

•- What are the opportunities and threats to implement citizen science activities in the woreda?

2.3. River discharge monitoring

The contents of this section include purposes of discharge monitoring, criteria for gauging site selection, monitoring using staff gauges, velocity measurement, and rating-curve development.

2.3.1. Purposes of discharge monitoring

Rivers are major sources of fresh water for human use. Hence, monitoring discharges provides valuable information to learn about water availability for various uses. River discharge represents the volume of water passing perpendicular to the river cross section per unit time (Figure 24). It is the most accurately measured component of the hydrological cycle. River-discharge data has a rich information content since it is an integrated response of the entire catchment, measured at the catchment outlet.

The equation for discharge (Q) reads:

$$Q = \bar{V} \times A \qquad (6)$$

where: V is the flow velocity; A is the wetted cross-sectional area and the overbar indicates that average velocity across the cross-section is used. The common units for flow velocity and wetted area are ms^{-1} and m^2 respectively whereas the common unit for discharge is m^3s^{-1}.

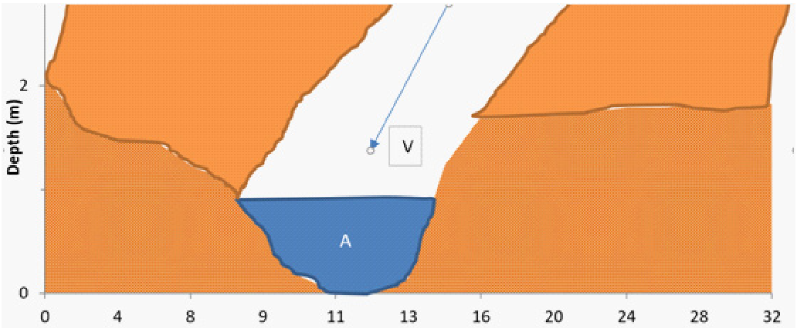


Figure 24 *Cross-sectional area of streamflow gauging station in Branti watershed, Ethiopia.*

River discharge measurement involves three stages:

- **Measuring river stage**: river stage refers to the elevation of the water surface in the river above a specified reference point, which is often referred to as benchmark.
- **Estimate discharge**: Estimation of discharge involves measuring the wetted area of the channel cross section and the streamflow velocity.
- **Establishing stage-discharge relationship**: discharge measurement is more expensive and difficult than stage measurement. Therefore, streamflow is commonly monitored by measuring its stage. Then, a stage-discharge relationship is used to convert the river stage to its discharge.

Measurement of discharge can serve a wide range of purposes (Figure 25). It serves management by providing information that can be used for water allocation among different sectors and users, to support relief management and to balance resource conservation and development. Millions of dollars are invested in sustainable land management in Ethiopia. However, the hydrological benefits of these investments are not well known. River-discharge monitoring can enable impact evaluation of these programs. Management of dam reservoirs requires timely discharge data otherwise overflow of these dams can cause catastrophic economic loss. In terms of economic efficiency, discharge monitoring can provide information to ensure equity through economic valuation of water use and comparison of management options. Discharge monitoring can benefit policy formulation since the discharge data can be used to estimate the available water resources to secure access to water for communities.

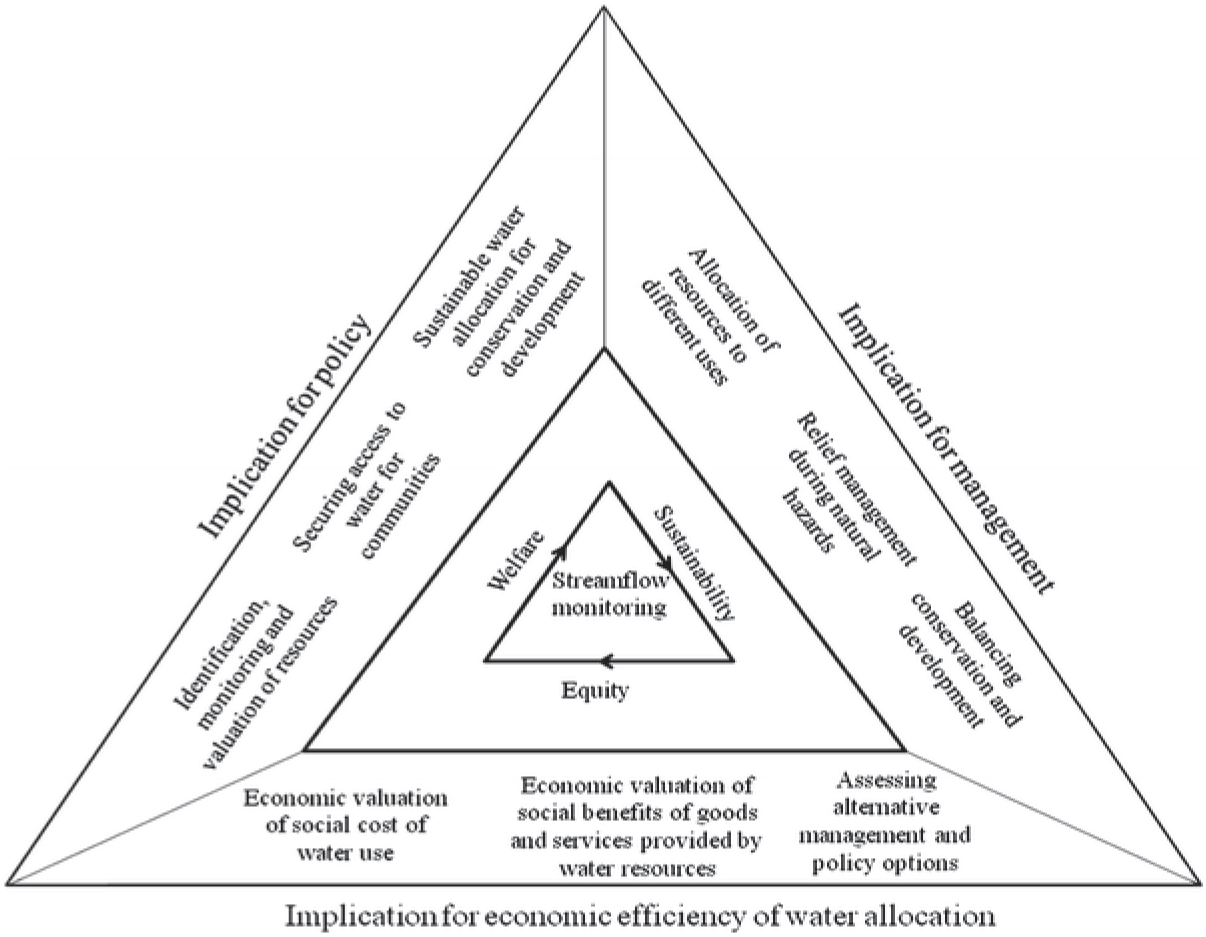


Figure 25 *Implication of stream-flow monitoring for policy and financial management (Dobriyal et al., 2017).*

The time interval between consecutive river stage measurements is affected by several factors. Monthly data is often enough for climate studies and water resource planning and management at catchment level. However, the design of hydraulic infrastructure and weather forecasting requires frequent discharge measurement, i.e. sub-daily or daily. Selection of appropriate observation intervals can also be affected by catchment size or discharge magnitude (See Figure 26). Large observation intervals will generate large discharge errors for small catchments with small discharges.

Continues monitoring of river discharge data is expensive using manual observation. In Ethiopia, the standard is to measure discharge twice per day, i.e., at 6:00 AM and 6:00 PM. Although this can be suitable for medium-sized and large catchments, its suitability for small catchments is questionable.

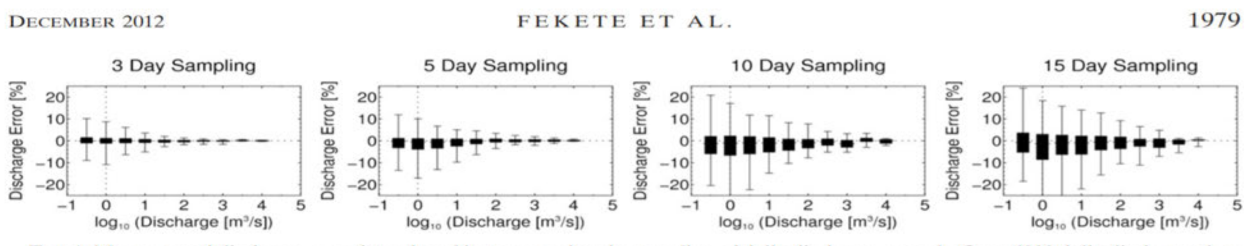


Figure 26 *Mean annual discharge error introduced by temporal under-sampling of daily discharge records (Fekete et al., 2012).*

2.2.2. Criteria for gauging site selection

It is important to always revisit the commonly applied criteria before field visits for site selection, since it helps us not to miss important criteria. Identification of suitable river sites for gauging stations is not always easy due to difficulty to find a site that meets all criteria. The commonly applied criteria for gauging site selection are summarized in Box 8.

Box 8. Criteria for Selecting Gauging Sites

- The river stretch is straight for about 100 m upstream and downstream from the gauge site.
- Total flow is confined to one channel at all stages (water depths) and no flow bypasses the site as subsurface flow.
- The streambed is free of aquatic plants and not subject to scour and fill.
- The banks of the river are permanent, high enough to contain floods (i.e. no flood overflows banks) and free of aquatic plants.
- The stream channel has an unchanging cross-section in the form of a bedrock, outcrop or other stable bed and bank material.
- A Pool is present upstream from the site at extremely low stages to ensure a recording of extremely low flows and to avoid occurrence of high velocities during periods of high streamflow.
- The gauging site is far enough from the confluence with another stream or from tidal effects to avoid any possible impacts on the measurement of stream stage.
- Reach of the measurement of discharge at all stages is available within the proximity of the gauge site.
- The site is readily accessible for ease of installation, operation and maintenance of the gauging station.

2.2.3. Velocity measurement

The common method for discharge measurement is to apply the velocity-area method by which we measure depth of flow, distance between vertical observations along the channel cross-section and streamflow velocity. Thus, discharge can be estimated from the sum of the product of depth, width, and streamflow velocity of each individual unit of the cross-section.

Velocity of flow at a point is usually measured by counting revolutions of a current meter rotor during a short-time period measured with a stopwatch. However, there are many other methods for velocity measurements. For instance, the float method is common where other standard equipment for velocity measurement is not available.

Various types of current meters are shown in Figure 27. There is wide variation in the price of current meters with the price difference exceeding two times or more. Current meters also vary with size. For instance, some of them are manufactured to measure flow in rivers (small, medium or large) whereas others are manufactured to measure flow in irrigation canals. Thus, the first step in velocity measurement is to select a current meter which is suitable for the intended purpose, accuracy and available budget.

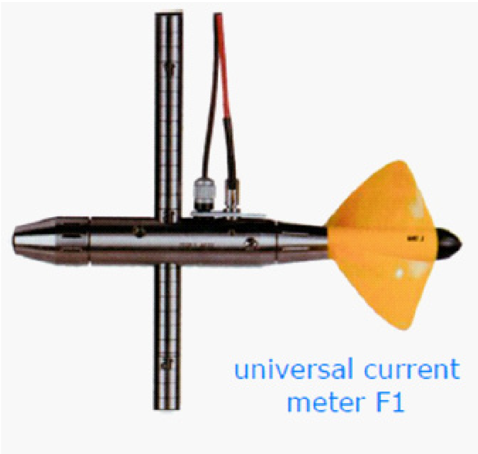


Figure 27 *Illustration of typical current meter.*

River channel cross-sections often have irregular shapes. Thus, we need to divide the entire cross-section into smaller units which are easy to measure. Each unit can be defined by its verticals (depth from top water surface to channel bed) and width (distance between consecutive verticals). The following rule of thumb can be followed to define the individual units of a cross-section:

- Observation verticals should be located to best define
  - the variation in channel bed elevation and
  - the horizontal variation in velocity.
- The interval between two verticals should not be greater than
  - 1/20 of the total channel width and
- The discharge of any unit should not exceed
  - 10 % of the total discharge.

Figure 28 shows an example of dividing a cross-section into several units whereas Figure 29 shows a picture of IWMI staff measuring velocity of the Kimakia River, Kenya. The first unit in the left side has a triangular shape and hence its cross-section is computed as follows:

$$a_1 = \frac{1}{2} \times d_1 \times b_1 \quad (7)$$

where: d_1 and b_1 refer to the vertical height and width of the unit.

The area for the second unit can be computed as follows:

$$a_2 = \frac{d_1 + d_2}{2} \times b_2 \quad (8)$$

Area of other units can be computed in a similar manner. For the n^th^ unit:

$$a_n = \frac{d_{n-1}+d_n}{2} \times b_n \tag{9}$$

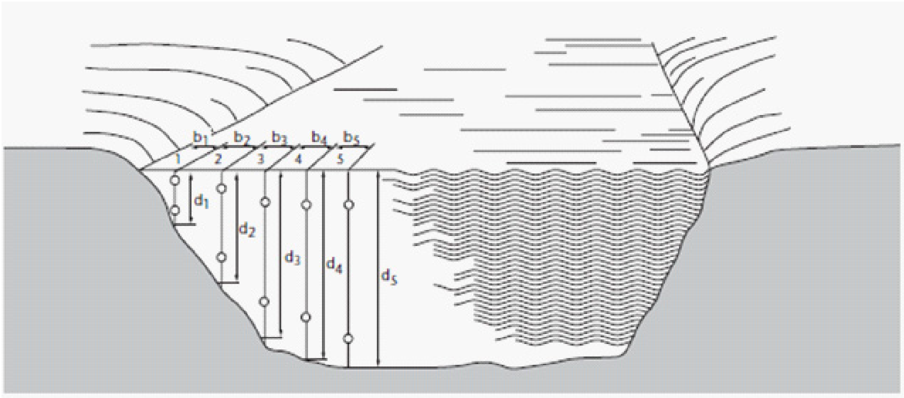


Figure 28 *Partitioning of river cross-section into smaller units for area estimation.*

Figure 29 *Velocity measurement at gauging site on Kimakia river in Kenya under an IWMI project in Kenya.*

Streamflow velocities are known to vary across depth and cross-section. Hence, velocity measurements are taken at multiple locations at a river cross-section. Measurements should be taken in each of the units (divisions) of the cross-section (see Figure 30). One or more velocity measurements are taken for each of the cross-section units depending on the range of velocity variation along the vertical.

For small flow depths with low velocity variation, only one velocity (V) measurement along the vertical can be sufficient. The method is called one-point method and the only measurement can be taken at 0.6 of the depth below the water surface. The two-point method is applied when the velocity shows large variation. In this method, two measurements are taken by placing the current meter at 0.2 and 0.8 of the depth below the water surface. The average of the two measurements is taken as the velocity (V) in that unit.

The total discharge (Q) of the stream can be estimated from the cross-sectional area (A) and the average velocity (V), as follows:

$$Q = A \times V \tag{10}$$

$$Q = a_1 \times V_1 + a_1 \times V_2 + \cdots . + a_1 \times V_n \tag{11}$$

where: all terms are defined as before.

There are other methods that can be applied for velocity measurement when a current meter is not available. For instance, the "float method" is very commonly applied. In this method the surface velocity is estimated by defining a pre-determined distance to the time that is taken by a floating material to travel the pre-determined distance (Figure 30). Discharge is estimated as the product of the velocity, average width and average depth of the channel. Examples of commonly used floats are a piece of wood or a smooth tree branch about 30 cm long and 5 cm wide.

The following steps can be followed for the float method:

- Choose a suitable river reach that meets previously discussed criteria for discharge measurement sites. The length of the reach can be determined by availability of a straight reach, but length that exceeds 10 m is preferred.
- Mark the start and end point of your reach with a stick or stone.
- Revise the length of the reach if the travel time is too short to measure.
- Drop the float into the stream upstream of your upstream marker.
- Start the watch when the object crosses the upstream marker and stop the watch when it crosses the downstream marker.
- You should repeat the measurement at least 3 times and use the average velocity in further calculations.
- Since the float method measures surface velocity, it requires correction. The correction factor can be estimated by simultaneously measuring velocity with both the float and current meter. When a current meter does not exist at the site, it is possible to use a coefficient of 0.85 to correct the velocity which is measured by the float method.

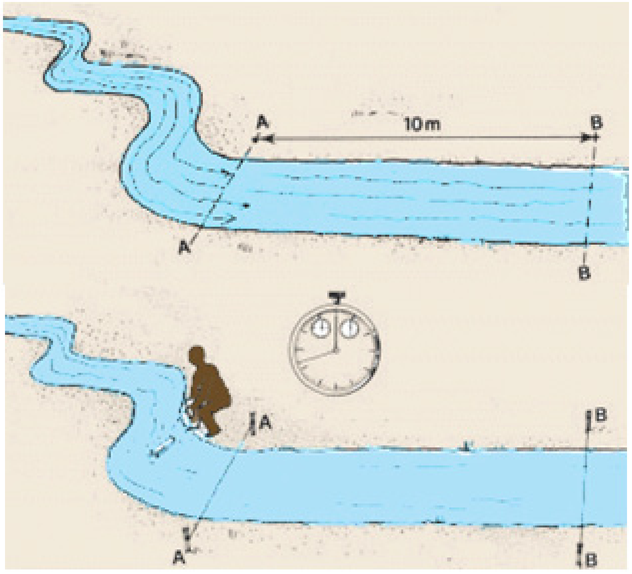


Figure 30 *Illustration of the float method.*

(Source:ftp://ftp.fao.org/fi/CDrom/FAO_Training/FAO_Training/General/x6705e/x6705e03.htm)

Development of stage-discharge relations (Rating curves)

The most frequently used equation of a rating curve follows a power curve of the following form:

$$Q = a(H - H_0)^b \tag{12}$$

where: Q is the discharge in m^3s^{-1}; H is the measured water stage in meters; a, H_0 and b are the calibration coefficients where a is the discharge when the effective depth of flow (H-H_0) is equal to 1; H_o is the gauge height of zero flow (stagnant water); b is the slope of the rating curve on logarithmic paper.

The rating curve equation can also be re-written as follows:

$$\log(Q) = \log a + b \times \log(H - Ho) \tag{13}$$

We can use $X = \log(H\text{-}H_0)$ on $Y = \log Q$ to convert the equation to a more familiar form of linear regression equation.

The slope of the linear regression, b is defined as:

$$b = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2)(\sum X)^2} \tag{14}$$

The intercept of the regression, c is defined as:

$$c = \frac{\sum Y - b(\sum X)}{N} \tag{15}$$

The coefficient, a is antilog of c,

$$a = 10^c \tag{16}$$

The rating curve can be evaluated by using the Pearson product moment correlation coefficient, r, as follows:

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2 - (\sum X^2][N(\sum Y^2) - (\sum Y^2)]}} \tag{17}$$

The performance of the rating curves can be computed using the Mean Square Error (MSE) as:

$$\text{MSE} = \frac{1}{N}\sum_{i-1}^{n}[(Q_{ac-}Q_{es})]^2 \tag{18}$$

where N is the sample size of stage discharge data; $Q_{ac}$is sum of actual discharge (m^3s^{-1}) and Q_{es} is sum of estimated discharge (m^3s^{-1}).

2.4. Shallow groundwater

Here, we will demonstrate simple techniques for monitoring shallow groundwater, and discussassociated challenges and opportunities. A brief discussion on soil moisture monitoring will be included under this session to familiarize participants with existing techniques.

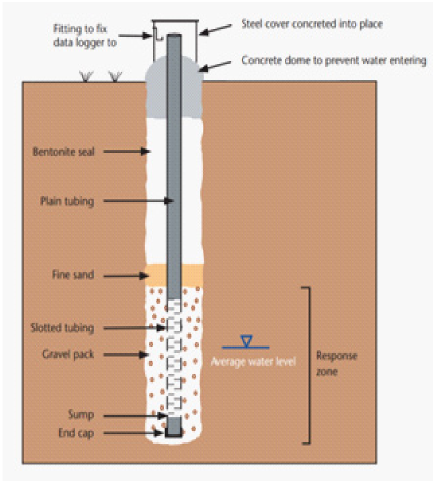
2.4.1. Benefits of monitoring shallow groundwater

Monitoring of shallow groundwater (SGW) resources is very important for several reasons. It can provide information to manage water resources properly and minimize over exploitation of the resource. In rural parts of Ethiopia, time series data on SGW can be used to derive information that can be useful to introduce household irrigation. It can also be used to estimate the effect of a rising water table on crop production.

2.4.2. Monitoring well

The most preferred method to monitor SGW is to construct monitoring wells. The bottom of the well should always be placed lower than the minimum historical water level at the site. Thus, you should first collect information about the depth to SGW in the nearby wells or springs before deciding the depth of the monitoring well. This can be done by interviewing well owners. The rule of thumb is that the depth to the water table is higher in hillslopes than floodplains. Hence, you can install two thirds of your monitoring wells in low elevation areas and one third of the wells in high elevation areas to minimize costs.

A plastic tube is installed in the well to protect the well from collapsing. The preferred diameter of the tube is 5 cm but can be slightly increased or decreased based on site conditions. An end cap is placed at the bottom of the plastic tube to protect entry of soil materials, whereas its lower part is perforated to allow water to enter the well. You can cover the perforated part of the plastic tube with a mesh to minimize entry of soil particles. A concrete dome is placed at the top to prevent entry of water, and then the top should be covered with steel that can be opened and closed with a key (Figure 31). Always mark the reference level with painting so that observers always measure depth to the water table from the same reference.



Always mark the reference level with painting so that observers always measure depth to the water table from the same reference.

Figure 31 *Monitoring borehole (Source: Environment Agency, 2003).*

2.4.3. Measuring instrument for SGW depth

Dip meter is an instrument than can be used to measure depth to the water level in monitoring wells (Figure 32). It gives a buzzer sound when its electrode probe touches the water level. Dip meter comes in different tape lengths such as 0-10m, 0-30m, 30-100m. It is therefore important to decide which tape size to purchase and use after preliminary assessment of the range of groundwater depths in the study site. One dip meter can cost from US$250 to US$400. The advantage is that it can be used for several years with proper handling.

SGW depths can be measured with local materials if a dip meter is not available. A combination of rope and tape ... all rock at one end of the rop ... l.

Figure 32 *Dip meter (left), demonstrating use of a dip meter for the community in Dangila (middle) and monitoring well (right) established by IWMI (Barotse floodplain, Zambia). (Middle and right Photos: Alemseged Tamiru Haile).*

The monitoring interval is determined by its purpose and resource availability for monitoring. Daily measurementsare preferred during wet seasons to capture the fluctuation of the water level in response to rainfall input. However, the observation interval can be reduced to two to seven days for the dry season since water level fluctuation is not significant then. Measurements can be taken at 6:00 AM when the water level is stable since abstraction is less likely in the night. Figure 33 shows rainfall and groundwater level measurements at daily intervals.

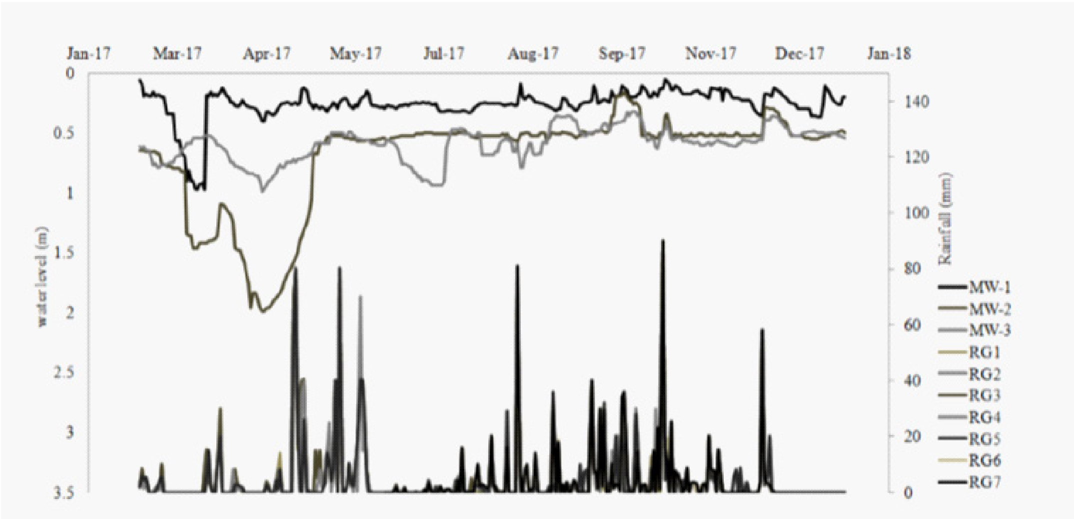
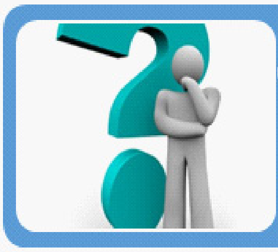


***Figure 33** Hydrograph of daily water level in MW and bar graph of daily precipitation in Esheto watershed in Zigity woreda near Arba Minch.*

Note: MW refers to monitoring well; RG refers to rain gauge (Ferede, 2018).



Questions

- Discuss gaps and opportunities for monitoring SGW resources in your woreda

2.5. Hydrological data quality assessment

In this section, we will address a very important issue in community-based monitoring, which is data quality. Simple techniques for identifying suspicious records in the collected and reported data will be presented to enable trainees conduct a data quality assessments.

2.5.1. Observer and gauging site errors

Data availability includes the amount, quality, and information content of the data. It is therefore important to understand sources of errors that can affect hydro-met data quality and take necessary measures to minimize these errors. Although the data is available, it may not be fit for further use.

Common sources of observer's errors in hydro-met data recording include:

- Wetting loss in rain gauge containers when emptied.
- Observations have been consistently or accidentally credited to the wrong day.
- Gross errors, for instance, reading rainfall collected by gauges for several days instead of daily.

- Misplaced decimal points, e.g., recording "1.1" instead of "1.01".
- Not differentiating 'no observation' and 'observation = 0'.
- Unclear handwriting becomes a problem during conversion of the hard copy into digital data (Figure 34).
- Suspicious patterns in the data which suggest records are filled in without visiting the gauging site (Figure 34).
- Single river water level reading during turbulence (repeated measurements are needed to reduce errors).
- Recording time error when observers change the recording time as per their convenience.
- Use of commas instead of decimal points (Table 5).

Figure 34: *Examples of observers recording books withsuspicious patterns (very regularly increasing water level) and unclear handwriting* (Source: IWMI working paper 192 (left and middle) and IWMI unpublished report (right)).

Table 5 *Use of commas instead of decimal points in Branti watershed, Dangila, Ethiopia.*

Month	Day	Rainfall	Well 1	Well 2	River 1	River 2
April	1	1.5	2.18	2.15	1.3	1.3
	2	2,1			1.3	1.3
	3	0	2.2	2,17	1.4	1.45
	4	0			1.3	1,6
	5	11. 7	2. 09	2.11	1.7	1,8
	6	6.6			1 .7	1.7
	7	0	2.16	2.12	1.6	0.74

Common sources of errors due to issues at the gauging sites include:

- Floods frequently damage the staff gauge.
- Boulders and tree logs dumped at gauging sites by floods affects stage-discharge relationship.
- River cross-section changes over time requiring updating of rating curve or moving the gauge to a stable site.
- Changes in the zero reading (water level at zero discharge) over time due to sedimentation.
- The staff gauge is tilted from the vertical position.
- Broken, missing and corroded staff gauges (Figure 35).
- Access to gauging site is not easy for observers.

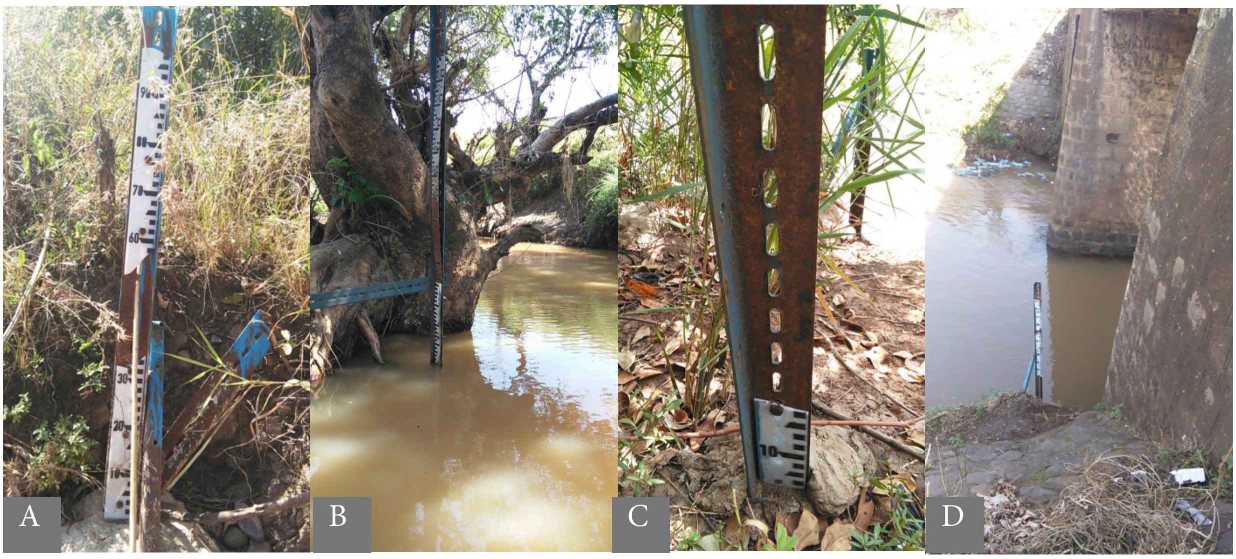


Figure 35 *Broken, missing and corroded staff gauges installed at a) Deme at OretaAlem, b) Rebu River Nr. Wolkite, c) Wabe River Nr. Wolkite and d) Darge River Nr. Tedelle*(Source: IWMI unpublished report).

2.5.2. Role of supervisors

Community data collection requires frequent supervision of observers. Supervisors can play two main roles to minimize data errors: (i) site inspection to timely correct any unnecessary changes in the gauging instrument or gauging site, and (ii) provide feedback to observers to minimize common sources of errors during observation. Any supervisor should undertake the following tasks during site inspection visits:

1. **Days and months** – Make sure that correct dates (days, months and years) are recorded in each data recording sheet.
2. **Locations** – Location attributes such as geographic coordinates and name and code of the gauging sites is filled in header of each data recording sheet.
3. **Completeness** – Check whether the data is completed without any blanks. However, ask the observers for explanations if there are blank records to make sure that an explanation is entered in the remark.
4. **Readability** – If the numbers are difficult to read, then ask the observer and write the correct number under the space for remark.
5. **Decimals** – Check misplaced decimals.
6. **Suspicious patterns** – If there are suspicious patterns in the data, then discuss with the observers and provide feedback to avoid these in the future.
7. **Extreme values** – if there are extremely large or small values in the data, then discuss with the observer to find explanations which can be written under the space for remarks.
8. **Remarks** – encourage observers to write remarks to explain any factors that affected data recording, e.g. gauges damaged by floods or vandalized, observer was sick or faced other problems that affected data recording, etc.
9. **Gauge zero reading** – check if the gauge zero reading is affected by sedimentation or other factors and write your observations as a remark.
10. **Damage to staff gauge and changes in river cross-section** – take appropriate measures or report to the office for prompt action.

Reference is made to Walker et al. (2019a,b) for details on setting up citizen science monitoring programs and guiding of para-hydrologists.

2.5.3. Detecting error from time series

There are several methods for detecting error from timeseries data. We look at the two basic methods as follows.

Rough Screening of the Data: This starts with checking the completeness of the data by counting the number of missing records and using consistent symbols to indicate missing data. For rainfall data, we can also tabulate daily observations by neighbouring stations (but observations from several stations should be available!). This allows us to detect records that are entered to a wrong date, unexpected large rainfall amount, cumulative records instead of daily records, and presence of misplaced decimal points (Table 6).

Table 6 *Rough screening of data by tabulating daily rainfall observations at neighbouring stations.*

Date	Station 1 (mm)	Station 2 (mm)	Station 3 (mm)	Station 4 (mm)	Rough screening of data
1-Jul-20	0.0	5.0	10.0	8.0	
2-Jul-20	0.0	10.0	15.0	13.0	
3-Jul-20	20.0	8.0	10.0	12.0	Observer @ Station 1 probably accumulated rainfall of 3 days
4-Jul-20	16.0	12.0	5.0	NA	
5-Jul-20	0.0	0.0	0.0	0.0	
6-Jul-20	0.0	NA	0.0	0.0	
7-Jul-20	2.0	5.0	7.0	100.0	Observer @ Station 4 probably misplaced decimals (wrote 100.00 instead of 10.00)
8-Jul-20	0.0	0.0	0.0	0.0	
9-Jul-20	NA	0.0	0.0	0.0	
10-Jul-20	18.1	28.1	0.0	35.7	Observer @ Station 3 probably recoded the rainfall of 10 July on the wrong data
11-Jul-20	0.0	0.0	25.3	0.0	

Plotting the data: Plotting data from multiple stations and variables supports detection of error in time series data. For instance, Figure 36 shows that there are sudden jumps in the groundwater data which occurred several times over the observation period. We should explore why these sudden jumps occurred. The figure also shows that the fluctuation of water levels were reduced in 2016 and 2017 as compared to that of 2015. This is caused by reduced observation frequency because of delays in incentives and supervision.

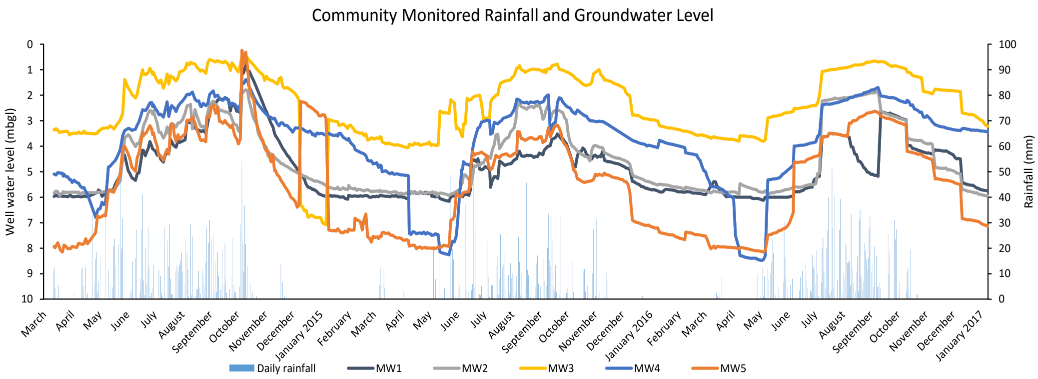


Figure 36 *Community monitored groundwater and rainfall data in Dangila.*

Source: REACH-WSRS project which was jointly undertaken by IWMI and Newcastle University.

Data from multiple stations may be mixed-up when a single observer monitors multiple stations, as could be the case during monitoring of shallow groundwater wells. Figure 37 shows that the

observer recoded the data of the MW1 station into the recording sheet of the MW5 station and vice versa. The figure also shows that the variation in well water level is mostly in response to rainfall, which is expected. This co-variation of rainfall and water level increases the credibility of the observations.

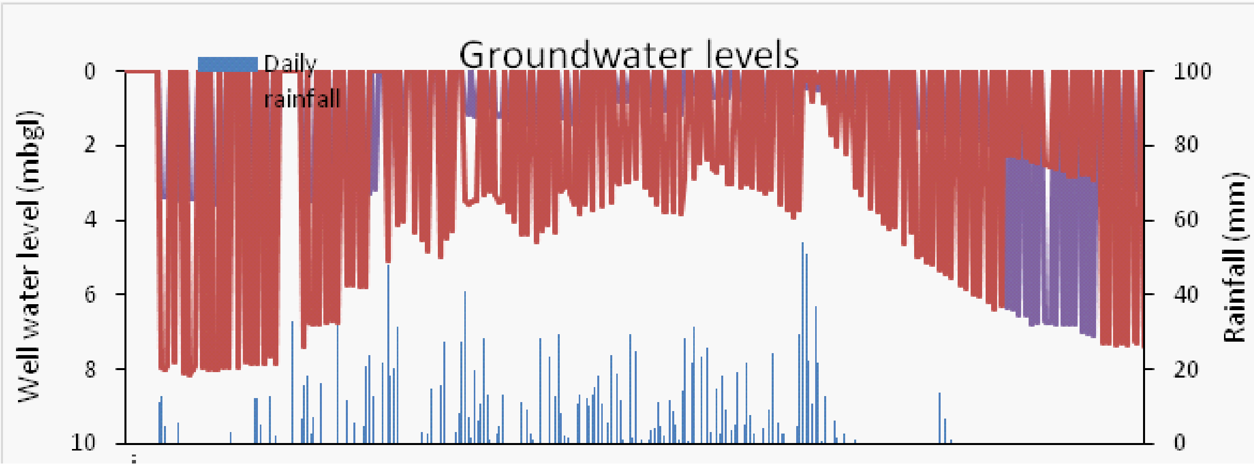


Figure 37 *graphical comparison of water level data from different wells to check if data from one station is wrongly entered in other stations data recording sheet*(Source: David Walker, personal communication).

Module 3

Climate Change, land cover and soil changes

In this section, possible changes in a watershed that cause changes in hydrological responsesare discussed. At the end of the section, trainees are expected (i) to understand the inter-related nature and time lag between changes in climate, land cover and soil properties, and (ii) how these changes alter runoff generation and water availability in a watershed.

3.1. Overview

The focus in this section is to describe how changes in climate, vegetation and soil affect runoff generation in a catchment. The climate, vegetation, and soil changes are often interrelated. The time lag between vegetation response to climate change and soil response to climate and vegetation changes is not easy to quantify. However, the theoretical cause-effect relationships between these factors are well known. The loss of vegetation cover exposes the soil to the impact of high intensity rainfall which promotes rapid runoff. This causes reduction in infiltration leading to reduced water storage in the catchment which further reduces vegetation cover. Thus, we must study these changes both separately and in combination since the changes can result in significant modifications in hydrological processes, especially the rainfall-runoff relationship.

Understanding changes in a watershed has immense benefits. Particularly in countries like Ethiopia, changes are imminent due to increasing population and economic development which will put additional pressure on water resources in a watershed. The major benefits of understanding the changes and their impacts can be summarized as follows:

- Change detection provides indications of ecosystem health. It helps to understand the extent to which the watershed can support various demands (provide ecosystem services) – in response to the changes.
- Change detection is used to identify, prioritize, and compare watersheds for future interventions. It can also inform identification of technologies that are appropriate to reverse the specific changes/degradation in a catchment.
- Changes in a watershed affect water availability and demand. Thus, decision makers need to understand how human activities and climate change may impact local water resources availability and demand. Natural resources management should look at the past and current situations and future scenarios.

Changes in watersheds can be characterized by:

- Source/cause
- Effect
- Frequency of occurrence (e.g. drought and flood frequency)
- Duration of the effects
- Intensity/magnitude of the effects

3.2. Climate variability and change

The study of weather is called "meteorology" whereas "meteorologists" are scientists studying thevweather. Weather is the state of the atmosphere at a given time instant and refers to a single occurrence at a given location (e.g. at Meki town). It also refers to the atmospheric state over durations that span over short periods (hours or days). Thus, it fluctuates from hour to hour or day to day (See Figure 38) mainly due to fluctuations in heat and the earth's surface (e.g. air and water).

Weather can be forecasted by studying pressure, wind direction and speed, and rainfall and the sea condition. The forecasts are commonly expressed in terms of rainfall and temperature. It is also represented by wind, cloud cover, sunshine, and humidity. Extremes events such as storms and extreme temperatures are also included when describing the weather. National meteorological agencies are responsible for distributing weather forecasts but there is also indigenous knowledge in many regions where farmers use their own methods to forecast the weather. Farmers rely on their observations of the phenology of certain plants and/or the behaviours of certain animals, and the cloud pattern and movement.

The agriculture sector is one of the main users of weather forecasts since weather affects crop growth, pests and diseases. Weather also affects agricultural prices as temperature affects storage and transport of products. The forecasts are also essential in other sectors including aviation, water resources management, disaster risk management, and many other sectors.

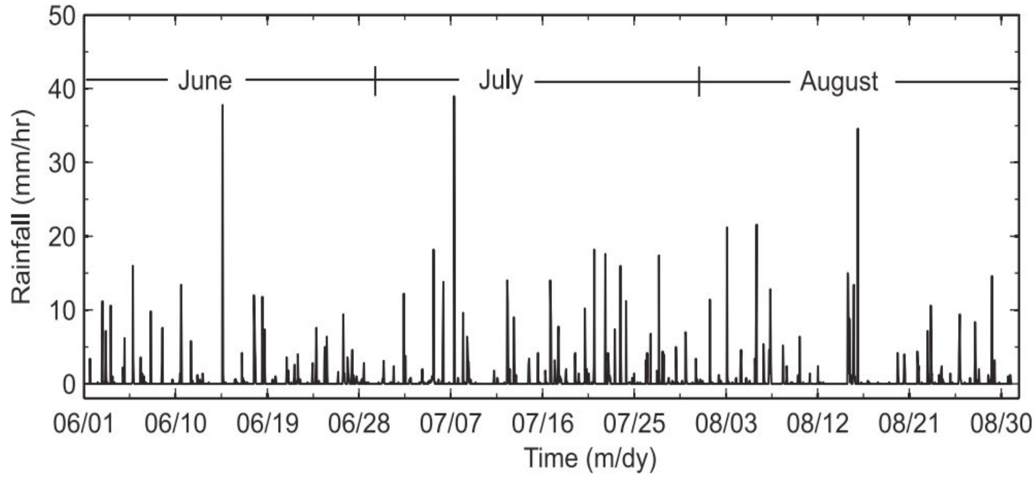


Figure 38 *Hourly fluctuation of the rainfall at Jema station in GilgelAbay catchment (Haile et al., 2009).*

Climate is usually defined as the average weather (state of the atmosphere) over a given time scale (duration). The standard time span for averaging weather variables (i.e. to describe climate of a certain region) is 30 years. Various statistical descriptions are used to describe the climate of specific location. Examples of these statistics include mean, range, standard deviation (variability) and autocorrelations.

Climate variability

Tropical African regions are characterized by a high climate variability across time and space. Climate variability refers to the variations beyond individual weather events. It is commonly quantified as the variation of a climate variable (e.g. rainfall and temperature) from its long-term mean state (Figure 39). Standard deviations and coefficients of variation are the common statistics to quantify variations from the mean spatial and temporal conditions. There are also several other climate indices that can be used to describe climate variability.

Climate variability causes meteorological conditions (e.g. temperature and rainfall) to deviate from the long term mean condition. It can also affect the distribution of climate variables resulting in more frequent extremes (i.e. flood and drought). Figure 39 shows the deviations of the annual rainfall amount from the long term mean at Menissa watershed, South Ethiopia.

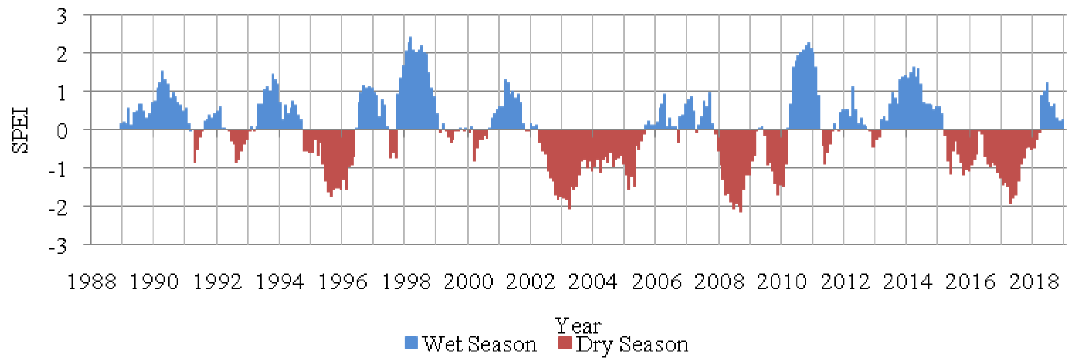


***Figure 39** Distribution of 12 months Standardized Precipitation-Evapotranspiration Index (SPEI) in at Menissa Watershed, Southern Ethioppia (1988-2018).*(Source: IWMI unpublished report).

Climate variability can be expressed by diurnal (within a day), intra-annual (within a year), and inter-annual (between years) time scales. Figure 40 shows how terrain elevation affects the diurnal variation of rainfall in the Upper Blue Nile of Ethiopia.

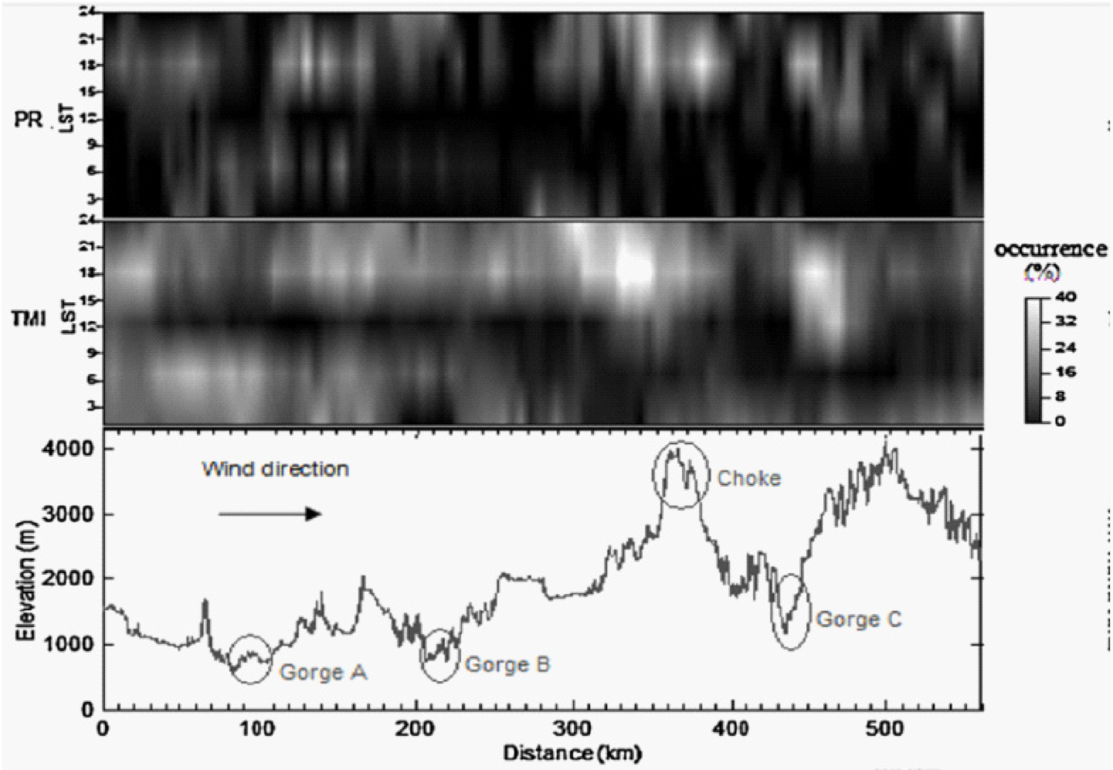


Figure 40 *Spatial and temporal variation of rainfall occurrence along transect from west to east (WE) and from north to south-east (NS) (Rientjes et al., 2013).*

Both extreme wet and dry climate due to climate variability can cause the following effects:

- Deterioration of human health with the possible death of thousands of people.
- Livestock are also significantly affected through health impacts and access to water and forage.
- Rainfed crop production is highly related to climate variability.
- Decline in fish production due to e.g. drying up of water bodies and sedimentation and siltation.
- Irrigation water supply and reservoir storage for energy production are highly affected by climate variability.
- Climate extremes can exacerbate conflicts by creating additional competition for natural resources.
- Droughts and floods can affect human migration in several ways, particularly via their complex interrelationships with economic, social, and political factors.
- There is strong relationship between rainfall variability and GDP for many African countries.

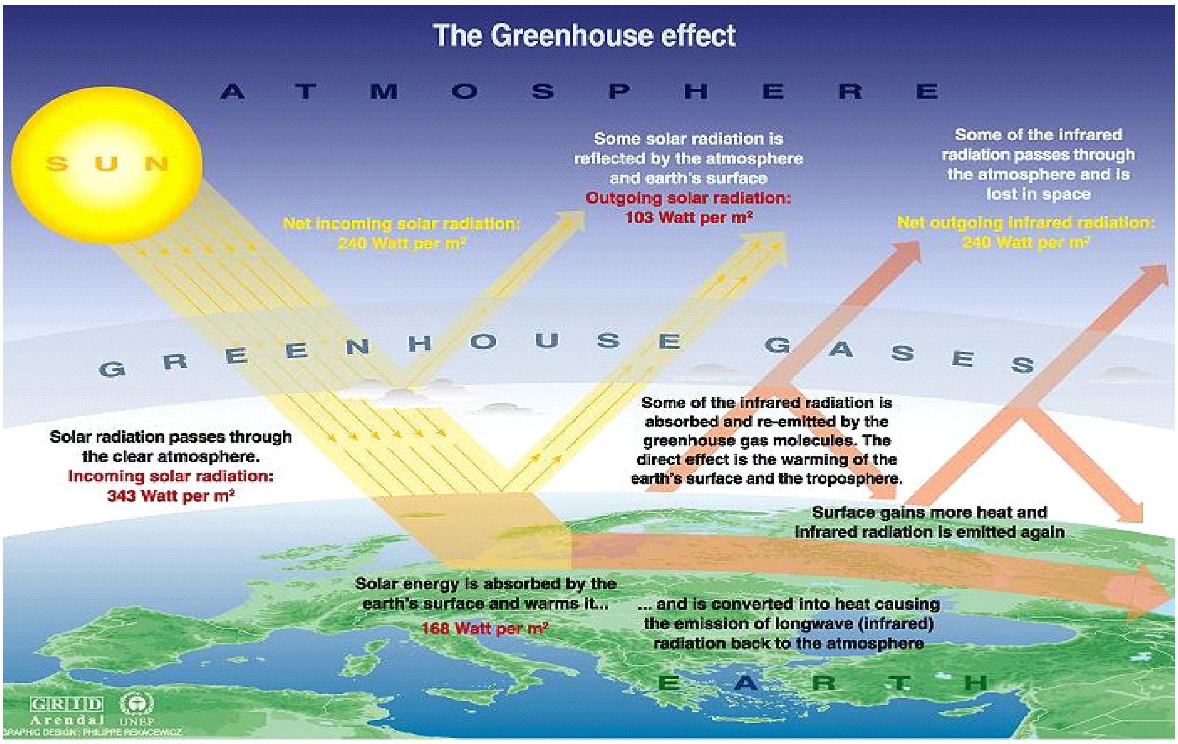
El Niño Southern Oscillation (ENSO) results from an unstable interaction between the atmosphere and the ocean. It integrates oceanic phenomena (El Niño) and Atmospheric phenomena (Southern Oscillation). Scientific evidence shows that there are teleconnections (significant correlations) between ENSO conditions in the Pacific Ocean areas and climate variability in other parts of the globe including Ethiopia.

Climate variability is affected by ENSO among other factors. The effect of ENSO includes reduction or enhancement of mean rainfall amount, and changes in climate extremes. These alterations in climatic conditions can result in significant societal impacts including loss of life as well as property. Hence, understanding the relationship between ENSO and climate variability of a certain region has huge potential to assist prediction of the seasonal climate of a region that can be used to advise farmers and other relevant stakeholders.

Climate change

"Climate change in the Intergovernmental Panel on Climate Change(IPCC) usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/ or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity."

Climate change is caused by both natural variability and human activities.Greenhouse gas refers to a blanket of gases that traps infrared radiation (light and heat); see Figure 41. Examples of greenhouse gases include CO_2: carbon dioxide; CH_4: methane; N_2O: Nitrous oxide. If there were no greenhouse gases in the atmosphere the average temperature on earth would be much less than 0°C. Ozone in the stratosphere helps to protect life at the Earth's surface by absorbing most of the harmful ultraviolet radiation in the sunlight. Reduction of ozone in the stratosphere is caused by human-produced chlorofluorocarbons (CFC) and other chlorine- and bromine-containing gases. Thus, greenhouse gases allow us to exist on earth.



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

Figure 41 *The greenhouse effect.*

The term "global warming" refers to a specific kind of climate change in which Earth's average temperature is increasing. Humans are responsible for global warming. There has been a huge shift to the intensive use of fossil fuels (essentially oil, coal, and gas) since the beginning of the industrial revolution in the late 18th century. There is sufficient evidence of increased amounts of CO_2 and other greenhouse gases in the atmosphere, which is enhancing the natural greenhouse effect. Crop production contributes to increased emissions of N_2O; cattle farming increases emissions of methane; deforestation, decay, peat and fires also increase emissions of CO_2, as does use of petrol for transport. Changes in land use, such as deforestation, alter how much sunlight is reflected into space (called the albedo).

Observations indicate that "global warming" is real. The fifth assessment report of the IPCC reported that each of the last recent decades have become successively warmer at the Earth's surface than any preceding decade since 1850. The period 1986–2005 is approximately 0.61 °C warmer than 1850–1900. The global temperature is expected to continue to increase in the future is emissions are not curbed (Figure 42).

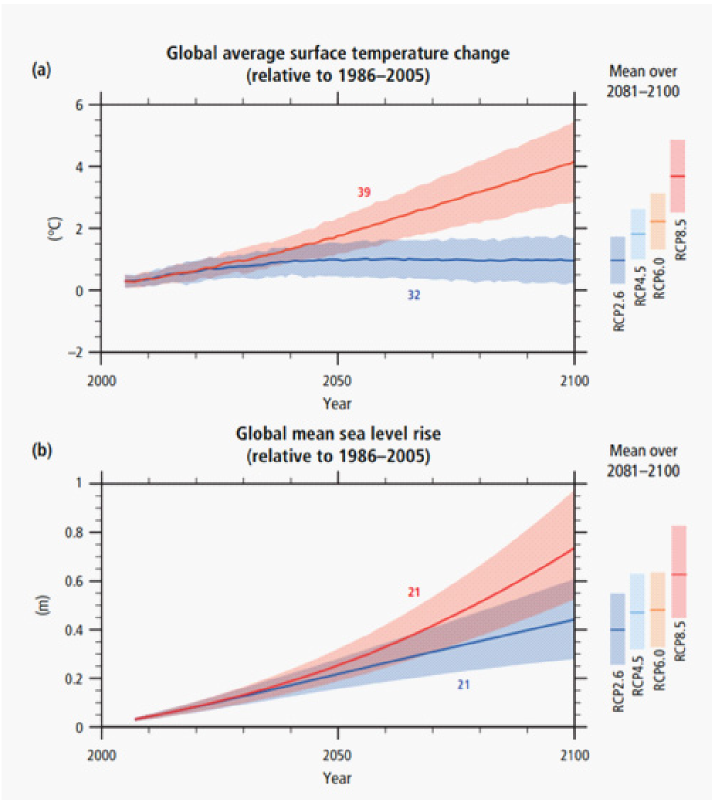


Figure 42 *Global average surface temperature change (a) and global mean sea level rise10 (b) from 2006 to 2100 as determined by multi-model simulations.*

Note: All changes are relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The mean and associated uncertainties averaged over 2081– 2100 are given for all RCP scenarios as coloured vertical bars at the right-hand side of each panel. The number of Coupled Model Inter-comparison Project Phase 5 (CMIP5) models used to calculate the multi-model mean is indicated. Source: AR5 of IPCC.

There is consensus among scientists for projected air temperatures to increase in the next decades, but rainfall trends are less clear. This is mainly related to the direct relationship between temperature and greenhouse gases. Figure 43 shows the possible changes in temperature because of climate change.

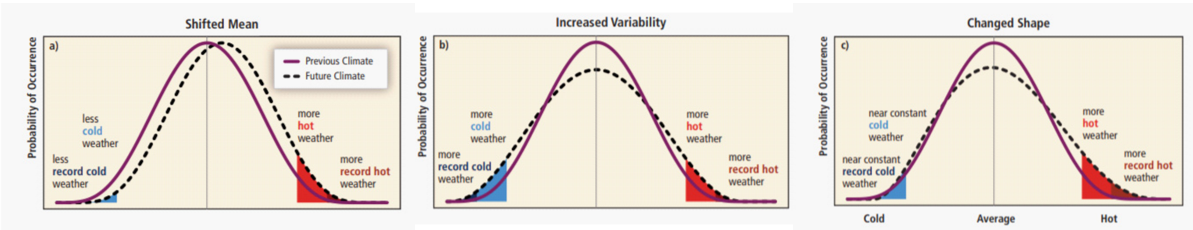


Figure 43 *The effect of changes in temperature distribution on extremes.*

Different changes in temperature distributions between present and future climate and their effects on extreme values of the distributions: a) effects of a simple shift of the entire distribution toward a warmer climate; b) effects of an increased temperature variability with no shift of the mean; and c) effects of an altered shape of the distribution, in this example an increased asymmetry toward the hotter part of the distribution. Source: Lavell et al. (2012)

Countries such as Ethiopia are struggling to cope with the adverse impacts of climate variability. This struggle will be further complicated by climate change which is expected to exacerbate climate variability. Future droughts and floods are expected to be both more severe and frequent. Thus, strengthen capacity to deal with existing climate variability is a first step towards preparations to deal with the adverse impacts of climate change.

Water storage becomes very importance in this context as it allows farmers to absorb climatic shocks that cause water shortages (Figure 44). Selection of the appropriate water storage technology depends on several site-specific sectors as well as financial, technological and technical resources. Overall, the deeper and/or larger the storage, a more reliable water supply can be ensured; the more 'natural' it is, the less complex and less costly it is to develop and access (IWMI Research Report, 152). It is also important to recognize that the different types of storage can be affected by climate change (Table 7).

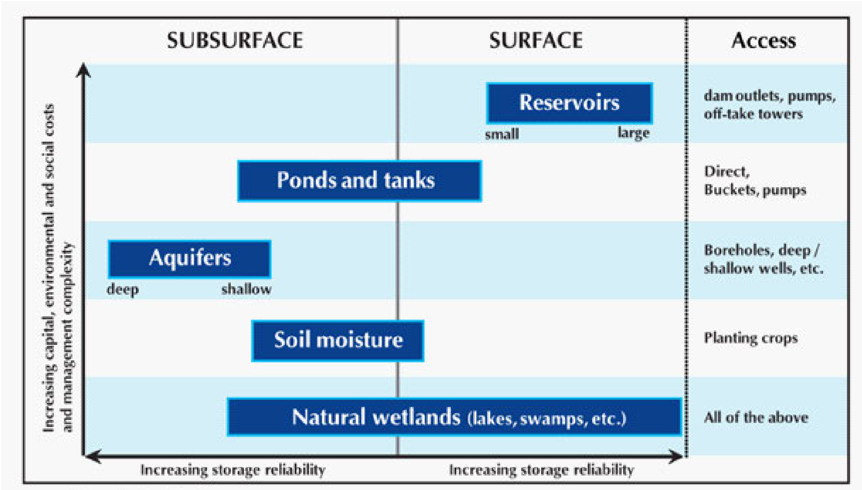
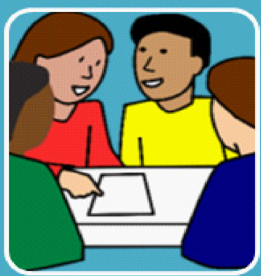


Figure 44 *Conceptualization of the physical water storage continuum (McCartney and Smakhtin, 2010).*



Group Exercise Four

Discuss the existing condition in your district in reference to the physical water storage continuum (Figure 44).

- Discuss indigenous knowledge that is used to forecast wheather in your district

Table 7 Climate change risks for different storage types in SSA and the possible social and economic implications (Source: IWMI Research Report, 152).

Storage type	Risks associated with CC*	Social and economic implications
Reservoirs	• Reduced inflow, resulting in longer periods between filling. • Higher evaporation, increasing the rate of reservoir depletion. • Infrastructure damage due to higher flood peaks. • Improved habitat for disease vectors (e.g., mosquitoes). • Increased risk of eutrophication and salinization. • Increased siltation.	• Increased failure to meet design specifications (irrigation and hydropower generation, etc.). • Increased costs due to the need to redesign infrastructure (e.g., spillways). • Increased risk of waterborne diseases (e.g., malaria).
Ponds/tanks	• Reduced inflow, resulting in longer periods between filling. • Higher evaporation, increasing rates of pond/tank depletion. • Infrastructure damage due to higher flood peaks. • Improved habitat for disease vectors (e.g., mosquitoes). • Increased risk of eutrophication and salinization. • Increased siltation.	• Increased failure to provide water requirements of the community and households. • Increased labor requirements and costs to repair structures. • Increased risk of waterborne diseases (e.g., malaria).
Aquifers	• Reduced recharge, resulting from modified rainfall intensities. • Reduced recharge, resulting from land-cover modification and increased soil moisture deficits. • Saline intrusion in aquifers near the coast.	• Falling water levels make it increasingly costly to access groundwater. • Poor water quality makes groundwater unsuitable for use.
Soil moisture	• Reduced infiltration, resulting from modified rainfall intensities. • Waterlogging, resulting from modified rainfall intensities and duration. • Longer dry periods, resulting from altered temporal distribution of rainfall. • Depleted soil moisture, arising from higher evaporative demand. • Soil erosion, resulting from modified rainfall intensities and duration. • Reduced soil quality (including water-holding capacity and nutrient status), resulting from modified rainfall and temperature.	• Decreased productivity – more frequent crop failures and reduction in yields.
Natural wetlands	• Reduced rainfall and runoff inputs, resulting in wetland desiccation. • Higher flood peaks, resulting in wetland expansion and flooding of fields and homes. • Improved habitat for disease vectors (e.g., mosquitoes).	• Increased failure to provide water requirements of the community and households. • Loss of water-dependent ecosystem services (including flow regulation and groundwater recharge). • Increased risk of waterborne diseases (e.g., malaria).

Note: * It is important to note that these risks will not be universal. In some places, CC will cause the reverse impact and may have positive rather than negative social and economic implications.

3.3. Land cover change

The vegetation cover of watersheds can be reduced or entirely lost because of deforestation, and disturbances to the vegetation composition. Various driving forces cause land cover change. These driving forces include:

- Demographic (the size and composition of population and households) shifts will shape economic developments and hence affect land cover.
- Economic factors that affect land cover include market forces (actors with ability to affect change in a market), trade policy and agreements, irrigation expansion, and growth in income.
- Institutional/policy factors: Land cover changes can be driven by international conventions (e.g. climate change), political and economic power, political stability, land use policy, and land tenure policy. Mitigation or adaptation strategies can also affect land cover.
- Technological developments: expansion of croplands at the expense of reduction in other land cover classes can be caused by technological developments.
- Bio-physical factors: Climate variability (inter-annual and intra-annual) and reduction of soil fertility affect land cover. Warmer and wetter future conditions are expected to drive vegetation, soil, and hydrological changes. Decline in rainfall amount or increased rainfall intensity can alter the vegetation cover.

The global land surface has been continuously altered by humans over thousands of years who are replacing natural vegetation with crop land and pasture. Land cover change impacts the hydrology of watersheds either directly (e.g. altered runoff) or indirectly (i.e. through feedback mechanisms with local climate). "A feedback mechanism is a loop system wherein the system responds to a perturbation".

Land and atmosphere interact through exchange of mass and energy. Thus, any changes or disturbances in the land surface have the potential to affect this interaction.

Figure 45 shows the effects of deforestation on exchange of flux (rainfall and evapotranspiration) between the land surface and the atmosphere.

"Much of the rainfall over tropical forests comes from water vapour that is carried by the atmosphere from elsewhere. But a large component is 'recycled' rain — water that is pumped by trees from the soil into the atmosphere through a process called evapotranspiration. Water exits from forests either as run-off into streams and rivers, or as evapotranspirated vapour that is carried away by the atmosphere (through winds). The atmospheric transport of water vapour into the forest is balanced by the exit of water in the form of vapour and run-off. Deforestation reduces evapotranspiration and so inhibits water recycling. This decreases the amount of moisture carried away by the atmosphere, reducing rainfall in downwind regions to which the moisture is transported. Decreasing evapotranspiration may also increase localized run-off and raise river levels." *Luiz* E. O. C.*Aragão(2012)*

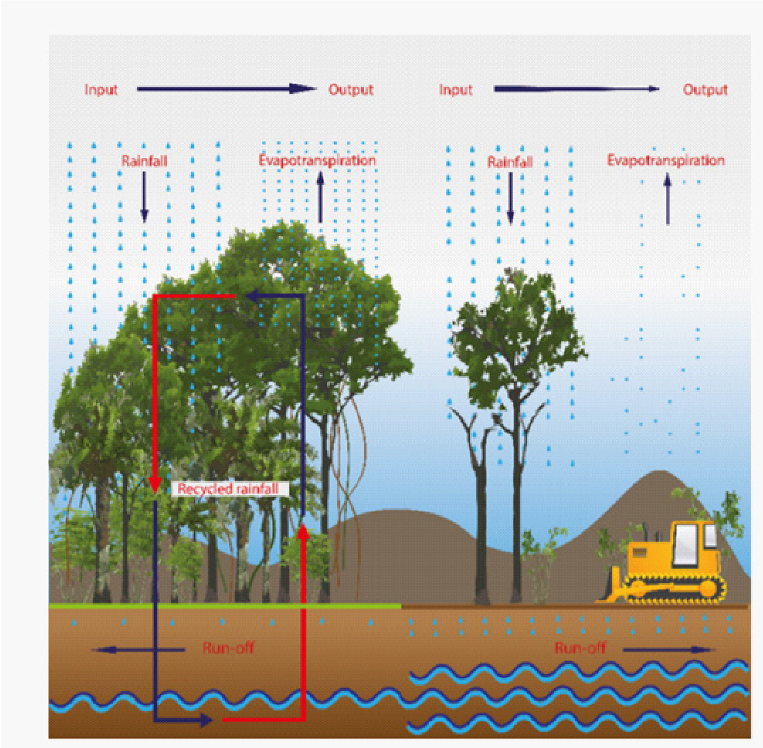


Figure 45 *Effect of deforestation on rainfall in the tropics.*

Sources: https://doi.org/10.1016/j.ancene.2015.12.001 *and* http://dx.doi.org/10.1038/nature11485

Land cover change can affect catchment hydrology by changing the evaporation-to-runoff ratio. In the long term (e.g. decades), the water balance of a watershed can be written as follows:

$$\Delta S = P - ET - Q \tag{19}$$

where: Q refers to discharge, ET represents the combined evaporation and transpiration in a watershed and P is precipitation. Here, ΔS represents change in watershed storage, which can be assumed negligible for large basins over the long-term, i.e., >10 years. Thus, the long-term water balance equation can be written as follows:

$$Q = P - ET \tag{20}$$

Land cover changes (e.g. expansion of cultivated land by clear cutting of forests) cause a change in ET since it will change surface albedo, which is the fraction of incident solar radiation reflected by a surface and hence determines the energy available for evapotranspiration. Forests generally have lower albedo whereas bare lands have higher albedo (Figure 46). As a result, the reflected solar energy is lower for forests than bare lands. Thus, deforestation will increase the reflected solar energy and reduce the energy available to warm the atmosphere, ground surface and to cause evapotranspiration.

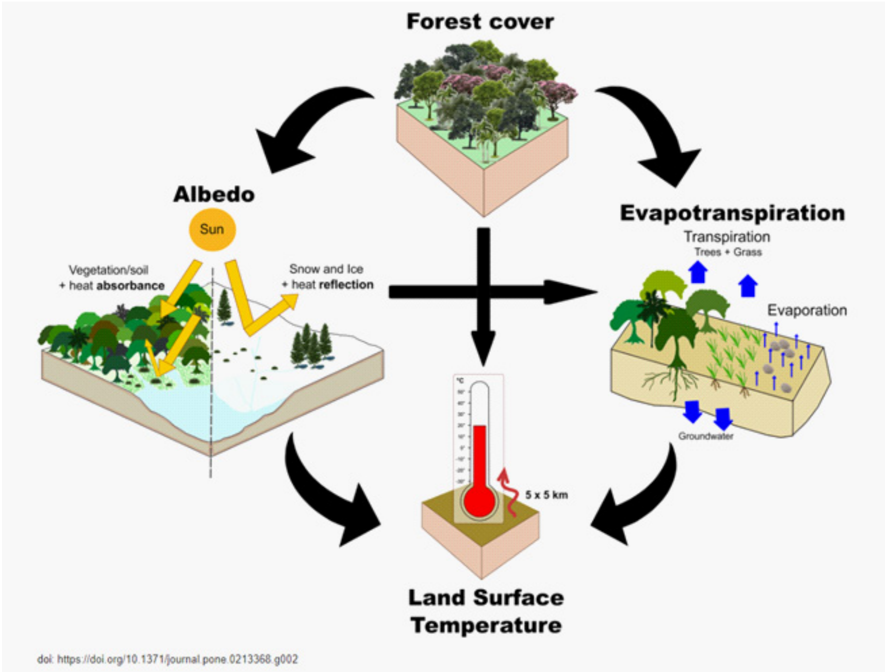


Figure 46 *Presumed relationships between forest cover and climatic variables (albedo and evapotranspiration). doi: https://doi.org/10.1371/journal.pone.0213368.g002.*

Figure 47 shows the crop coefficient, which is the ratio of actual and reference evapotranspiration, as a function of crop growth stage. Large values of the crop coefficient indicate high evapotranspiration rates. The crop coefficient curve clearly indicates that the evapotranspiration is low at the initial growing stage of a crop, it increases linearly during the development stage, peaks during the mid-season and then declines during the late season of the crop. The soil is not well covered by vegetation during the initial stage and hence there is only evaporation from the soil surface whereas transpiration from the crop is small. The soil is well covered by vegetation during the mid-development stage of the crop and hence evapotranspiration is high. This shows that the rate of evapotranspiration is determined by vegetation cover. It also suggests that evapotranspiration is reduced through reduction of transpiration and interception as natural vegetation is replaced by crops and pasture (grazing land).

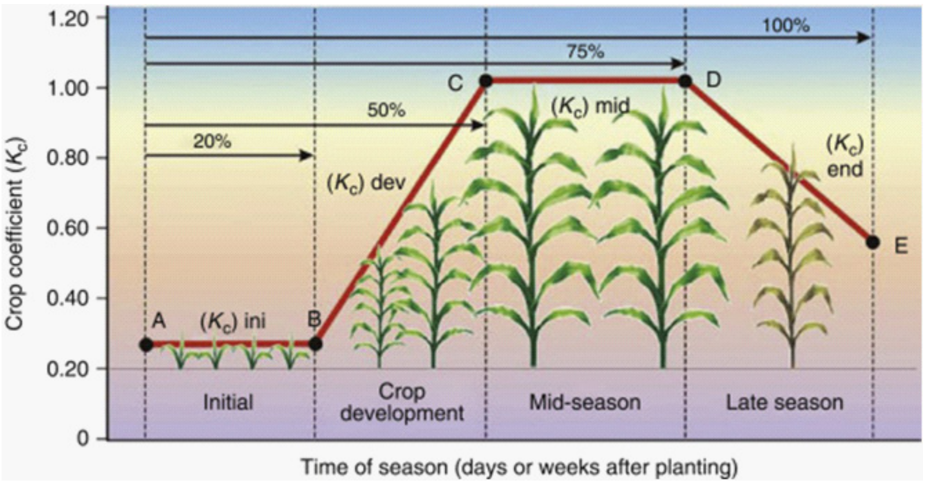


Figure 47 *Temporal variation of crop coefficient (ratio of actual to potential evapotranspiration).*

"Interception is the fast evaporation mechanism that dries moist land cover during and directly after the rain". It can be estimated as the net sum of three variables (i.e. "Rainfall – surface runoff – infiltration") during and immediately after a rainfall event.

Interception is an important process that affects runoff generation in a catchment. The amount of interception loss can even reach up to 50% in some forested catchments. It varies with (i) terrain characteristics, (ii)) amount of rainfall, (iii) intensity of rainfall, (iv) the type of land cover, and (iv) climate of the area. The magnitude of interception depends on the type and density of vegetation cover. Hence, any vegetation cover change affects the magnitude of interception and consequently the rate and magnitude of runoff from a watershed.

3.4. Changes in soil properties

In soils, sand, silt, and clay are assembled to appear as larger particles called aggregates. The way these particles are assembled is referred to as soil structure. Water storage and hydraulic conductivity of the soil is controlled by the soil structure.

Properties of soils can change due to intensification of human pressure on natural resources to produce fibers and food, including (i) intensive agriculture without proper management practices and increased cultivation of steep slopes, and (ii) overstocking of livestock.Reduction or loss of vegetation cover can expose the soil to high rainfall intensities; compacted or crusted surfaces strongly diminish rainfall infiltration and greatly enhances surface runoff volumes; changes in the organic matter content can greatly affect soil moisture, infiltration, groundwater recharge, and runoff processes, affecting the vegetation-soil balance of landscapes.

Soil compaction

Soil compaction is commonly caused by animal grazing and by farm machinery. Compaction replaces the pore space of unsaturated soil, which was previously occupied by air and water, with small soil particles. It causes reduction of the volume of large pores, alters pore shape and pore size distribution, and increases bulk density (the dry weight of soil divided by its volume).

Soil compaction reduces the porosity of soils leading to decreased infiltration (the flow of water from aboveground into the sub-surface), hydraulic conductivity (how easily water can pass through pore spaces and fractures into the sub-surface) and water storage. It also causes the development of a thin impermeable layer, reducing plant root penetration, preventing water movement.

For compacted soils, water moves laterally above the zone of compaction over the soil surface or beneath it. As a result, rainfall is immediately converted to either surface runoff or sub-surface lateral flow instead of infiltrating into the compacted soils, causing reduction in recharge and thus a steady decline in groundwater levels. Other effect of compaction on the hydrological cycle is reducing vegetation cover and hence reducing interception and evaporation.

Land use effects

Vegetation cover has high influence on soil hydrological properties. Changes in vegetation cover for instance in the form of deforestation will affect soil hydrological properties and thus alter rainfall-runoff relationships in a catchment. Thus, temporal changes of land cover can provide early warning to the potential deterioration of soil hydrological properties.

Surface roughness is high when the landscape is covered by vegetation, especially forest. It takes long time for runoff to be initiated over rough landscapes. Runoff is also slowed down by vegetation cover resulting in small peak flows. Increased surface roughness increases the opportunity time for infiltration resulting in reduced runoff volume but increased soil moisture storage and recharge to the groundwater. Hence, partial or complete loss of vegetation cover causes accelerated runoff generation, reduced infiltration and reduced recharge to the groundwater. For instance, conversion of forest to bare land reduces water retention, allowing accelerated runoff and soil erosion.

Infiltration is also affected by the distribution of plant roots. In forested areas, macro-pores (large openings in the sub-surface soil) can be formed by decay of tree roots which may create preferential flow paths for water through these macro-pores. Trees also improve the soil structure by increasing organic inputs to the soil. Overall, there is a "trade-off" between the higher water use of forests and their role in improved infiltration opportunities.

On soils without vegetation cover, a soil crust, which is a thin layer of re-arranged soil particles, will form. The soil crusts are characterized by high density, low porosity and low infiltration capacity. Also, soil acidification disaggregates soil structure and hence reduces macro-pores.

With respect to soil erosion, vegetation cover reduces soil detachment by dissipating the kinetic energy of raindrops, traps fine particles reducing their transport via erosion, and increases formation of soil aggregates by keeping the soil moisture high. Organic matter (decomposed plants) binds soil particles together (forming aggregates) that will reduce soil erosion.

Figure 48shows impacts of vegetation loss on runoff of a catchment that can be described as follows:

- "Flashy" response to intense rainfall events
  - Short lag time to flood peak (delays in peak flow response and rainfall event).
  - High flood peaks due to rapid surface runoff.
  - Increased risk of flood damage during wet periods.
- Reduced flow during low-flow periods due to reduced groundwater input (recharge)
  - Reduced surface water availability during dry periods

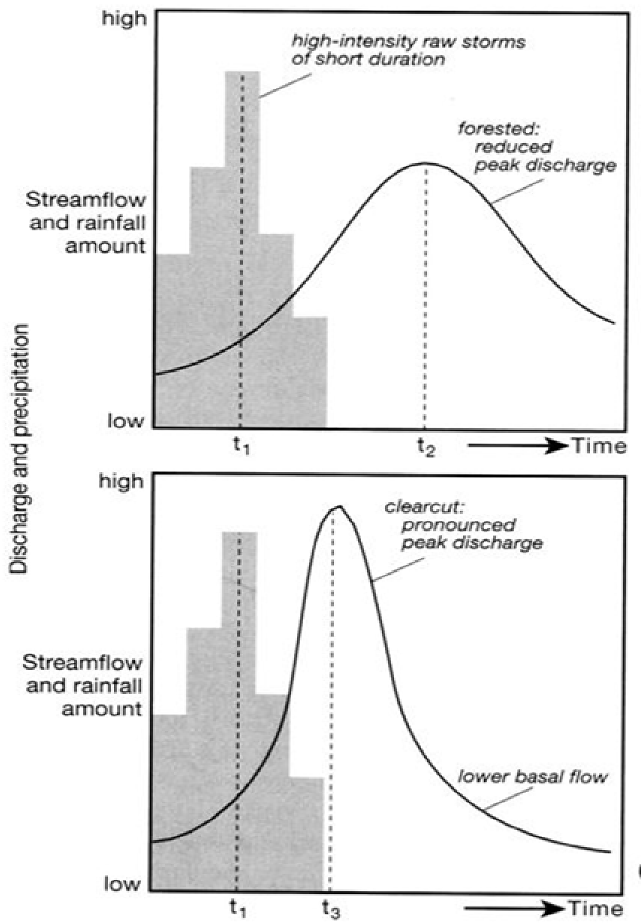


Figure 48 *Impact of vegetation loss on hydrograph of a runoff event.*

Environmental effects

Environmental and climate factors can alter soil hydrological properties. Intense rainfall disaggregates surface soil structure over deforested land. This causes reduced infiltration. Capillary rise affects soil structure through aggregation when drying and disaggregation upon wetting. Erosion also alters soil properties in turn altering water storage and hydraulic conductivity. It also removes fine soil particles and litter which reduces organic matter and nutrient concentration in the soil, which limits plant growth.

Management practices

Management practices alter the soil surface properties and the soil structure. This in turn alters the relationships between the solid, liquid and gaseous phases of soil. No-tillage practice for an extended period of time can conserve the soil structure. However, tillage increases the number of large pores and hence modifies soil structure. The negative effect of tillage includes that it may disrupt pore-network connectivity.

Crop rotation modifies soil structure since it changes vegetation cover and root depth and distribution. Changes in roots alter soil properties as a result of changes in organic matter, micro-biological decomposition, temporal pore clogging, development of macro-pores, local compaction, enhanced wetting-drying, and hydrophobicity of rooted pore holes. Root growth and decomposition increase the capacity and rate of soils to infiltrate rainfall and reduce overland flow.

Soil structure can be modified by removing livestock to reduce compaction. It then enhances infiltration and evaporation while reducing surface flow volumes. A rule of thumb is that light grazing reduces infiltration by a factor of 0.25 and heavy grazing by a factor of 0.5.

Reforestation is often perceived as an effective way of restoring degraded landscapes. It can positively impact the hydrological cycle and alsorestore soil hydraulic properties.

3.5. Impacts of changes in Ethiopian watersheds

The climate of Ethiopia is characterized by high temperature and rainfall variability across space and time. The highlands are characterized by low temperatures, while it is warm in the lowlands. There is a clear east-west division of the country by amount of rainfall. The eastern part is known for receiving low rainfall amounts (<500mm per annum) whereas the western part receives large rainfall amounts (up to 2500 mm per annum).

The Central Rift Valley (CRV) lakes sub-basin is characterized by semi-arid to sub-humid climatic condition. It has a temperature that varies within a small range of values annually and seasonally. The mean annual maximum temperatures range from 23.6 to 26.3 and minimum temperatures range from 9.3 to 11.9, with the long-term annual average of 17.5 .The mean annual rainfall over the CRV sub-basin is low and varies from 500 to 1100 mm, with a long-term average of 883 mm. The rainfall of the sub-basin shows a distinct seasonal cycle with a minor peak in May and major peak in July or August with monthly rainfall amount less than 150 mm on average. Most of the rainfall is received during the rainy season from July to September. The potential evapotranspiration (PET) varies between approximately 1300 and 1500 mm per year. Thus, the annual PET is higher than its rainfall counterpart indicating a moisture deficit in the sub-basin at least on an annual time scale.

Box 9 Information on climate variability in Ethiopia

- The climate of Ethiopia shows large variability which is characterized by recurrent floods and droughts. The following are documented impacts of climate variability in Ethiopia:
- Rainfall anomalies in the form of extreme wet (1962–1966, 1979, 1998/99 and 2006/07) and extreme dry (1971–1973, 1984–1986, 1992 and 2002–2004) years in the country substantially affected agriculture and other sectors.
- The 1983/1984 drought had the most devasting impact in terms of costing the life of people (300,000 deaths), affecting 7.8 million people. Its impact was felt most in the north-eastern, central and eastern part of the country. The 2003 drought affected 12.6 million people whereas the 2015/16 drought affected 10 million people.
- The impact of the 2015 El Niño in Ethiopia:
- Worst drought for North and central Ethiopia in decades
- The drought affected nearly 10 million Ethiopians due to an accumulation of pre-El Niño and El Niño related declines in rainfall.
- The water level of CRV lakes (Ziway, Langaon, Abiyata and Shala) significantly declined. Particularly the water level of Lake Ziway required several months to recover. This affected small-scale farmers who produce vegetables for the market using water from Lake Ziway and its tributary rivers.
- The 2020 heavy rainfall affected millions of people across Awash, around Lake Tana, Lake Ziway, Omo River and other basins. Over 500,000 people were affected and around 300,000 were displaced between July and September 2020. Other negative impacts of flooding include loss of life, damages to standing crops and livestock, and deterioration of human and animal health among others.
- Figure 49 shows the strong relationship between the Gross Domestic Product (GDP) and annual rainfall of Ethiopia.

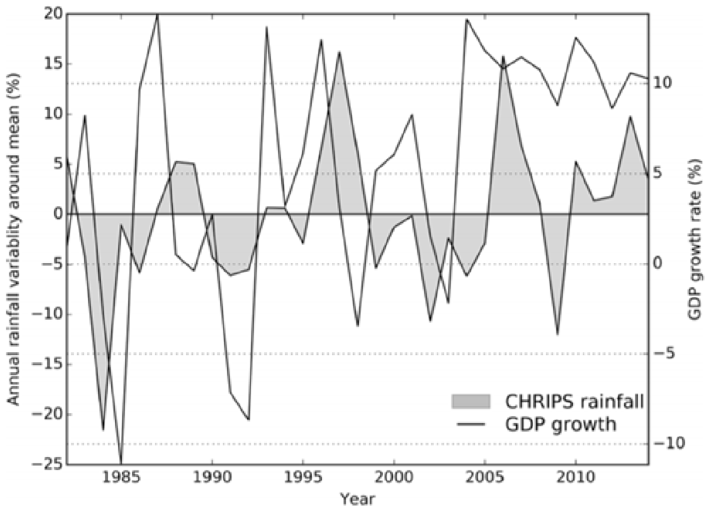


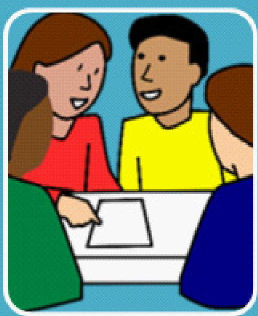
Figure 49 *Ethiopian rainfall and GDP growth rate using CHIRPS rainfall (Funk et al. 2015) data correlation.*

Historical data analysis by various authors showed that the climate of Ethiopia experienced the following changes:

- Mean annual temperature over the country increased by 1.3°C between 1960 and 2006. This show a warming by 0.28°C per decade.
- Annual rainfall is declining in the eastern, southern and southwestern parts of the country since 1982.
- Wet season (June to September) rainfall amount has declined in the eastern, southern, southwestern and central parts of Ethiopia.

The following are reported in the literature regarding historical climate change in CRV:

- Annual rainfall amount did not significantly change over the past three decades whereas the mean temperature increased significantly.
- The length of intermediate dry spells between rainfall events decreased.
- Water storage of Lake Abiyata is showing significant decline mostly due to human activity.



Group Exercise Five

- Discuss the impacts of the 2015 drought and 2020 flood in the CRV sub-basin based on your experience. How did it affect your district? How did people cope with these events?
- Have you witnessed the effect of climate change in your district? What are these changes? How have these changes impacted people? How are people dealing with these impacts?

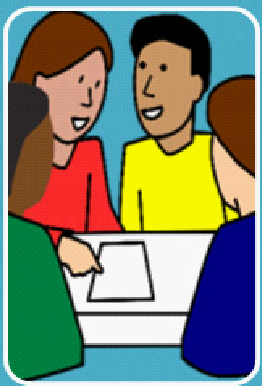
Summary of findings in the literature with regard to impacts of land use and land cover (LULC) change:

- The hydrological impact of LULC changes is mainly due to the associated changes in vegetation interception, soil evaporation, plant transpiration, infiltration and soil water content. LULC change alters the water cycle through direct changes to the timing and magnitude of evapotranspiration (ET). ET also increases with an increase in plantation age and leaf area.
- Forests use more water than shrubs and grasses in general. Thus, removing trees increases streamflow volumes particularly during times of baseflow (dry season flow). On the other hand, reforestation and afforestation lead to major reductions in streamflow, especially baseflow.

- LULC change affects the frequency and magnitude of floods, groundwater recharge, base flow, and low flow conditions. The conversion of farmland to forest affects streamflow variation, while a change of agricultural land to bare land reduces ET and increases overland runoff.

- Factors controlling the magnitude and direction of the effect of land cover change on runoff include the specific land cover change, climate zone, topographic setting, soil properties and catchment size. This explains why some studies were unable to detect any change in hydrological regimes despite a significant change in land cover by deforestation. There could also be time lag between cause (e.g. deforestation) and effect (change in runoff) due to the memory effect of catchments.

- Hydrological impacts become more pronounced when the area over which changes occur increases, but also when changes occur over relatively short time periods such as, for instance, in the case of rapid urban expansion or forest fire.



Group Exercise Six

- Group discussion: Break out into 4 groups and undertake the following tasks:
  - Discuss the driving factors and pressures that caused the following changes occurring in the central rift valley lakes sub-basin
    - In the past, woodland was the dominant land cover in the CRV. However, it decreased from 92.4% in 1973 to 42.4 % in 2013.
    - Agricultural land increased from 1.1% in 1973 to 44.7% in 2013 in the CRV sub-basin
    - In Lake Ziway sub-basin, woodlands declined by 76% while cultivation and agroforestry increased by 45% and 11%, respectively, between 1973 and 2018.
  - Discuss how the above changes in CRV possibly affected the hydrology (water balance, rainfall-runoff relation, lake storage etc.) of the sub basin? What do you suggest to reverse these effects?

Module 4

Evaluating Hydrological Impact of Watershed Interventions

4.1. Overview

One of the main objectives of watershed management is to improve water availability. However, evaluating the hydrological impact of watershed management has not received the attention it deserves. Several factors contribute to this lack of attention but the main factors are (i) data availability, as the national hydrological and meteorological agencies do not prioritize monitoring of small watersheds, (ii) hydrological changes require long-term data to be detected and project-based monitoring is restricted in duration, and (iii) capacity is often missing at local level to assess hydrological impacts. Therefore, the aim in this module is to enhance the understanding of local experts of evaluation of hydrological impacts because of watershed management. First, the impacts of terraces and check dams is presented. This is followed by description of available approaches for evaluating hydrological impacts. Finally, some remarks are presented on the hydrologic impact of watershed management in Ethiopia.

4.2. Impacts of watershed management

4.2.1. Terraces

Terraces are the most common type of structures in watershed management. They consist of a flat section and a vertical or slightly slopping riser. By constructing terraces, humans reconfigure the hillside fields to lower slope gradients and shorten slope lengths. There are several types of terraces which sometimes creates confusion. The terraces are named based on the inclination of the bed (e.g. level or gradedterraces), shape (e.g. semi-circle terraces), or in local language (e.g. Fanyajuu terraces – Swahili term describing the way soil is 'thrown upwards' to build the bund). Figure 50 demonstrates some of the common terrace types.

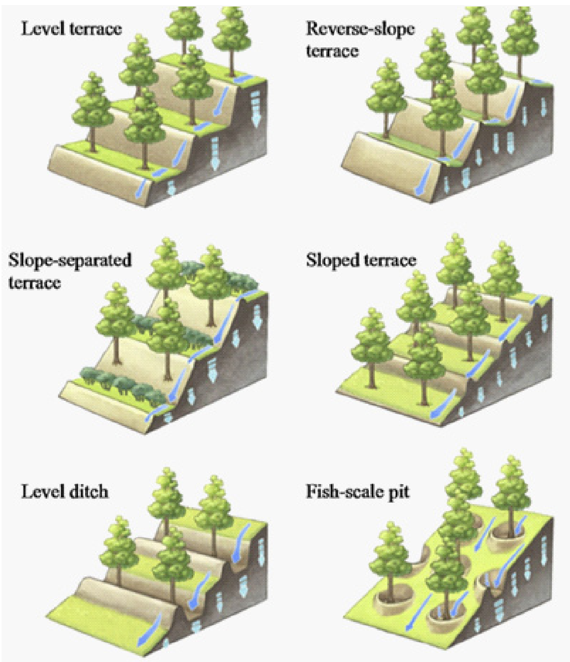


***Figure 50** Terracing types based on differences in physical structures (Chen et al., 2020).*

Terraces affect hydrological processes over the hillslope by changing the distribution of rainfall, evapotranspiration and altering flow connectivity downslope. They trap the rainfall and increase the opportunity time for most of the rainfall to infiltrate into the soil which increases the soil moisture. This has multiple benefits including enhancing soil moisture and nutrient uptake of crops, drought resistance, recharge, and restoration of degraded landscape and regeneration of indigenous trees.

Terraces change the hydrological behaviour of a watershed. The platforms of terraces enhance local storage of rainfall (increase soil moisture) and reduce the runoff velocity to increase infiltration. The terrace ridges (if ridges are included in the construction) prevent surface runoff from flowing downhill to the lower platforms. Ridges are often included when the rainfall intensity is very high. They also reduce sediment generation. When terraces are constructed in semi-arid areas, evapotranspiration significantly affects the amount of rainfall which is converted to soil moisture and runoff.

Untreated steep hillslopes often generate rapid runoff making surface overland flow to be the dominant runoff component. However, a rapidly responding watershed will respond slowly after construction of terraces. This can enhance moisture exchange between the root zone and shallow groundwater zone, that leads to increased contribution of sub-surface or saturated excess overland flow. Particularly, sub-surface runoff can be generated in external parts of terraces or when the infiltrated water reaches the original soil or an impermeable layer.

Terraces cause reduction in hydraulic connectivity that affects the contributing areas and peak flows. Well maintained terraces can stay long and as a result can reduce the magnitude and frequency of floods.

The common hydrological problems for terraces include:

- Crust formation can reduce infiltration, promote runoff and lead to increased sediment transport. Crusts can be formed when terraces are constructed on marls (A sedimentary rock containing a mix of clay and calcium carbonate) in a semi-arid environment and when terraces are abandoned,
- Once soil piping has started, it will develop quickly due to the high slope gradient that can lead to terrace collapse. This can even lead to formation of gullies,
- Collapse of terraces by plant root penetration of the gaps between stones,
- Deterioration of drainage networks due to lack of maintenance affects the performance of terraces,
- Ineffectiveness of terraces to serve their intended purpose deteriorates with the age of their abandonment.

Sharing of Expereinces

- Share your experience on (i) major problems, and (ii) factors that affect the hydrological impact of terraces in your district, with specific examples.
- Please share your experience with Check Dams – success and failures in generating the intended hydrological impact.

4.2.2. Gully treatment

A check dam is the most common conservation structure used to control gully erosion. The structure is commonly constructed across the existing gully drainage to serve as a barrier for controlling soil and water losses and enhancing sediment accumulation. Construction of check dams consumes only limited land since it is constructed across the existing gully drainage. This also reduces construction costs for instance to construct trenches. Locally available materials are commonly used as construction materials (e.g. wood, stone, concrete blocks).

Several factors affect the success of check dams in serving the intended purpose. They are effective when implemented on shallow and young (active) gullies. Tall and wide check dams may easily collapse and significantly reduce surface runoff to downstream areas when over-dimensioned (large structure). Inadequate dimension can (i) lead to failure of check dams by floods, debris flow and impacts of boulders, and (ii) inadequate moisture conservation for vegetation growth. Success of these structures can also depend on the level of conservation measures implemented in the upstream/catchment area. Hence, check dams can be successful when combined with introduction of watershed interventions (e.g. terraces, infiltration ditches, diverting runoff upstream of the gully to adjacent area such as exclosures or to save protected waterways). Gully rehabilitation can also be successful when integrated measures (e.g. gully shaping, gully head treatment, plantation, and gully bed treatment) are combined.

Check dams have proved effective in semi-arid areas, and in active gullies in upper parts of watersheds where subsurface flow is limited and with deep groundwater tables. However, check dams can be ineffective in humid and Vertisol areas where subsurface flow can lead to soil piping in the gully side walls. In presence of piping, gullies can be rehabilitated using gully head treatment or subsurface geomembrane dams.

The construction of check dam across gullies results in the following hydrological impacts:

- Enhances sediment deposition in the gully bed.
- Control Debris flow.
- Delays runoff initiation and time to peak runoff, and reduction of runoff volume due to increased hydraulic roughness and water transmission losses.
- Elevates groundwater level to the ground surface due to enhanced recharge.

- Can reduce salinity in groundwater.
- Favours vegetation growth.

4.3. Methods to quantify hydrological impacts

Here, two conceptual model approaches and one empirical approach are introduced. These approaches are being commonly used in the literature to evaluate the hydrological impacts of watershed management practices.

4.3.1. Modelling

Here, we present hydrological models that have received a wide range of applications for evaluating the hydrological impact of watershed management practices. These models are SWAT (Soil and Water Assessment Tool), Parameter Efficient Distributed (PED) model, and empirical models.

a) SWAT (Soil and Water Assessment Tool)

SWAT is a process-based model (Arnold et al., 1998; Arnold and Fohrer, 2005) that uses the following water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t}(P_i - Q_{sup,i} - Q_{lat,i} - ET_i - Q_{sub,i}) \quad (21)$$

where: SW_t is the water content of the soil on day t (mm), SW_o is the initial soil water content on day i =1 (mm), P_i is the precipitation on day i (mm), $Q_{sup,i}$ is the surface runoff on day i (mm), $Q_{lat,i}$ is the lateral flow on day i (mm), ET_i is the evapotranspiration on day i (mm), $Q_{subx,i}$ is the groundwater flow on day i (mm) and t is the time (days). Several empirical equations are also used to simulate hydrological processes in SWAT. For instance, it commonly uses the SCS-CN method for surface runoff estimation.

SWAT simulates sediment yield using the Modified Universal Soil Loss Equation (MUSLE) that reads as follows:

$$Q_s = 11.8\left(Q_r \cdot q_{peak} \cdot A_{HRU}\right)^{0.56} \cdot K \cdot C \cdot P \cdot LS \cdot CFRG \quad (22)$$

where: Q_s is sediment yield (ton/day), Q_r is volume of runoff (in m^3/ha), q_p is peak runoff rate (in $m^3 s^{-1}$) and *K, C, P,* and *LS* are soil erodibility, cover and management factor, support practice factor and topographic factor, respectively.

In SWAT, the watershed is first divided into sub-watersheds and then sediment and runoff are routed following the river network. The sub-watersheds are further divided into small modelling elements called hydrological response units (HRU) based on terrain slope, land use and soil properties. Each HRU is assumed to have unique hydrological properties and thus runoff and sediment are simulated for each HRU.

Input data for SWAT modelling include land use and management, soil physical characteristics (soil depth, texture of each soil layer and available water capacity), digital elevation model, and climate data. The model can be calibrated for the pre-intervention period using available time series climate and streamflow data.

The SWAT model can be downloaded from https://swat.tamu.edu/software/arcswat/

Box 10 Representation of soil and water conservation measures in SWAT

- The effect of conservation measures can be evaluated in the model by changing the value of Curve Number (CN) for the HRUs that are intervened. Low CN values represent reduction of surface runoff due to increased infiltration whereas high CN values represent increased surface runoff. The CN values for a combination of slope, soil and land use (cover) types can be estimated (i) using paired rainfall and runoff data from experimental plots or watersheds, and (ii) published reports or papers for other watersheds.
- Contour ridges can be modelled as a pothole that is a depression without an outlet. Runoff that is generated within these areas flows to the lowest portion of the pothole rather than contributing to flow in the main channel, i.e. it infiltrates and does not flow out of the HRU (Abouabdillah et al., 2014). The contour ridges are described in SWAT by their physical characteristics that include the height, distance between contours ridges, and slope.
- The effect of conservation measures on sediment yield can be represented in the model by adjusting the parameters of support practices (P factor) to prevent soil erosion by reducing the rate of water runoff; slope length (SL), and HRU slope steepness (HRU_SLP) in the treated HRU. The parameter SLE_P values can be adjusted to capture changes in sediment yield trap efficiencies because of introducing conservation measures

b) PED (Parameter Efficient Distributed model) model

The Parameter Efficient Distributed (PED) model was first developed by Collick et al (2009). Then, it was modified and applied to the Upper Blue Nile (Abay) basin by Steenhuis et al. (2009). Recently, Geoff et al. (2020) further refined the model and called their revised model the Land Resource Management (LRM) model. The discussion in this section is based on the LRM model features.

LRM is a water balance approach that computes the balance in water input and output of the modelling elements. For small watersheds, the accuracy of the model simulations increases as long-time intervals are used for the simulation (e.g. longer than 5 days).

In LRM, a semi-distributed modelling approach is followed in which the landscape is partitioned into three parts that are termed as zones or modelling units (Figure 51). Water balance equations are solved for each zone. In each zone, runoff is generated when storage exceeds the specified threshold. The three zones are:

- Zone 1 (Downslope valley floor) – covers areas close to the river channel with relatively flat terrain. The soil of this zone becomes saturated at the start of the rainy season. Hence, all the rainfall is converted to overland flow based on saturation excess runoff generation mechanism. Zone 1 of some watersheds loses water through sub-surface flow laterally or vertically from the groundwater storage.
- Zone 2 (Hillslope) – represents the high infiltration hillslope areas where rainfall can percolate to the groundwater store. This zone generates both surface overland flow and subsurface flow. Groundwater flow is allowed from zone 2 to zone 3.

- Zone 3 (Degraded upland) – covers that part of the hillslope that is degraded. Zone 3 is characterized by an exposed hardpan or bedrock, shallow soil depth and has low infiltration capacity. It is assumed that the groundwater storage of this zone does not contribute to sub-surface runoff. Thus, Zone 3 generates only overland (surface) flow that is immediately generated when the rainfall rate exceeds the low infiltration rate of this zone.

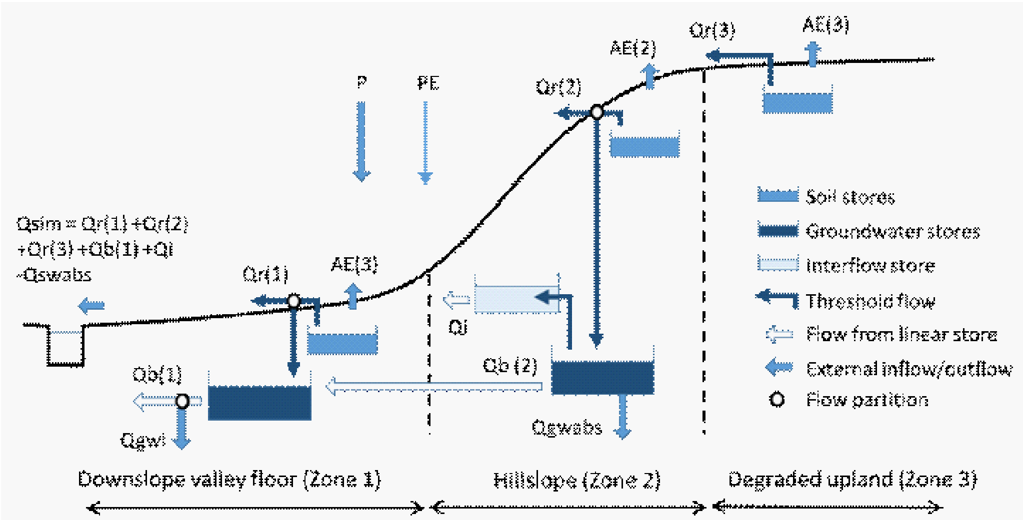


***Figure 51** Schematic of The LRM model (Geoff et al., 2020).*

The input data for the LRM model are rainfall, potential evapotranspiration, stream flow, and surface area covered by each of the zones. Field surveys and remote sensing images are the common data sources for estimating the area for the zones. Table 8 shows the model parameters. It has 12 parameters in total, of which 3 (partial areas) are fixed by spatial mapping. Initial values of the remaining 9 parameters can be estimated by systematic hydrological data analysis or by model calibration when observed streamflow data is obtained.

***Table 8** Parameters of the LRM model (Geoff et al., 2020).*

Parameter	Zones	Symbol	Units
Partial catchment areas	1, 2, 3	A_1, A_2, A_3	%
Maximum soil capacity	1, 2, 3	S_{max1}, S_{max2}, S_{max3}	mm
Maximum groundwater capacity	2	S_{gw2}	mm
Groundwater store half-life	1, 2	$T_{half,gw1}$, $T_{half,gw2}$	days
Interflow store half-life	2	$T_{half,if}$	days
Surface flow partition factor	1 and 2	f_{runoff}	-
Baseflow partition factor	1	f_{bflow}	-

To estimate the effect of watershed interventions using LRM, the model can first be calibrated to streamflow data for the pre-intervention period. Then, the effect of treatment/intervention is represented by decreasing the portion of the degraded zone and increasing the permeable (hillslope) zone considering the intervention spatial extent.

4.3.2. Empirical methods

Empirical methods have found a wide range of applications in hydrology due to their simplicity and require only readily available data, despite the fact that their application is limited by site, climatic and other conditions for which they were developed. The most applied empirical methods for runoff estimation are the Soil Conservation Service Curve Number (SCS-CN) and the rational method. The SCS-CN method is described in this section. Figure 52 shows components of the SCS-CN equation. Part of the rainfall will be lost before runoff occurs. This loss is termed as initial abstraction. After runoff initiation, rainfall is partitioned into runoff and infiltration loss. The infiltration curve shows that the infiltration loss declines as time elapses.

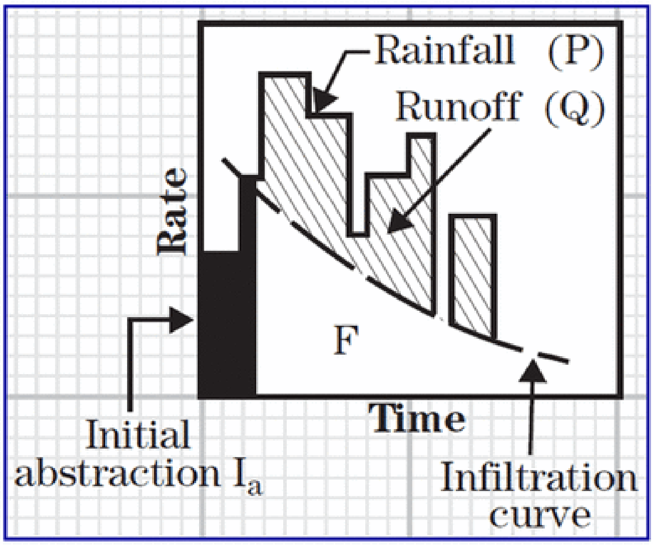


Figure 52 *Components of the SCS-CN equation.*

(Source: http://www.professorpatel.com/curve-number-introduction.html)

The SCS-CN model was developed (SCS, 1985) based on the concept of water balance as follows:

$$P = I_a + F + Q \qquad (23)$$

Equation (23) can be rewritten as follows (the ratio of actual runoff to potential maximum runoff was equal to the ratio of actual retention to potential maximum retention):

$$\frac{Q}{P-I_a} = \frac{F}{S} \qquad (24)$$

where:

P is total rainfall amount of the rainfall event (mm),

- I_a refers to the amount of initial abstraction (mm),
- *F* refers to the actual retention excluding initial abstraction (mm),
- *Q* is direct runoff (mm),
- *S* is the potential maximum retention (mm),

- *S* includes all other losses except for the initial abstractions.Hence, the maximum loss of rainfall is $S + I_a$
- The left-hand side of equation (4) represents the ratio of actual runoff to potential maximum runoff (effective rainfall), and
- The right-hand side of equation (4) represents the ratio of actual retention to potential maximum retention.

Combining equation 23 and 24 results in the following general form of the SCS-CN method:

$$Q = \frac{(P-I_a)^2}{(P-I_a+S)} \quad (25)$$

The SCS-CN model assumes that initial abstraction is related to the maximum retention potential:

$$I_a = \lambda \times S = 0.2 \times S \quad (26)$$

where $\boldsymbol{\lambda}$ is the proportionality constant which is assumed to be 0.2 when the equation was developed for agricultural watersheds in USA.

The potential maximum retention (*S)* is estimated from curve number (*CN*) as follows:

$$S = \frac{25400}{CN} - 254 \quad (27)$$

$$CN = \frac{25400}{S+254} \quad (28)$$

$$Q = \frac{(P-(0.2 \times S))^2}{(P+(0.8 \times S))} \quad (29)$$

where: *CN* is a dimensionless number which relates rainfall and runoff using initial abstraction and potential maximum retention. Its value ranges between 0 (no runoff) to 100 (largest possible runoff). The maximum retention potential (S) for individual rainfall events can be determined from observed precipitation and runoff data using for $\boldsymbol{\lambda}$ = 0.2 as follows:

$$S = 5\left(P + 2Q - \sqrt{4Q^2 + 5PQ}\right) \quad (30)$$

The CN value is then estimated by substituting the value of S, in equation (28). However, streamflow data is not available for most small watersheds. For such conditions, CN is quantified using land use type, surface conditions, hydrologic soil type, and antecedent moisture conditions (AMC). The NEH-4 (SCS. 1985) CN table was developed for λ value 0.2 (initial abstraction = 20% of storage). Note that the CN values are limited to single events of maximum 24 hours duration and are applied to direct runoff estimation.

The value of CN can be determined from CN table based on the following factors:

Soils are classified into 4 hydrologic soil group (HSG), based on their minimum infiltration without any vegetation cover (i.e. bare soil). HSG for a particular watershed can be obtained from soil texture data as shown in Table 9. When soil texture data is not available, global data set provides information of HSG (e.g. https://webmap.ornl.gov/ogc/dataset.jsp?ds_id=1566).

Table 9 Description of hydrologic soil groups (HSG) for CN based runoff modelling.

HSG	Description	Texture class
A	Low runoff potential (>90% sand and <10% clay)	Sand
B	Moderately low runoff potential (50-90% sand and 10-20% clay)	Sandy loam, Loamy sand
C	Moderately high runoff potential (<50% sand and 20-40% clay)	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt
D	High runoff potential (<50% sand and >40% clay)	Clay, Silty clay, Sandy clay

- Cover type – vegetation affects runoff by maintaining the infiltration potential, evaporation of intercepted water, and delayed contribution of the rain to runoff generation. Common cover types include fallow, row crops, small grain, close-seeded or broadcast legumes or rotation meadow (e.g. Alfalfa).

- Treatment – describes how the land is managed or conserved. Conservation structures affect runoff generation by reducing the runoff volume. Example of treatment types include terracing, crop rotations and reduced or no tillage.

- Hydrologic condition – This is based on a combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness. The hydrologic condition is considered "Poor" if the factors impair infiltration and tend to increase runoff, and it is considered "Good" if the factors encourage average and better than average infiltration and tend to decrease runoff.

- Antecedent moisture condition (AMC). In SCS-CN method, CN values of runoff events is assumed to depend on three antecedent moisture conditions (AMC). These three AMC classes are AMC I (dry - the soil moisture content is at wilting point), AMC II (medium) and AMC III (wet - the soil moisture content is at field capacity) conditions.

The estimation of runoff depth for each event is done based on the antecedent moisture condition of respected event. Table 10 shows the NEH-4 table for CN values.

***Table 10** Curve numbers under medium antecedent moisture condition – SR – straight row, C = contoured.*

Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
			Curve numbers for hydrologic soil group			
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

CN FOR ANTECEDENT MOISTURE CONDITION	*CN* FOR ANTECEDENT MOISTURE CONDITION	
II	I	III
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	56	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60
35	18	55
30	15	50
25	12	43
20	9	37
15	6	30
10	4	22
5	2	13

[1]*Average runoff condition, and Ia=0.2S*

[2]*Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.*

[3]*Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.*

When concurrent rainfall and runoff data is available, then it is preferable to quantify CN from the rainfall-runoff data.

Group Exercise Seven

- Estimate the watershed average CN value for dry AMC based on the information provided in Table 11.

Table 11 *Estimate the watershed average CN value for dry AMC based on the information below.*

Texture	Cover description	Treatment	Hydrologic condition	Area (km^2)	CN II	CN I	Watershed CN
Sandy loam	Row crops	Straight row and crop residue in good condition	Factors impair infiltration	7			
Sand	Fallow	Bare land	Factors encourage average and better than average infiltration	3			

Group Exercise Eight

- A rain event resulted in a rainfall depth = 40mm. The watershed is covered by cultivated land (clay loam) = 40%, cultivated land (sandy loam) = 30%, grazing land (clay loam) = 15%, bush land (loam) = 15%. Before intervention, the CN value of the cultivated land (clay loam) = 94%, cultivated land (sandy loam) = 92%, grazing land (clay loam) = 95%, bush land (loam) = 93% for AMC II. The CN value of the bush land decreased to 88% after introducing exclosures with trench. Please estimate direct runoff from the watershed before and after intervention for a rainfall depth = 40 mm over 2 hours event duration.
- Group discussion on how to engage the community and local experts to document and evaluate hydrological impacts of watershed interventions.

4.4. Remarks on the hydrologic impact of watershed management in Ethiopia

Soil and water conservation (SWC) in Ethiopia can be categorized into 3 classes: Farmland management, hillside management and gully rehabilitation (Table 12). Some of the practices are categorized across the three classes (e.g. cut-off drains). There is also another way of categorizing the conservation measures: those implemented in cultivated land, forest land, grasslands and those that are common to all land uses (Mekuria et al. 2020). Which of these SWC practices are common in your woreda?

Farmland management	Hillside management	Gully rehabilitation/stabilization
Soil bund	Hillside terrace	Stone check dam
Stone bund	Diversion ditch	Brushwood check dam
Stone faced soil bund	Stone faced trench	Gabion check dam
Double stone faced soil bund	Micro-basin	Sediment storage dam
Fanya juu terrace	Bench terrace	Live check dam
Tied ridges	Semi-circular terrace	Stone Check dam
Bench terrace	Eyebrow basin	Gully reshaping and planting
Zai pit	Deep trench	Sand/soil filled check dam
Trash line	Terrace and trench	Cut-off drains
Cut-off drains	Cut-off-drains	Diversion ditch
Waterways	Waterways	

***Table 12** Selected SWC practices widely implemented in Ethiopia by category (Source: IWMI working paper 182).*

Documenting photographs of watershed conditions before, during and after watershed management provides an important input to evaluation of hydrological impacts. Figure 53 shows photographs taken in Farawocha kebele of Boloso Bombe woreda (Assefa et al., 2020).

Figure 53 *Restoration of degraded land and its benefit to the local community in terms of enhanced plant growth.*

a. Deep gully observed in 2014 with gabion check dams (Farawocha*kebele*, Buna Gandisa; Photo Courtesy: Boloso Bombe woreda agriculture and rural development office); **b.** Restored gully in 2019 covered by banana and grass; (Photo Courtesy: Boloso Bombe woreda agriculture and rural development office); **c.** Degraded land observed in 2015 (Farawocha*kebele*, Buna Gandisa; Photo Courtesy: Boloso Bombe woreda agriculture and rural development office); **d.** Restored hillside in 2019 covered by forage grass and vegetation; (Photo Courtesy: Aklilu Assefa); **e.** People using re-emerged springs for domestic purposes; (Photo Courtesy: Aklilu Assefa); **f.** Ginger, banana and coffee plantation from farmers' land in Farawocha*kebele* (Photo Courtesy: Aklilu Assefa).

Soil loss from gullies contributes more sediment per unit area than do sheet and rill erosion. Box 12 shows the relative contribution of gully vs. sheet & rill vs. solid waste on sediment sources in Awassa sub-basin.

[1] Comparison in terms of erosion rate:

= Average rate of gully erosion in the sub-basin ≈ 22 ton/ha/yr (*Hoogenboom, 2013*)

= Average rate of sheet + rill erosion in the sub-basin = 7.5 ton/ha/yr

$$= \text{Ratio} = \frac{Gully=22}{Sheet+Rill=7.5} \approx 3\ fold$$

[2] Comparison in terms of volume:

= Volume of sediment erosion due to gully = 68,575 m³/yr. (Derived from *Hoogenboom, 2013*)

= Volume of sediment erosion due to sheet + rill =

= 7.5 ton/ha/yr x 1337 ha of land = 10,028 ton/yr

= 10,028 ton/yr x 1.4 t/m³= 14,039 m³/yr (Assuming bulk density of sediment (*Ghimire et al. 2013*)

$$= \text{Ratio} = \frac{Gully=68{,}575\ m3/yr}{Sheet+Rill=14{,}039\ m3/yr} \approx 5\ fold$$

[3] Solid waster as a contributor to lake sedimentation as compared to gully erosion:

Amount of solid waste lost in the environment in Hawassa City= 55.25 ton/day = 20,166 m³/yr (*RiPPLE, 2014*)

$$= \text{Ratio} = \frac{Gully=68{,}575\ m3/yr}{Solid\ waste=20{,}166\ m3/yr} \approx 3.4\ fold$$

Box 12. *Relative contribution of gully vs. sheet & rill vs. solid waste on sediment sources in Awassa sub-basin (Source: Belete (2019)).*

There is strong need to match the type of the watershed intervention to the local context. Commonly, one single type of intervention is not adequate to bring significant hydrological impact. This is shown in Figure 54 where a combination of mitigation measures is suggested for the Lake Awasa sub-basin.

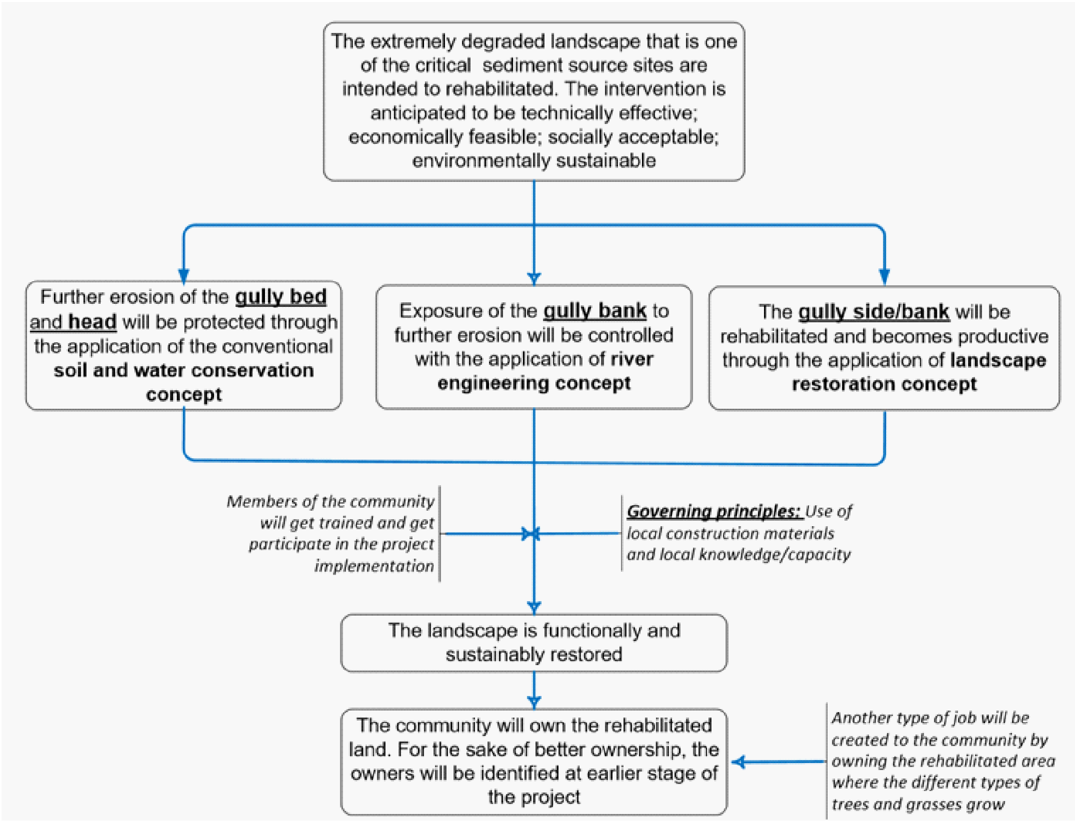
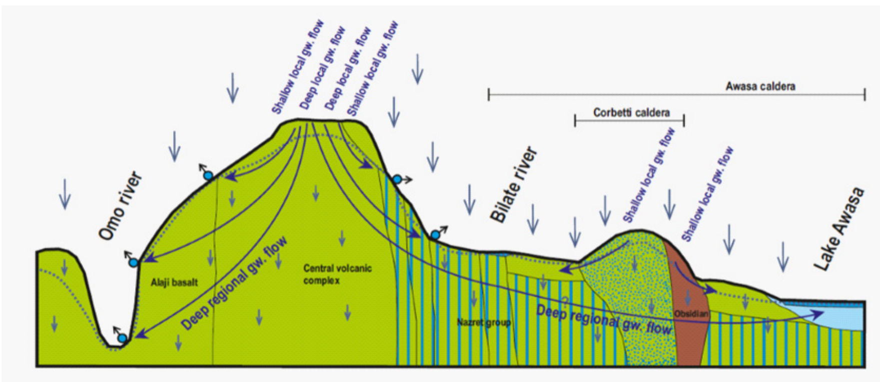


Figure 54 *Pathway of changes of the proposed management system (Belete, 2009).*

Watershed management should recognize that there are local and regional hydrological connections. The management interventions can affect local hydrological processes and interactions but their effect on regional interactions can be negligible or slow. Figure 55 shows groundwater interactions between Lake Hawassasub-basin with neighbouring sub-basins. It indicates that there is local as well as regional groundwater flows that affect the lake and hence both should be considering when studying the hydrology of the sub-basin.



Rift valley – west (Awasa)

Figure 55 *Conceptual model of the groundwater systems surrounding Lake Awassa. (Source: presentation by Jiri Sima).*

Empirical studies have been used in a wide range of applications without calibrating the value of their parameters for the study area. This limitation can be overcome through experimental monitoring of rainfall and runoff that provides valuable information for evaluation of hydrological impacts of watershed interventions. For instance, Berihun et al. (2020) reported curve number values for control and intervened conditions based on watershed characteristics and management practices in Tigray (Table 13).

Table 13 *Curve number (CN2) values for different land uses and management practices in the study watersheds (Tigray) calculated based on the daily data from experimental runoff plots (Source: Berihun et al. (2020)-*

Land use	Slope (%)	Soil texture	Management practices tested	Number of runoff events	Curve number (CN2)					
					Max	Min	Mean	Median	SDV	CN2* (SDV)
Cultivated land	5	Clay loam	Control	163.00	99.97	69.33	84.65	93.84	±6.06	84.65 (±6.06)
			Soil bund	75.00	99.83	46.87	73.35	88.92	±11.06	73.90 (±11.00)
			Fanyu juu	76.00	99.97	48.93	74.45	89.20	±10.82	
			Soil bund with grass	74.00	99.82	47.99	73.91	88.99	±11.10	
Cultivated land	15	Sandy loam	Control	133.00	99.81	64.36	82.09	91.52	±7.44	82.09 (±7.44)
			Soil bund	85.00	99.94	49.26	74.60	88.74	±10.88	74.53 (±11.12)
			Fanyu juu	84.00	99.14	49.46	74.30	87.52	±11.40	
			Soil bund with grass	84.00	99.17	50.17	74.67	87.97	±11.08	
Grazing land	15	Clay loam	Control	157.00	99.97	69.26	84.62	94.43	±5.49	84.62 (±5.49)
			Exclosure	73.00	99.10	61.71	80.41	93.06	±9.03	79.96 (±9.49)
			Exclosure with trench	78.00	99.51	59.52	79.52	91.18	±9.95	
Bush land	35	Loam	Control	162.00	99.81	70.49	85.15	92.63	±6.41	85.15 (±6.41)
			Exclosure	98.00	99.96	46.63	73.29	90.54	±9.42	72.73 (±9.93)
			Exclosure with trench	102.00	99.87	44.48	72.18	88.24	±10.43	

CN*: Curve number value considered in calibration process; SDV: standard deviation.

4. Conclusions

The manual has introduced key hydrological concepts important in watershed management and landscape restoration together with hydrological data collection and interpretation, including citizen science. It canbe used to guide setting-up of hydrological monitoring with community engagement using the citizen science concept and principles. It is expected that extension workers can follow the manual to conduct preliminary evaluation of the impacts of ongoing changes to the climate, land cover and soil. The manual also prepares them to easily communicate and work with high level experts who will apply complex approaches to evaluate the hydrological impact of watershed management.Further, itenables them to design and adapt watershed interventions that are resilient and sustainably enhance the productivity of landscapes in the Central Rift Valley of Ethiopia.

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