MANUAL 4

Hydrological Impacts of Watershed Management

Part of a series of six manuals for Integrated landscape and water management training

SIWI

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Introduction

This manual is the fourth manual out of six that provide basic training on water management in multifunctional and productive landscapes. It is an abbreviated version of a manual developed by the Stockholm International Water Institute (SIWI) and the International Water Management Institute (IWMI) on Hydrological Impacts of Watershed Management that was commissioned by the Sida-funded programme of Strengthening Water and Landscape Governance in Ethiopia, implemented by SIWI from 2018 to 2022.

1. Introduction to key concepts

1.1 Water balance

Guiding questions

Which parameters are required for water budgeting?

What kind of water is included in watershed storage?

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 surfaces, soils, groundwater systems, and the solid Earth. Water evaporates from water bodies (lakes, oceans); the evaporated water undergoes condensation at high altitudes with colder temperatures in the atmosphere leading to formation of clouds (Figure 1).

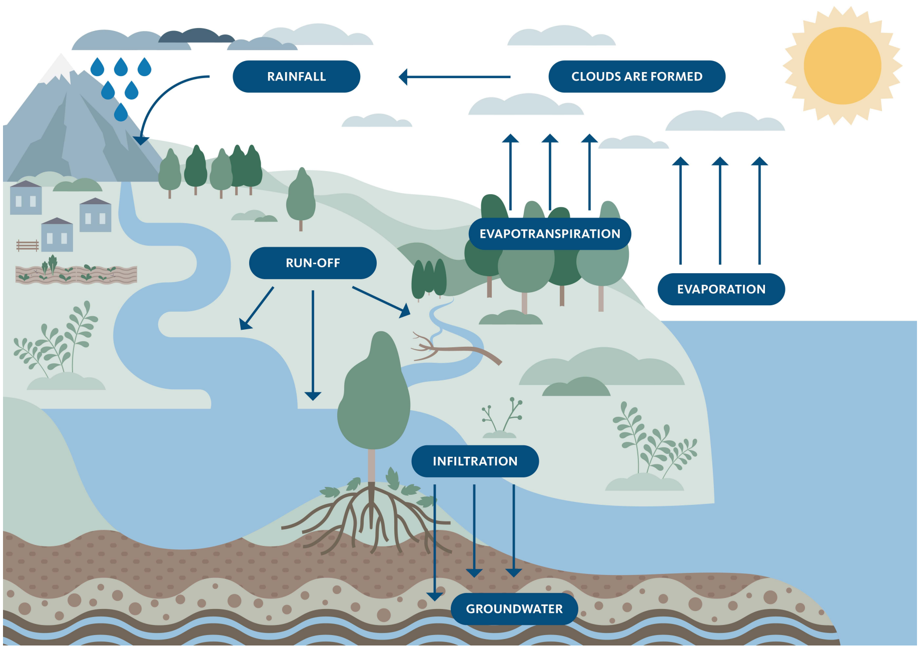

Figure 1. The hydrological cycle and the forest-water nexus.

When the condensed water vapour has enough weight to overcome gravity, precipitation (rainfall and snowfall) will occur over the land surfaces. Some of the precipitation will satisfy the evaporation, transpiration, surface storage and percolation demand., while 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).

Vegetation plays a significant role in maintaining the hydrologic cycle through the transpiration, interception, and retention of moisture. Trees and forests, in particular, 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 1). Forest-related changes in land use, such as deforestation, reforestation and afforestation, can affect both nearby and distant water supplies: for example, a decrease in evapotranspiration following deforestation in one area may reduce rainfall in downwind areas. Climate change and an increase in extreme weather events are disturbing water cycles and threatening the stability of water flows. Meanwhile, water supplies are affected by an increase in human water consumption to meet domestic, agricultural, and industrial needs. Increasing demand for water is reducing freshwater flows and groundwater levels, often with negative effects on biodiversity, ecosystems, and ecosystem services.

1.1.2 Watershed/catchment

A watershed is defined as any surface area from which runoff resulting from rainfall is collected and drained through a common confluence point. Figure 2 shows a simple schematization of a watershed.

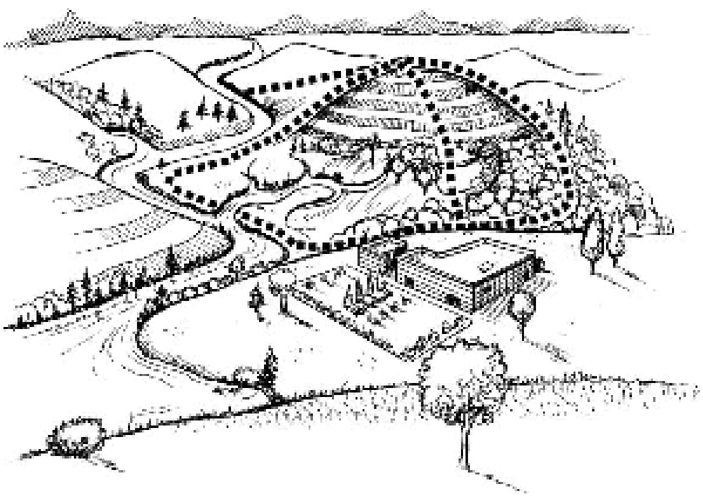

Figure 2. Schematic illustration of watersheds with the broken line representing watershed boundary. Source: ctic.purdue.edu/Know%20Your%20Watershed/What%20is%20a%20Watershed?/

The Food and Agriculture Organization (FAO) Conservation Guide 16 says that: "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.

1.1.3 Watershed storage

In a watershed, water can be stored throughout the land surface, soil matrix and aquifer (Figure 3). Overland surface depressions and vegetation canopies store water for a few minutes up 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.

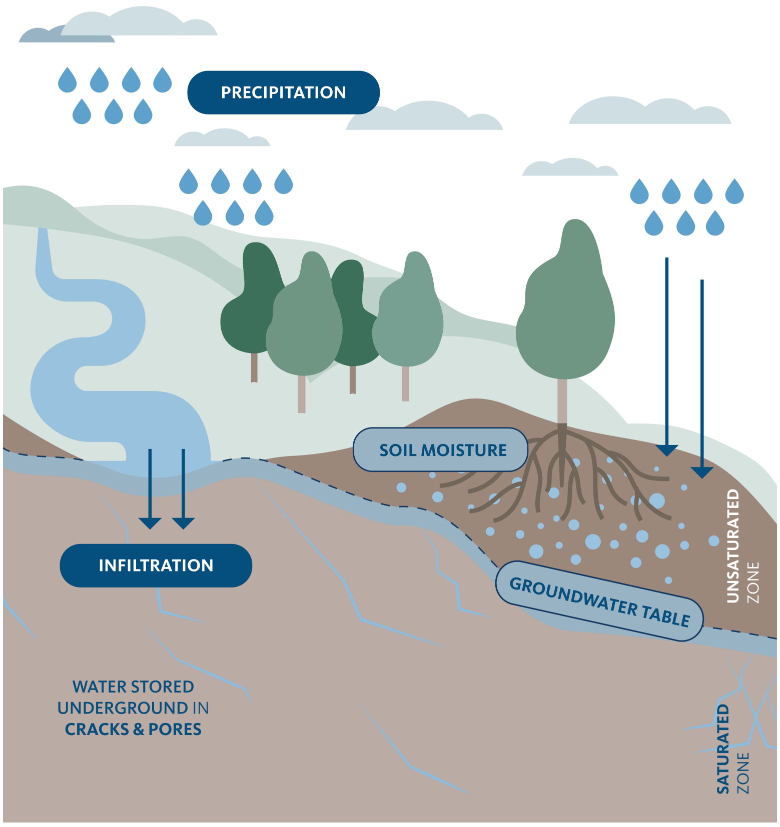

Figure 3. Water storage throughout land surface, soil matrix and aquifers. Source: https://ozarksliving.com

Water is also stored underground in rock cracks or pores. Catchment storage can be affected by the amount of rainfall, such as during storms or droughts. 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, such as intensity and duration. The factors that affect catchment storage at the onset of a rainless period are the history of the catchment, amount of storage relative to the total capacity, and magnitude of recent precipitation.

1.1.4 Water balance equations

For planning and management purposes, the water budget from local scales is important. Hence, water budgets are commonly computed for agricultural fields, watersheds, lakes or reservoirs, river basins, or administrative units (e.g. woreda) and is often an estimation of the 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 1.

Box 1. 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 within 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) or for 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:

$$\Delta S = I - O$$

(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.
For the 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:
$\Delta S = P - E - S - I$

(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:
$\Delta S = I + C - E - T - R - Pe$

(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 4).

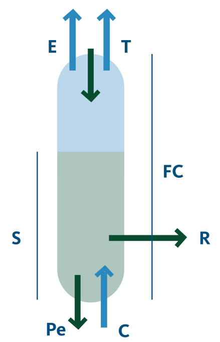

Figure 4. Schematic illustration of the water budget in soils

For the groundwater system (aquifer) with an impermeable bottom layer, the main inputs are Recharge (Re) and Groundwater inflow (GWi), whereas outflows are Capillary rise © and Groundwater outflow (GWo). The equation reads as follows:
$\Delta S = Re + GWi - C - GWo$

(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 5.

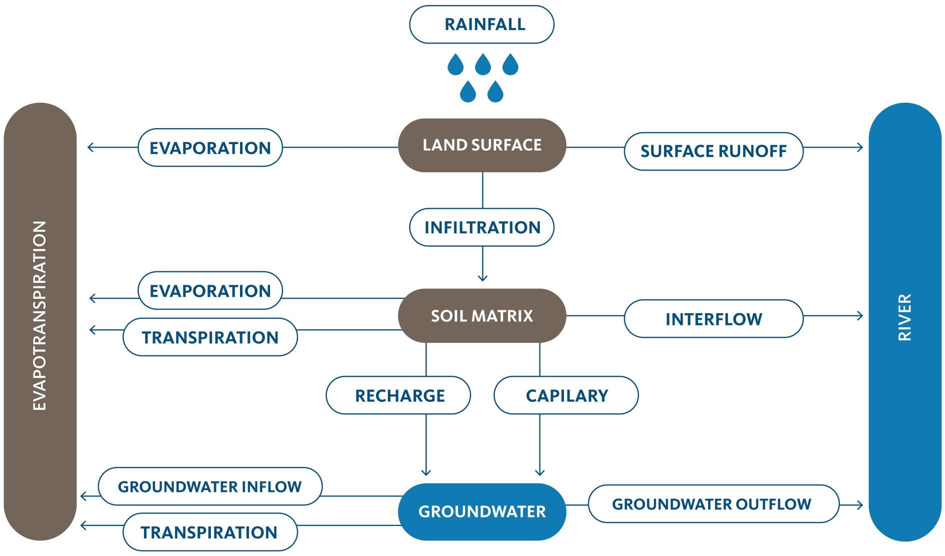

Figure 5. Illustration of water budget components for land surface, soil matrix and groundwater system. Note: recharge is defined here as percolation minus sub-surface lateral flow.

In the long term (e.g. decades), the water balance of a watershed (Figure 11) can be written as follows:
$\Delta S = P - ET - Q$

(5) Where: Q refers to discharge, ET represents the combined evaporation and transpiration in a watershed and P is as defined before, as rainfall. Here, ΔS represents the change in watershed storage.

1.2 Runoff generation mechanism

Guiding questions

Which types of runoff generation are most affected by rainfall intensity?

How does soil moisture affect runoff initiation?

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.

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 up to 70% of the total rainfall amount). Part of the rain is intercepted by the vegetation canopy, however only a tiny fraction of the intercepted rainfall will reach the ground surface because most of the intercepted water is evaporated back into the atmosphere. A small portion of the rainfall amount runs down the branches, trunks and stems as stemflow (Figure 12), making up about 10% or more of the incident rainfall. Since 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.

1.2.2 Runoff generation mechanisms

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

Partial area infiltration excess overland flow: This concept originated from the known notion that the area contributing to infiltration excess runoff may only be a small portion of the watershed. The variations in overland flow velocities, the heterogeneities of soil characteristics, and the infiltration rates are important in controlling partial area responses. Runoff can be generated in one part of the hillslope by utilizing 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: 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 where: there is convergence of flow typically in valley bottom areas, within thin soils where storage capacity is limited, in low permeability and in low slope areas. Return flow occurs when subsurface flow returns to the surface.
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.

1.3 Shallow groundwater

Guiding questions

Why is Shallow Groundwater (SGW) preferred by farmers?

What are the factors affecting SGW availability?

1.3.1 Definition

Hydrological processes also occur beneath the land surface, however these processes are often invisible to us. If we dig a well deep enough, we may encounter an aquifer, or a water-bearing substance that readily transmits water.

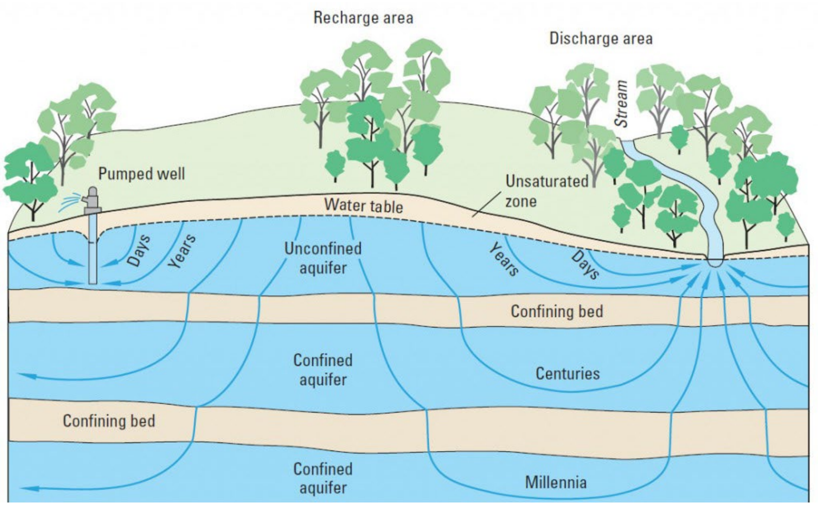

Figure 6. Unconfined and confined aquifers and possible water flow pathways

Aquifers may be hundreds or thousands of square kilometres in lateral extent and may be tens to hundreds of meters thick. As shown in Figure 6, an aquifer can be confined or unconfined. In unconfined aquifers, there is an unsaturated zone above the water table. The unsaturated zone still contains water to be extracted by plants, but also contains air, and hence is not saturated. To both increase water stored in the unsaturated zone, and mediate loss of water through transpiration, trees play an integral role in water facilitation of these areas.

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

Depending on the distance and depth from the stream bed, aquifers will release water to streams within days or up to years once they receive new water. Aquifers can also gain water from streams, however, water exchange between confined aquifers and streams can often take centuries or even longer to occur.

Shallow groundwater (SGW) refers to any aquifer with a depth of 50 to 60m. This definition can be utilized when machinery is 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 less clear. Farmers in Ethiopia cannot easily access water deeper than 20 m due to technological and power (fuel) related constraints, therefore, a working definition of SGW for irrigation in the rural Ethiopia context can be any aquifer with less than 20m depth below the ground level.

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

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 as it offers an individual mode of access and can be readily available on demand. As a result of the individual mode of access, farmers are less involved in conflicts with other users of the resource. SGW also offers flexibility in the timing and amount of water that is applied. 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 the effects of climate variability and change, as it is known to be a reliable source of water in both dry and wet seasons. As a result, SGW irrigation helps farmers to cope with current rain-fed agricultural vulnerabilities, and enhances 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 will fall during the dry season.
- Topographic factors: a higher abundance of SGW is expected in valleys than on hillsides, but exceptions occur. Gentle slope areas provide an opportunity for rainwater to infiltrate and be stored in aquifers.
- Surface geology (up to 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) to store the most water.
- Water bodies: Presence of springs, swamps, or lakes indicate presence of shallow groundwater.
- Plant life: Presence of "water-loving" plants (phreatophytes) such as salt cedar and cottonwood trees indicate presence of SGW.
- Geomorphology: low drainage density facilitates recharge and indicates presence of SGW.

2. Community participation in hydrological data collection

Guiding questions

What characterizes citizen science and how could it support hydrological monitoring?

2.1.1 Definitions

Definition of key terms relevant to this module are provided below. 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): this approach includes 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. A citizen scientist is considered 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: is defined as 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: is defined as an expert with local knowledge, being largely trained on the job in hydrological monitoring and processes.

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 7) are presented below:

Figure 7. Process followed to introduce citizen science in Dangila woreda, Ethiopia

Define purpose: The purpose of a 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 seeks to obtain feedback from local experts about the 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. 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 for this consultation could be to request access to the community, facilitate community engagement, and/or to prioritize watersheds in the district. It is also important to identify any para-hydrologists 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 by discussing the community's perception of the hydrologic cycle. The objective of the citizen science project should be described in the local language and, where possible, the measuring equipment should be demonstrated. This can be followed by an explanation of the criteria for the selection of citizen scientists and for monitoring sites.

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, and 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.

It is mandatory to provide proper training to citizen scientists, as the quality and extent of the training will determine the data quality. The training should be conducted during the installation of instruments, then 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.

3. Land cover change

Guiding questions

What are the relationships between forest cover, albedo and evapotranspiration?

Various driving forces can cause land cover change. These driving forces include factors related to demographics, economics, institutions and policies, technological development, and biophysical factors. The vegetation cover of watersheds can be reduced or entirely lost because of deforestation, or due to disturbances in the vegetation composition.

Land cover change can affect catchment hydrology by changing the evaporation-to-runoff ratio. Land cover changes (e.g. expansion of cultivated land by clear cutting of forests) cause a change in evapotranspiration (ET) changing 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 8). 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.

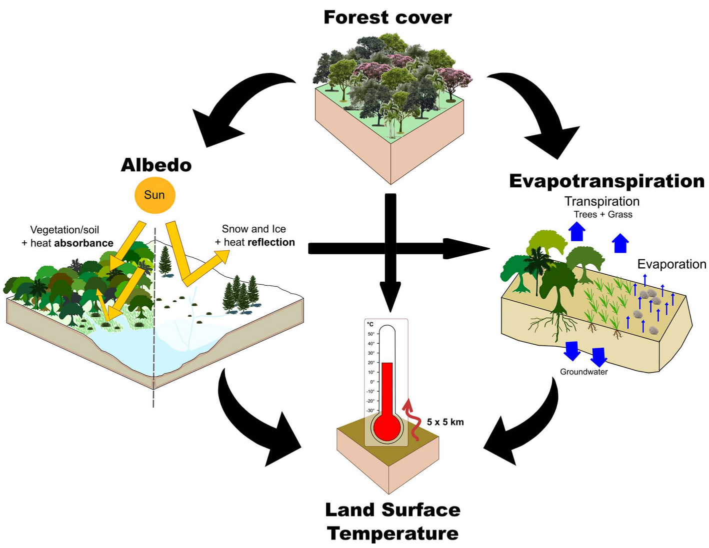

Figure 8. Presumed relationships between forest cover and climatic variables (albedo and evapotranspiration). https://doi. org/10.1371/journal.pone.0213368.g002.

4. Evaluating Hydrological Impact of Watershed Interventions

Guiding questions

What are the different classes of soil and water conservation in Ethiopia and how should they be used?

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 the 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.

Available approaches for evaluating hydrological impacts include hydrological models, such as SWAT (Soil and Water Assessment Tool), Parameter Efficient Distributed (PED) model, and empirical models. These approaches are described in further detail in the longer technical manual that this short version is based on (provide weblink).

Soil and water conservation (SWC) in Ethiopia can be categorized into 3 classes: farmland management, hillside management, and gully rehabilitation (Table 1). Some 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. Which of these SWC practices are common in your woreda?

Table 1. Selected SWC practices widely implemented in Ethiopia by category (Source: IWMI working paper 182).

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	

There is a 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 9 where a combination of mitigation measures is suggested for the Lake Awasa sub-basin.

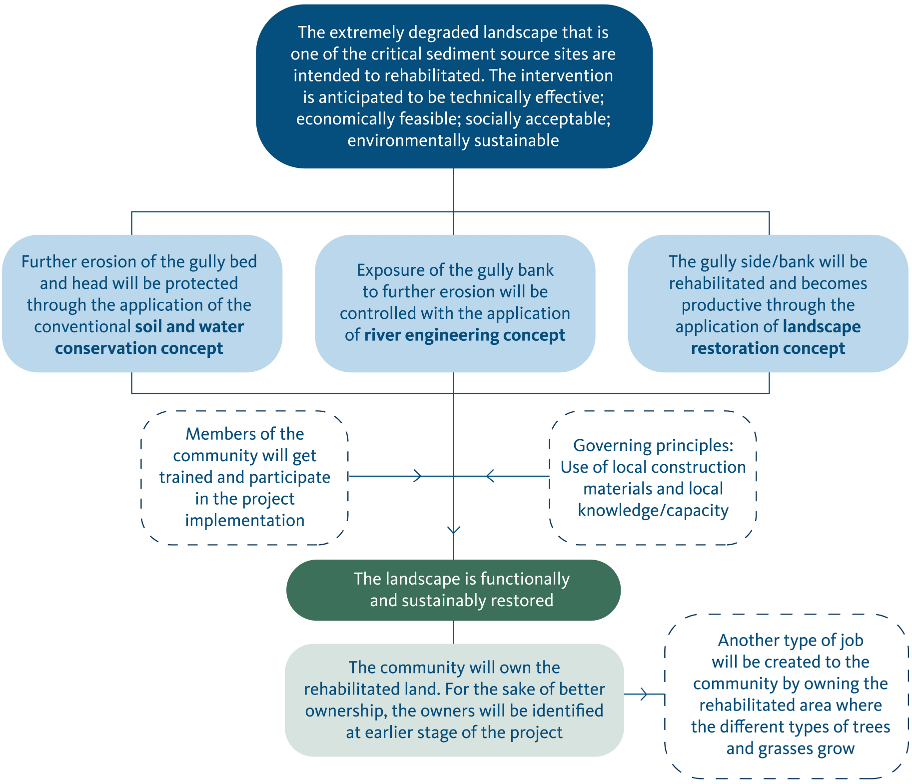

Figure 9. Pathway of changes of the proposed management system for the Lake Awasa sub-basin, Ethiopia (Source: Belete, 2009)

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. 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.

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