CGIAR SUSTAINABLE FARMING

Integrated Water Management Solution

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This training manual was prepared to build the technical capacity of partners from SFP intervention woredas and academic and research institutions on integrated water management solutions.

Contents

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Preamble

Water scarcity, climate variability, land degradation, and increasing competition over water resources are placing growing pressure on rural livelihoods and agroecosystems. In many contexts, particularly in smallholder farming systems, water-related challenges are closely linked to food insecurity, ecosystem degradation, and social inequities. Addressing these challenges requires moving beyond fragmented water interventions toward integrated, climate-resilient, and socially inclusive water management approaches. Integrated Water Resources Management (IWRM) offers a comprehensive framework that recognizes the interconnections between water, land, ecosystems, and people. When combined with practical water harvesting, groundwater recharge, soil moisture conservation, and climate-smart technologies, IWRM can significantly enhance water availability, productivity, and resilience at household, community, and landscape levels. This training is designed to strengthen the technical, analytical, and participatory capacities of practitioners (including Woreda experts, development agents, and academicians) to design and implement integrated water management solutions that are locally appropriate, gender-responsive, and governance-aware.

Key Considerations:

The design and delivery of this training are directed by the following key considerations:

- Systems and Integration Perspective- Water management interventions should be planned and implemented as interconnected systems, integrating surface water, groundwater, soil moisture, and land management rather than stand-alone solutions.
- Climate Variability and Uncertainty- Increasing climate variability, including droughts and erratic rainfall, necessitates water management approaches that are flexible, adaptive, and climate-smart, enhancing resilience at multiple scales.
- Context and local specific and demand-driven Solutions-Integrated water management practices must be tailored to local biophysical, socio-economic, and institutional contexts, with particular attention to smallholder farmers and home gardening systems.
- Productive and multiple water uses- Water interventions should support multiple uses, including domestic, agricultural, and ecosystem services, while balancing efficiency, equity, and sustainability.
- Equity, Gender, and Social Inclusion- Gender roles, power relations, and differential access to water resources must be explicitly considered to ensure fair participation, benefit sharing, and decision-making.
- Governance and Institutional Arrangements- Effective water management depends on enabling policies, local institutions, customary rules, and coordination across sectors and scales.
- Participation and Knowledge Co-Creation-Community engagement, participatory learning, and the integration of local and indigenous knowledge are essential for ownership, adoption, and long-term sustainability.
- Bundled and scalable Interventions-Greater impact can be achieved by bundling complementary water management practices into integrated packages that can be scaled and adapted across similar contexts.
- Sustainability and long-term Impact-Environmental sustainability, operation and maintenance, and capacity strengthening are central to ensuring lasting benefits beyond project lifetimes.

1. Background

1.1. Introduction

The training on “Integrated Water Management Solutions” aims to equip participants with both conceptual understanding and practical skills to improve water management for sustainable agriculture, livelihoods, and ecosystem health. It emphasizes the integration of surface water, groundwater, soil moisture, and climate-smart technologies, with particular attention to home gardening, small-scale farming systems, and community-based interventions. The training combines theoretical concepts with hands-on learning, experience sharing, and participatory approaches. Participants will explore how different water management practices can be bundled into coherent, context-specific solutions that maximize impact under conditions of climate variability and limited resources. Special emphasis is placed on governance, gender equity, and community engagement to ensure that integrated water management interventions are inclusive, scalable, and sustainable. Participants will actively contribute their own experiences through assignments and group work, fostering peer learning and practical application.

1.2. Training objective

The overall objective of the training is to enhance participants' capacity to design, implement, and promote integrated, climate-smart, and inclusive water management solutions that improve water use efficiency, agricultural productivity, and resilience at household and community levels.

Specific Objectives: By the end of the training, participants will be able to:

- Understand and apply the concepts and principles of IWRM in the context of smallholder agriculture and rural livelihoods.
- Identify and design appropriate water harvesting and storage systems, with particular emphasis on supporting home gardening and small-scale productive water use.
- Explain and promote groundwater recharge and shallow well management practices that enhance sustainable groundwater use and water security.
- Assess and apply soil moisture conservation practices, including the effective management and utilization of residual soil moisture for crop production.
- Evaluate and promote climate-smart water technologies that enhance adaptation to climate variability and reduce vulnerability to water-related risks.
- Develop bundled, integrated water management solutions by combining multiple interventions (surface water, groundwater, soil moisture, and technologies) to maximize overall impact, based on local contexts and participant experiences.
- Apply participatory approaches to water management planning and implementation, drawing on community knowledge and stakeholder engagement.
- Integrate governance, gender, and social inclusion considerations into water management interventions to ensure equitable access, decision-making, and sustainability.

1.3. Training components

- Concepts and principles of IWRM
- Water harvesting and storage systems (Particularly to support home gardening)
- Groundwater recharge and shallow well management
- Soil moisture conservation practices (including the management and use of residual soil moisture)
- Climate-smart water technologies
- Bundled (a set of integrated interventions of the above) solutions to maximize the impact of water resource management
- Governance, gender, and community engagement in IWRM

1.4. Training methodology and approach

Provision of theoretical and practical (using case studies) training.

- Lectures and use cases
- Q&A sessions and Discussion
- Experience sharing

2. Integrated Water Resources Management

2.1. Concepts and principles of IWRM

IWRM is a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare equitably without compromising the sustainability of vital ecosystems.

2.1.1. "Integration" in IWRM

Integration necessary but not sufficient; According to the Webster Dictionary the need for integration arises when dealing with the situation of "regular interaction of interdependent groups of items forming a uniform whole". Integration, then, is the "art and science" of blending the right proportions of these items into a whole. However, those involved in water resources management know that integration per se cannot guarantee development of optimal strategies, plans, and management schemes (mixing two poor ingredients does not make a good meal).

Natural and human system interaction; The concept of Integrated Water Resources Management, in contrast to "traditional", fragmented water resources management at its most fundamental level, is as concerned with the management of water demand as with its supply. Thus, integration can be considered under two basic categories:

• the natural system, with its critical importance for **resource availability and quality**, and

• the human system, which fundamentally determines the **resource use, waste production and pollution of the resource,** and which must also set the development priorities.

Integration has to occur both within and between these categories, taking into account variability in time and space.

Natural system integration: Integration of freshwater management and coastal zone management; Freshwater management and coastal zone management should be integrated, reflecting the "continuum" of freshwater and coastal waters. This is a special case of the **upstream-downstream issue,** which is receiving increased attention in all countries.

Integration of land and water management; An integrated approach to the management of land and water takes as its departure the **hydrological cycle, transporting water** between the compartments air, soil, vegetation, surface, and groundwater sources. As a result, land use developments and vegetation cover (including crop selection) influence the physical distribution and quality of water and must be considered in the overall planning and management of the water resources (Figure 1)

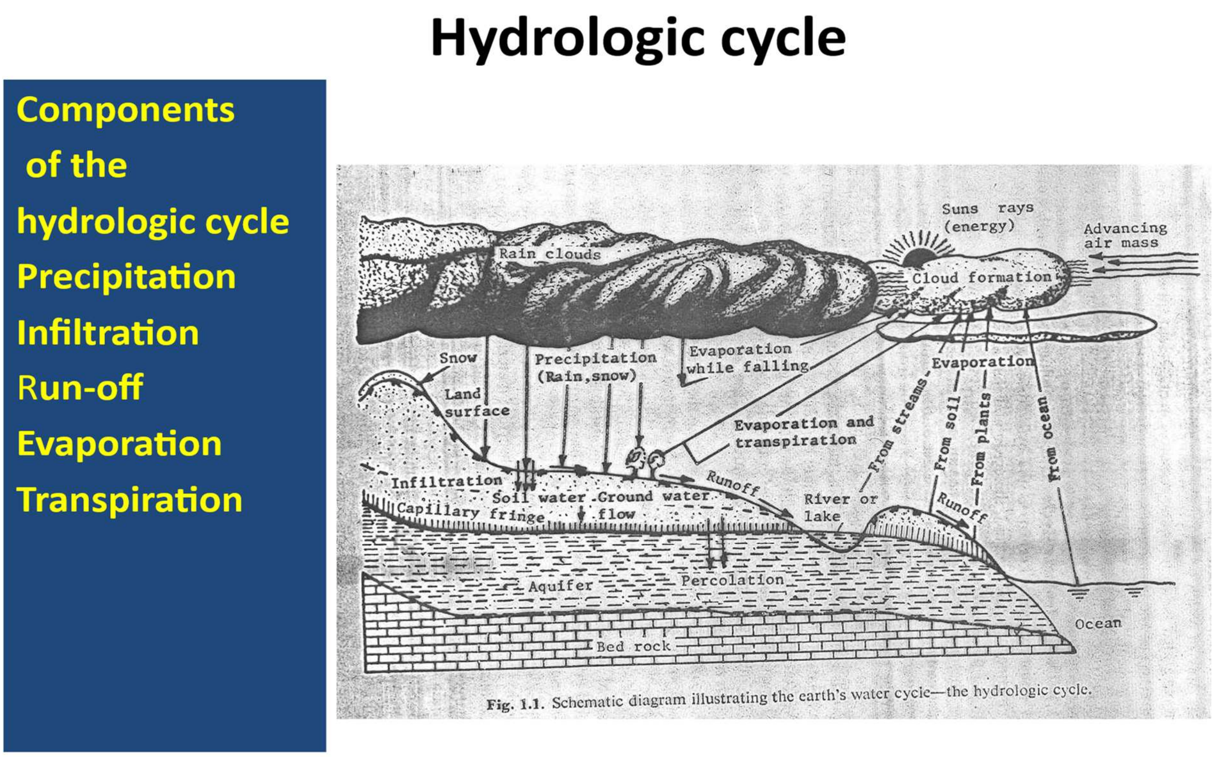

Figure 1: Hydrological Cycle

Another aspect is the fact that water is a key determinant of the character and health of all ecosystems (terrestrial as well as aquatic), and their water quantity and quality requirements therefore have to be taken into account in the **overall allocation of available water resources**.

The promotion of catchment and river basin management is an acknowledgement that these are logical planning units for IWRM from a natural system perspective. Catchment and basin level management is not only important as a means of integrating land use and water issues but is also critical in managing the relationships between quantity and quality and between upstream and downstream water interests.

"Green water" and "blue water"; A conceptual distinction can be made between water that is used directly for **biomass production and "lost" in evapotranspiration ("green water**") and **water flowing in rivers and aquifers ("blue water").** Terrestrial ecosystems are "green water "dependent, whereas aquatic ecosystems are "blue water" dependent.

Most water management, including the literature on IWRM, tends to focus on the "blue water", thus neglecting rain and soil water management. Management of "green water" flows holds significant potential for **water savings (crop per evaporated drop in rainfed and irrigated agriculture)**, increasing water use efficiency and the protection of vital ecosystems.

Integration of surface water and groundwater management; The **hydrological cycle** also calls for integration between surface and groundwater management. The drop of water retained at the surface of a catchment may appear alternately as surface and groundwater on its way downstream through the catchment. Large proportions of the world's population depend on groundwater for water supply. The widespread use of **agro-chemicals and pollution from other non-point sources** already pose significant threats to groundwater quality and force managers to consider the linkages between surface and groundwater. Groundwater pollution is frequently, for all practical purposes, **irreversible over a human timescale,** given present technology and the remedy costs involved.

Integration of quantity and quality in water resources management; Water resources management entails the development of appropriate quantities of water with an adequate quality. **Water quality management is thus an essential component of IWRM**. The deterioration of water quality reduces the usability of the resource for downstream stakeholders. Clearly, institutions capable of integrating the quantity and quality aspects have to be promoted to influence the way human systems operate in generating, abating, and disposing of waste products.

Integration of upstream and downstream water-related interests; An integrated approach to water resources management entails identification of **conflicts of interest between upstream and down-stream stakeholders**. The **consumptive "losses" upstream will reduce river flows**. The **pollution loads** discharged upstream will degrade river water quality. **Land use changes upstream** may alter groundwater recharge and river flow seasonality. **Flood control measures** upstream may threaten **flood-dependent livelihoods downstream**. Such conflicts of interest must be considered in IWRM with full acknowledgement of the range of physical and social linkages that exist in complex systems. Recognition of downstream vulnerability to upstream activities is imperative. Once again, management involves both natural and human systems.

Human system integration:

Mainstreaming of water resources; When it comes to analyzing human activities or service systems, virtually all aspects of integration involve an **understanding of the natural system**, **its capacity, vulnerability, and limits.** Such integration is inevitably a complex task, and perfect integration is unrealistic. It involves:

• attempting to ensure that **governmental policies**, financial priorities, and planning (physical, economic, and social) take account of the implications for **water resources development, water-related risks, and water use.**

• influencing **private sector decision-makers** to make **technological, production, and consumption** choices based on the **real value of water and the need to sustain the natural resource assets over time.**

• providing fora /opportunities and mechanisms to **ensure that all stakeholders** can participate in **water resource allocation decisions**, **conflict resolution and trade-off choices**.

Hence, **integrative measures** are needed at all levels from the individual household to international product markets.

Cross-sectoral integration in national policy development; The IWRM approach implies that water-related developments within all economic and social sectors should be taken into account in the overall management of the water resources. Thus, water resources policy must be integrated with national economic policy, as well as with national sectoral policies. Conversely, economic and social policies need to take account of the water resource implications; for instance, national energy and food policies may have a profound impact on water resources and vice versa.

Hence, developments must be evaluated for possible impacts on or requirements for the water resource, and such evaluations should be considered when designing and prioritizing development projects. The development and management of water resources have an impact on the economy and society through various pathways, such as **migration, settlement growth, and changes in the composition of industries.** Consequently, the water resources management system must include **cross-sectoral information exchange** and **coordination procedures**, as well as techniques for the evaluation of individual projects with respect to their implications for the water resources in particular and society in general.

Macro-economic effects of water developments: In situations where large amounts of capital are mobilized for water sector investments, the macro-economic impacts are often quite large and deleterious to overall economic development. The increased demand for goods and services in the non-water sectors caused by the capital inflows raises their prices and thus leads to inflation. This has often induced long-term macroeconomic effects that are far from desirable.

Basic principles for integrated policy-making; Cross-sectoral and "integrated" policy-making is extremely hard to achieve in practice, but there are basic principles, such as:

- economic planners must carefully assess the inflation, balance of payments, and macro-economic growth impacts before embarking on any large-scale capital investment program in the water sector;
- **land use policy-makers** must be informed about the water consequences downstream and the external costs and benefits imposed on the natural water system (e.g. deforestation or urbanization of catchments could **alter water flow regimes and exacerbate risks such as floods**). This does not mean that these external costs should not be incurred, but that the relevant policy-makers weigh these costs against the expected benefits arising from their policy or plan;
- policies which act to increase the demand for water, including its use to remove waste products, should be developed with knowledge of the full incremental costs involved
- policies which effectively allocate water between various uses should take into account the relative values in use, measured in economic and social terms;
- policy-makers need to be aware of the trade-offs between short-term benefits and long-term costs and of situations where the application of the precautionary principle can reduce total costs over time;
- policy-makers should be aware that subsidiarity in water resources management is essential so that different tasks are undertaken at the lowest appropriate level.

Influencing economic sector decisions; The decisions of economic sector actors (from trans-national or large state-owned companies to individual farmers or households) will in most countries have a significant impact on water demands, water-related risks, and the availability and quality of the resource. These decisions will not be water sensitive unless clear and consistent information is available on the full costs of their actions; importantly, incentives to take into account the external costs of their decisions have to be given.

Integration of all stakeholders in the planning and decision process. The involvement of the concerned stakeholders in the management and planning of water resources is universally recognized as a key element in obtaining a balanced and sustainable utilization of water. But in many cases, stakeholders represent conflicting interests, and their objectives concerning water resources management may substantially differ. To deal with such situations, the IWRM should develop operational tools for conflict management and resolution as well as for the evaluation of trade-offs between different objectives, plans, and actions. An important issue here is the need to identify and designate water resources management functions according to their lowest appropriate level of implementation; at each implementation level, the relevant stakeholders need to be identified and mobilized.

Integrating water and wastewater management; Water is a **renewable and reusable resource**. Where use is non-consumptive and returned after use, mechanisms are needed to ensure that wastewater flows are a useful addition to resource flows or water supply. Without coordinated management, waste flows often simply reduce effective supplies by impairing water quality and increasing future costs of water supply. **Incentives for reuse** can be provided to individual users, but to be effective, reuse opportunities have to be designed into the political, economic, social, and administrative systems.

2.1.2. IWRM components

Integrated Water Resource Management has the following three e's /components/ pillars (Figure 2).

• **Economic efficiency in water use**: Because of the increasing scarcity of water and financial resources, the **finite and vulnerable** nature of water as a resource, and the increasing demands upon it, water must be used with maximum possible efficiency;

• **Equity:** The basic right for all people to have access to water of **adequate quantity and quality** for the sustenance of human wellbeing must be universally recognized;

• **Environmental and ecological sustainability**: The present use of the resource should be managed in a way that does not undermine the life-support system, thereby compromising use by future generations of the same resource.

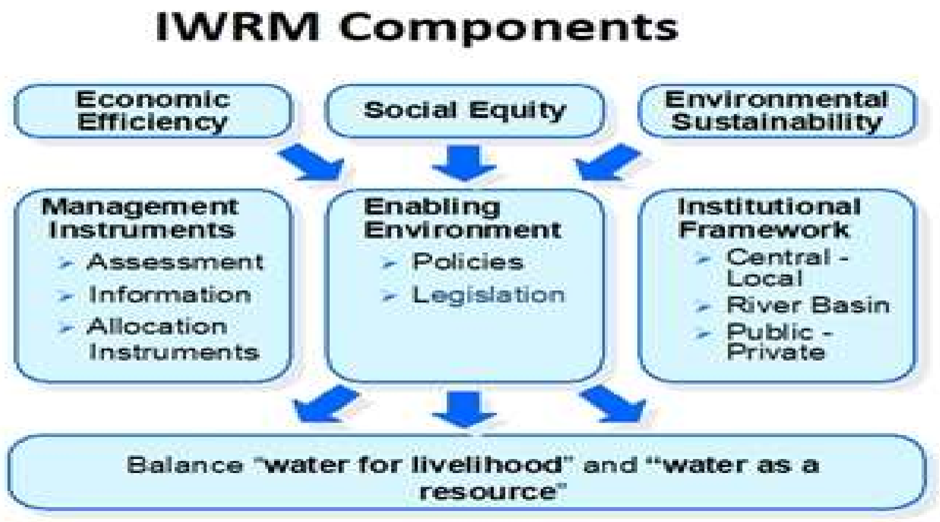

Figure 2: IWRM components

2.1.3. Integrated Water Resource Management Principles

Integrated water management is a **holistic approach to planning and managing** all parts of the water cycle, including drinking water, wastewater, and stormwater, to achieve sustainability, security, and public health. It involves coordinating water, land, and related resources to balance competing demands from various sectors like domestic, agricultural, and industrial uses, while also protecting ecosystems for future generations. This method emphasizes collaboration among stakeholders and considers the impacts of climate change and population growth.

Integrated Water Resource Management (IWRM) principles include managing water, land, and related resources holistically to ensure **economic efficiency**, **social equity**, and **environmental sustainability**. This is achieved through a **participatory approach** involving all users and stakeholders, recognizing water as a **finite resource**, and managing it across a **whole basin** or aquifer.

The four Dublin principles (Figure 3) are:

I. Fresh water is a **finite and vulnerable resource**, essential to sustain life, development and the environment

II. Water development and management should be based on a **participatory approach**, involving users, planners, and policy-makers at all levels.

III. **Women play** a central part in the provision, management, and safeguarding of water.

IV. Water has an **economic value** in all its competing uses and should be recognized as an **economic good**

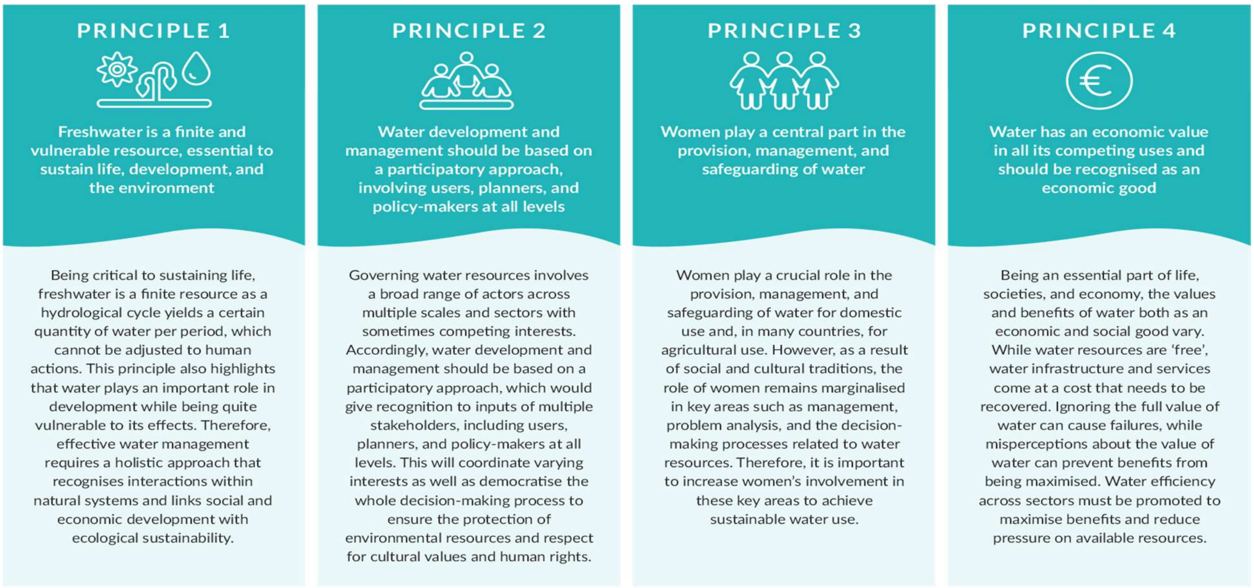

Figure 3: IWRM Principles (source: Dublin Conference,1992)

Principle I: Water as a finite and vulnerable resource

A holistic approach: This principle recalls the need for a holistic approach to management, recognizing all the characteristics of the hydrological cycle and its interaction with other natural resources and ecosystems. The statement also recognizes that water is required for many different purposes, functions and services; holistic management, therefore, has to involve consideration of the demands placed on the resource and the threats to it.

Resource yield has natural limits; The notion that freshwater is a finite resource arises as the hydrological cycle, on average, yields a fixed quantity of water per time period; this overall quantity cannot be altered significantly by human actions (desalination of seawater is becoming feasible in some locations but still at a very limited scale). The freshwater resource may be regarded as a natural capital asset, which needs to be maintained to ensure that the desired services it provides are sustained.

Effects of human activities; Human beings can clearly affect the productivity of the water resource. They can reduce the availability and quality of water by actions, such as **mining of groundwater, polluting surface and groundwater and changing land use (afforestation, deforestation, urbanization),** which **alter flow regimes** within surface water systems. More positive effects can, however, arise from **regulation** of the natural temporal and spatial variability of flows. When water is used for non-consumptive purposes and involves return flows, planned **reuse** can increase effective resource flows and the total quantity of services provided. It also has to be recognized that the value or welfare derived from the water resource assets will vary with the uses to which the assets are put.

Upstream-downstream user relations; The effects of human activities lead to the need for recognition of the linkages between upstream and downstream users of water. **Upstream users must recognize the legitimate demands of downstream users to share the available water resources and sustain usability**. Excessive consumptive use or pollution of water by upstream users may deprive the downstream users of their legitimate use of the shared resource. This clearly implies that dialogue or **conflict resolution** mechanisms are needed in order to reconcile the needs of upstream and downstream users.

A holistic institutional approach; Holistic management not only involves the management of natural systems; it also necessitates coordination between the range of human activities which create the demands for water, determine land uses and generate water-borne waste products. Creating a water sensitive political economy requires coordinated policy-making at all levels (from national ministries to local government or community-based institutions). There is also a need for mechanisms which ensure that economic sector decision-makers take **water costs and sustainability** into account when making production and consumption choices. The development of an institutional framework capable of integrating human systems, economic, social and political represents a considerable challenge.

Principle II: Participatory approach:

Real participation; Water is a subject in which everyone is a stake-holder. **Real participation only takes place when stakeholders are part of the decision-making process.** This can occur directly when local communities come together to make water supply, management and use choices. Participation also occurs if democratically elected or other-wise accountable agencies or spokespersons can represent stakeholder groups. Additionally, there are circumstances in which participation in decision-making can take place through market processes; if appropriate pricing systems are in place, local governments, community organizations or irrigation districts could signal their demands for bulk water services. The type of participation will depend upon the spatial scale relevant to particular water management and investment decisions and upon the nature of the political economy in which such decisions take place.

Participation is more than consultation; Participation requires that stakeholders at all levels of the social structure have an impact on decisions at different levels of water management. Consultative mechanisms, ranging from questionnaires to stakeholder meetings, will not allow real participation if they are merely employed to legitimize decisions already made, to defuse political opposition or to delay the implementation of measures which could adversely impinge upon a powerful interest group.

Achieving consensus; **A participatory approach is the only means for achieving long-lasting consensus and common agreement.** However, for this to occur, stakeholders and officials from water management agencies have to recognize that the sustainability of the resource is a common problem and that all parties are going to have to sacrifice some desires for the common good.

Participation is about taking responsibility, recognizing the **effect of sectoral actions on other water users and aquatic ecosystems,** and accepting the need for change to improve the efficiency of water use and allow the sustainable development of the resource. Participation will not always achieve consensus, arbitration processes or other conflict resolution mechanisms will also need to be put in place.

Creating participatory mechanisms and capacity; Governments at national, regional and local levels have the responsibility for making participation possible. This involves the creation of mechanisms for stakeholder consultation at all spatial scales, such as national, basin or aquifer, catchment, and community levels.

However, while the creation of consultative mechanisms is necessary, it will by itself not lead to real participation. Governments also have to help create participatory capacity, particularly amongst women and other marginalized social groups. This may not only involve awareness raising, confidence building, and education, but also the provision of the economic resources needed to facilitate participation and the **establishment of good and transparent sources of information.** It has to be recognized that simply creating participatory opportunities will do nothing for currently disadvantaged groups **unless their capacity to participate is enhanced**.

The lowest appropriate level. Participation is an instrument that can be used to pursue an **appropriate balance between a top-down and a bottom-up approach to IWRM**. For some decisions, the appropriate decision unit is the household or the farm; participation depends on the provision of mechanisms and information to allow individuals and communities to make water-sensitive choices. **At the other end of the spatial scale, the management of international river basins will require some form of cross-national coordinating committees and mechanisms for conflict resolution.**

Principle III: The important role of women

Involvement of women in decision-making: Women’s participation as decision-makers is interwoven with gender hierarchies and roles within different cultures, leading to the existence of communities that ignore or impede women’s participation in water management. Therefore, special efforts must be made to ensure women’s participation at all organizational Levels.

Women as water users; It is widely acknowledged that women play a key role in the collection and safeguarding of water for domestic and in many cases, agricultural use, but that they have a much less influential role than men in management, problem analysis, and in the decision-making process related to water resources. The fact that social and cultural circumstances vary between societies suggests that the need exists to explore different mechanisms for increasing women’s access to decision-making and widening the spectrum of activities through which women can participate in IWRM.

IWRM requires gender awareness; In developing the full and effective participation of women at all levels of decision-making, consideration has to be given to the way different societies assign particular social, economic and cultural roles to men and women. There is a need to ensure that the water sector as a whole is gender aware, a process which should begin with the implementation of training programs for water professionals and community or grassroots mobilizers.

Principle IV: Water as an economic good

Water has a value as an economic good; Many past failures in water resources management are attributable to the fact that water has been and is still viewed as a **free good,** or at least that the full value of water has not been recognized. In a situation of competition for scarce water resources, such a notion may lead to water being allocated to low value uses and provide no incentives to treat water as a limited asset. In order to extract the maximum benefits from the available water resources, there is a need to change perceptions about water values and to recognize the opportunity costs involved in current allocative patterns.

Value and charges are two different things; Concern has been voiced over the social consequences of "the economic good" concept: How would this affect poor people's access to water? To avoid confusion over this concept there is a need to distinguish clearly between valuing and charging for water. The value of water in alternative uses is important for the rational allocation of **water as a scarce resource** (using the "opportunity cost" concept), whether by regulatory or economic means. Charging for water is applying an economic instrument to affect behavior towards conservation and efficient water usage, to provide incentives for demand management, **ensure cost recovery and to signal consumers'** willingness to pay for additional investments in water services.

Useful water value concepts: The following concepts of water value have been found useful within IWRM. The full value of water consists of its **use value** or **economic value** and the **intrinsic /basic value**. The economic value, which depends on the user and the way it is used, includes value to (**direct**) users of water, **net benefits from water that is lost through evapotranspiration** or other sinks (e.g., **return flows**), and the contribution of water towards the attainment of **social** objectives.

Useful water cost concepts: The full cost of providing water includes the full **economic cost** and the **environmental externalities associated with public health and ecosystem maintenance**. The **full economic cost consists** of the **full supply cost** due to resource management, operating and maintenance expenditures and capital charges, the **opportunity costs from alternative water uses**, and the **economic externalities** arising from changes in economic activities of indirectly affected sectors.

The goal of full cost recovery; The recovery of full cost should be the goal for all water uses unless there are compelling reasons for not doing so. While, in principle, the full cost needs to be estimated and made known for purposes of **rational allocation and management decisions**, it need not necessarily be charged to the users. The cost, however, will have to be borne by someone. Estimation of full cost may be very difficult. In situations involving conflict over water attempts should be made to at least estimate the full economic cost as the basis for allocation.

Managing demand through economic instruments; Treating water as an economic good may help balance **the supply and demand of water**, thereby sustaining the flow of goods and services from this important natural asset. When water becomes increasingly scarce, continuing the traditional policy of **extending supply is no longer a feasible option**. There is a clear need for operational economic concepts and instruments that can contribute to management by **limiting the demand for water.** Importantly, if charges for water goods and services reflect the full cost involved, managers will be in a better position to judge when the demand for different water products justifies the **expenditure of scarce capital resources** to expand supply.

Financial self-sufficiency versus water as a social good; In order for water resources management agencies and water utilities to be effective, there is a need to ensure that they have adequate resources to be financially independent of general revenues. Thus, as a minimum, **full supply costs should generally be recovered in order to ensure the sustainability of investments**. But high supply costs and social concerns may require direct **subsidies** to specific disadvantaged groups. While **subsidies "across the board"** generally **distort water markets** and should be discouraged, **direct subsidies for targeted groups** may be relevant, but they need to be transparent. There are, however, several institutional prerequisites for the successful implementation of targeted subsidies; these include adequate taxation or general revenue collection systems, mechanisms to identify the target groups and the capacity to monitor and follow up on fund utilization. Transparent financial linkages among different organizations and between users and management agencies are fundamental to the successful implementation of water policies. The **principle "subsidize the good, tax the bad"** has considerable merit when exercised in a transparent manner, although it has to be recognized that all subsidies have to be paid for by someone. In general, subsidies paid for from taxation will be less distorting than systems that rely on **cross-subsidies between different groups of consumers**; however, it is acknowledged that in many administrations, cross-subsidies are easier to implement.

3. Water harvesting and storage systems

A water harvesting (WH) and storage system is a method of **collecting, concentrating, and storing rainwater** that **runs off a natural or man-made catchment surface** for various uses like domestic drinking & livestock, sanitation, agriculture, and groundwater recharge. A basic system includes a catchment area (like a **roof or ground**

surface), a **conveyance system** to move the water (such as gutters and pipes), and a **storage facility** (like a tank or cistern). WH plays a key role in groundwater recharge and management. Captured surface runoff percolates into the ground, replenishing aquifers and helping maintain groundwater levels, especially in overexploited areas. By reducing reliance on groundwater for domestic, agricultural, and industrial uses, it slows groundwater depletion and supports aquifer recovery. Rainwater harvesting, in particular, offers relatively clean water for recharge, diluting contaminants and improving the groundwater quality. Integrating WH into management strategies promotes resource sustainability, supports ecosystems, and maintains stream flows and wetlands. Different types of systems exist, including those for household use, community projects, and agricultural applications, and they can be designed as either rooftop or surface catchments.

3.1. Water Harvesting Types and Techniques

Water Harvesting (WH) refers to the process of collecting and storing rainwater or surface runoff on the ground, underground, in the soil, or in reservoirs for future use. This practice can be implemented at various scales, from small household levels to large-scale municipal or watershed projects. The primary objective of WH is to capture and conserve water for purposes such as drinking, irrigation, Ground Water Recharge (GWR), and other needs, particularly in regions experiencing water scarcity or regions having longer periods of dry seasons. WH offers a range of benefits, including (a) drought mitigation, (b) efficient water use, (c) flood management, (d) soil conservation, (e) groundwater improvement, and (f) energy conservation, and also point out numerous benefits in the form of economic, environmental, technological, and social advantages.

WH, a time-honored practice, encompasses three key components that are essential for effectively capturing and utilizing rainwater or runoff. These components are the collection system, transportation system and a storage system. The collection System is the part of the system where rainwater or surface runoff is initially gathered. This system typically includes surfaces such as rooftops or catchment areas that direct water into a designated collection point. Once the water is collected, it must be transported to a storage location, which is facilitated by a transportation system that often involves pipes, channels, or gutters to guide the water from the collection point to the storage unit. The final component is the storage system, where the water is stored for later use; this can be in tanks, cisterns, or other reservoirs that hold the water until it is needed for drinking, irrigation, or other purposes.

WH can be classified into three main types: (1) rainwater harvesting, (2) flood harvesting, and (3) groundwater harvesting, which involve both surface and subsurface storage reservoirs. The primary WH structures employed include short-term options such as contour bunds, trapezoidal bunds, semi-circular hoops, rock catchments, and ground catchments. Additionally, long-term structures like dugout ponds, farm ponds, irrigation dams, silt/sand detention dams, and percolation dams are commonly practiced, alongside subsurface dams. These systems collectively enhance water resource management and contribute to sustainable water use, particularly in areas facing water scarcity.

3.1.1. Rainwater Harvesting (RWH)

RWH is the process of capturing and storing rainwater from precipitation, specifically rain that falls directly onto rooftops, surfaces, or catchment areas. This practice involves a systematic collection method, utilizing components such as gutters, downspouts, and storage tanks to gather and store rainwater efficiently. The primary objective of RWH is to provide a sustainable water supply for a variety of uses, including domestic needs, irrigation, and other applications, particularly during dry periods or regions with water scarcity (Figure 4).

The design of RWH systems typically targets smaller, more frequent rainfall events, emphasizing adequate storage capacity and effective filtration mechanisms to ensure water quality. These systems are versatile and can be implemented in both urban and rural areas, adapting to varying rainfall patterns. In urban areas, RWH focuses on localized collection from rooftops and impervious surfaces, reducing reliance on municipal water supplies and mitigating urban flooding. In rural areas, the techniques are often employed to enhance agricultural productivity and provide consistent water access for communities.

RWH also plays a critical role in water resource management and climate change adaptation strategies. By capturing rainwater at its source, it helps reduce surface runoff, prevents soils erosion, and supports GWR. Moreover, it contributes to building resilience in regions prone to droughts and water shortages. The adoption of RWH systems is increasingly encouraged as a sustainable solution for addressing global water challenges, promoting efficient water use, and supporting environmental conservation.

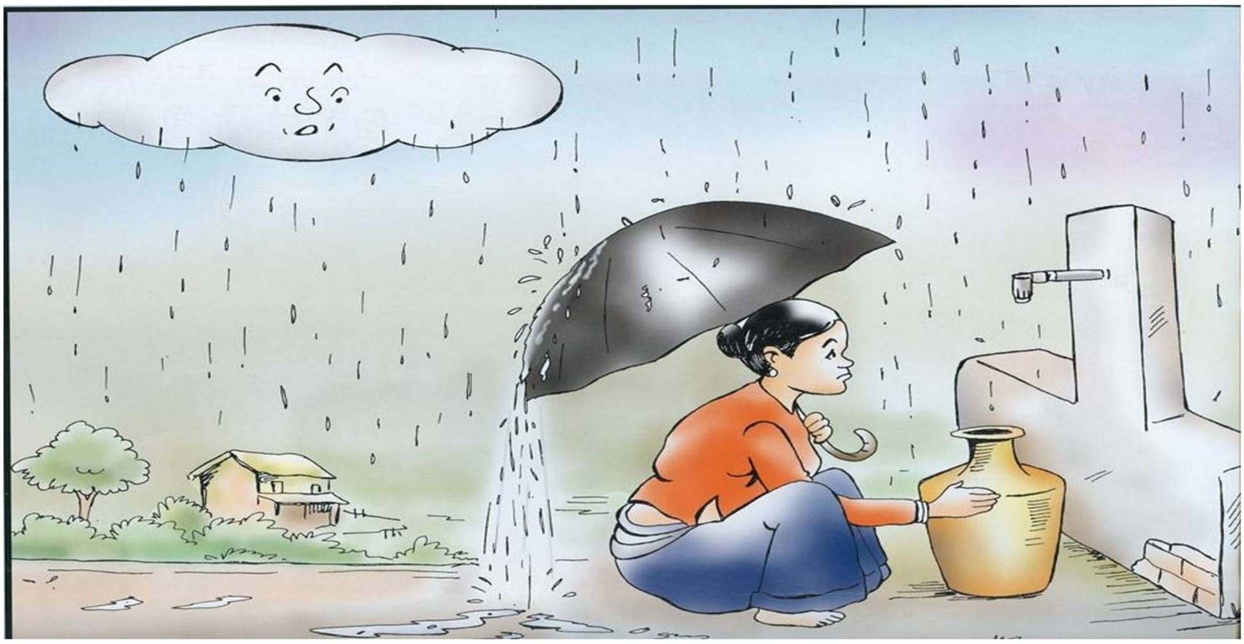

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Figure 4: Perception of women on rainwater harvesting practices

3.1.2. Flood Water Harvesting (FWH)

FWH involves the collection and management of excess water from flooding events, such as heavy rainfall, storm surges, or river overflows. This method employs various structures such as check dams, percolation tanks, and infiltration ponds to temporarily store and regulate large volumes of floodwater. The primary objectives of FWH include mitigating the adverse impacts of flooding, managing surplus water, and enhancing GWR during and after flood events

Unlike RWH, FWH systems are designed to handle significantly larger and more rapid inflows of water. As a result, these structures often require robust engineering and durable materials to withstand the high pressures and dynamic conditions of flood events. For example, check dams help slow down water flow and allow it to percolate into the ground, while percolation tanks are used to store floodwater for infiltration into aquifers, improving GWR. Additionally, FWH pits are implemented to collect and contain water temporarily, preventing uncontrolled runoff that can cause soil erosion and damage infrastructure.

This method is particularly relevant in regions prone to seasonal flooding or areas with intense and erratic rainfall patterns. FWH often involves large-scale landscape management, requiring coordinated efforts at both community and governmental levels. Beyond mitigating flood risks, this technique provides numerous benefits, such as improving water availability during dry periods, enhancing soil moisture for agriculture, and restoring ecological balance in flood-prone areas.

FWH is increasingly recognized as a valuable climate adaptation strategy in the face of changing rainfall patterns and extreme weather events caused by climate change. By capturing and managing floodwaters effectively, this approach not only addresses immediate water-related challenges but also contributes to long-term water security and sustainability

3.1.3. Groundwater Harvesting (GWH)

GWH involves the extraction and sustainable utilization of water stored in underground aquifers, typically accessed through wells, boreholes, or springs. This method is an essential part of water resource management, particularly in arid and semi-arid regions where surface water is scarce. GWH also includes the use of specialized techniques and structures such as subsurface dams, **Qanat systems** (a combination of shaft and tunnel system), and specialized wells, to enhance GWR and ensure long-term water availability. Qanat systems are ancient, ingenious networks of underground tunnels that transport water from aquifers in hills to lower-lying arid lands using only gravity, providing sustainable water for irrigation and drinking without pumps (Figure 5).

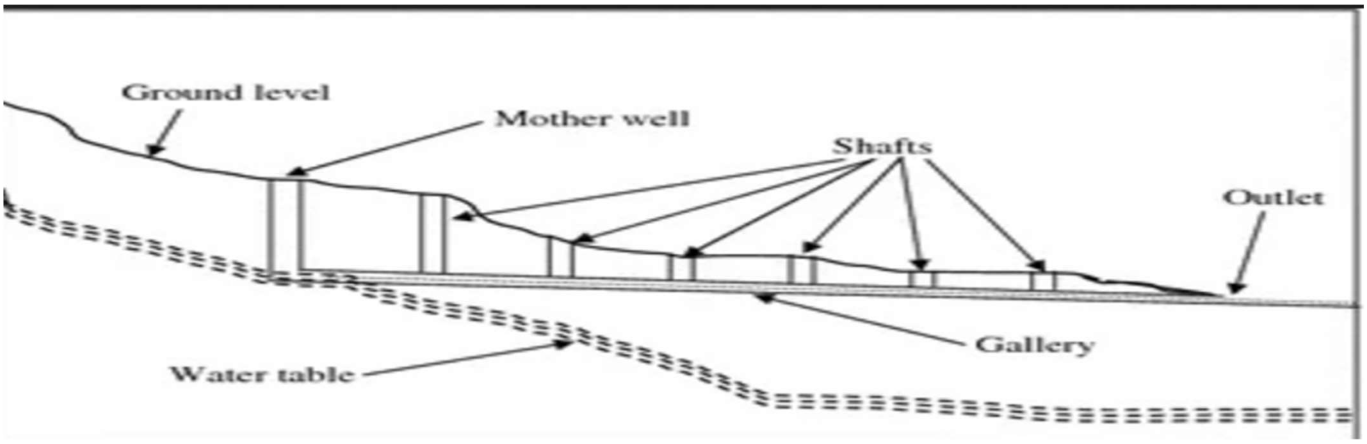

Figure 5: Qunat systems (combination of shaft and tunnel system)

Qanat systems are used in the Middle East and North Africa and are remarkable engineering systems consisting of a series of underground tunnels and vertical shafts. These structures transport groundwater from higher elevation aquifers to the surface using gravity alone, eliminating the need for mechanical pumps. Qanats are highly efficient in regions with sloping terrains and help deliver water to arid plains for agriculture, drinking, and domestic use. Specialized wells, such as infiltration wells and recharge wells, are designed to facilitate the percolation of surface water into the underground aquifers.

Subsurface dams are built within riverbeds to obstruct the flow of ephemeral streams during seasonal rains by trapping water in the sediment below the ground surface. Subsurface dams reduce water loss from evaporation and provide a sustainable source of water for aquifer recharge. The stored water can then be accessed later through wells or other extraction methods, making it a reliable source for drinking, irrigation, and other uses. Sand dam/ subsurface dam constructed by Ethiopian Rainwater Harvesting Association (ERHA) (Figure 6)

Figure 6: Sand dam/subsurface dam at Borena and Dire Dawa constructed by ERHA

Surface Catchment**:** Uses natural runoff from land surfaces. Surface catchment harvesting systems consist of four main types: rock catchments, earth dams and excavated reservoirs, which harvest water running off the catchment during rainstorms; water is collected and stored at strategic locations before it can rush away as floodwater or seep away out of reach into the ground (Figures 7 and 8).

Figure 7: Hill side irrigation technologies in the hilly areas

Figure 8: Surface runoff water harvesting through surface pond at Shenkora Woreda

Rooftop Catchment: The most common type for domestic use, where water from a roof is collected through gutters and downspouts into a storage tank. Rooftop catchment systems consist of a rooftop catchment area, usually of iron-sheet but occasionally of thatch, connected by gutters and downpipes to one or more storage containers ranging from simple pots to large ferrocement tanks (Figure 9).

Underground WHS, Minjar   Above ground WHS, Adami Tulu

Figure 9: underground and Roof water harvesting structures constructed by ERHA

3.1.4. In-situ water harvesting system

In-situ water harvesting techniques capture and infiltrate rainwater directly where it falls, improving soil moisture for crops and recharging groundwater using methods like contour bunding, terracing, tied-ridging, furrows/beds, mulching, and micro-catchments (like Negarim), which slow runoff, prevent erosion, and enhance water retention within the field, crucial for dryland farming (Figure 10).

Figure 10: Tied ridge and pits as in-situ water harvesting techniques in dry land areas, Ethiopia

Impacts of water harvesting systems

Water harvesting has three clear impacts: it preserves water during times when it is plentiful for use. when it is scarce, or when normal supply is interrupted; it provides a more convenient distribution of water closer to population centers or individual households; and it provides higher quality water than would traditionally be available from unimproved sources.

Time-saving benefits

The development of additional or improved water harvesting sources for drinking, livestock and household needs improves the ease of access to water. This is particularly important to women who are relieved from some of their daily burden of water collection. Time saved is often used in agriculture, particularly at ploughing and planting time. This, coupled with the use of runoff fanning, can lead to a better and more secure annual harvest. More time is also spent on childcare.

Improvements in water quality

Water harvesting usually provides water of high acceptability to users, both in terms of taste and appearance. It fits in well with traditional sources and collection practices. The quality of water provided is usually considerably better than most unimproved water sources. However, it does not always reach nationally approved standards. Some contamination by faecal coliforms, turbidity, and insect larvae is common, particularly with surface catchment reservoirs. The potential for disease transmission can be raised if the water point is not managed carefully. For instance, breeding of mosquitoes next to the home can increase the incidence of Malaria, and earth dams are considered high-risk sites for guinea worm or bilharzia transmission. These problems can be largely solved by providing various forms of protection, from a sealed roof for a household tank to fencing an open reservoir to keep people and cattle out, and providing a draw-off pipe and tapping station downstream. Local solutions are sometimes adopted to keep the water clean, such as the practice of growing fish in rock catchment dams in Kenya. Fish help keep insect larvae to a minimum, particularly mosquitoes.

Yield increases from runoff farming

Runoff farming is a water harvesting method where rainfall runoff from a larger, unused area (catchment) is intentionally diverted to a smaller, cultivated area (run-on) to grow crops, effectively using the land's soil as a natural water storage tank. It's crucial in arid regions, preventing erosion and supplementing rainfall by channeling water from roads, hillsides, or other surfaces into fields or ponds, enabling irrigation and crop diversification where water scarcity usually limits production.

Benefits of water harvesting and storage

- **Climate change adaptation:** Provides a buffer against unpredictable weather patterns and seasonal water scarcity.
- **Improved food security:** Especially in arid and semi-arid regions, it helps support smallholder farmers during dry seasons.
- **Reduced reliance on other water sources:** Can lessen the demand on municipal water supplies.
- **Groundwater recharge:** Excess harvested water can be directed to recharge wells and replenish underground aquifers.

Components of a water harvesting and storage system

- **Catchment Area:** The surface where rainwater is collected. This can be a rooftop, a paved area, a hillside, or even a specially prepared surface.
- **Conveyance System:** The channels, pipes, or gutters that transport water from the catchment area to the storage facility.
    - **Dry line systems:** Used when the storage is close to the catchment; pipes are empty between rain events.
    - **Wet line systems:** Used when the tank is located at a different elevation or distance; the pipe remains full of water.
    - **Debris screens:** Devices like leaf screens or filters are essential to prevent debris from entering the system.
- **Storage Facility:** A container to hold the harvested water. Common options include:

- **Tanks:** Can be made of plastic, fiberglass, concrete, metal, or other materials.
- **Cisterns:** Often cylindrical and can be built underground, such as the traditional "taanka" in India.
- **Ponds and reservoirs:** Larger storage for community use, often excavated into the ground.

4. Groundwater recharge and shallow well management

Ethiopia possesses significant groundwater potential, with estimates varying widely (2.5 to 40+ billion cubic meters), serving as a crucial resource for domestic supply (around 80% of needs) and increasing agricultural use, despite challenges like data scarcity, uneven distribution, and high fluoride contamination in Rift Valley areas, requiring advanced mapping and management.

Key Findings on Potential

- **Varying Estimates**: Total potential estimates range from 2.5 BCM (billion cubic meters) to as high as 40-47 BCM, indicating deep aquifers and large reserves.
- **Regional Variation**: Specific regional aquifers (Kobo, Raya, Adaa Bechoo) show substantial reserves, with groundwater movement often crossing surface basin boundaries.
- **Geological Factors**: Complex geology, topography, climate, and soil significantly influence groundwater, with fractured bedrock and lineaments (structural breaks) aiding flow.

Groundwater is a vital source of domestic, agricultural, and industrial supply as well as for ecosystems in many parts of the world, especially in arid and semi-arid regions. However, over-pumping and/or overexploitation of aquifers to satisfy various competing water uses, climate change, etc., are causing groundwater levels to decline. Groundwater depletion has several effects, including (a) lowering of the water table; (b) reduction in water in streams and lakes; c) ground subsidence; (d) increased costs to the user; (e) deterioration of water quality and ecological damage, etc.

Urbanization increases/accelerates groundwater demand while reducing the groundwater recharge areas, leading to the decline and complete extraction of groundwater. This issue is particularly severe in arid and semi-arid regions, which make up over 40% of the Earth's surface, causing significant groundwater depletion globally.

Recharge is essential to sustain water resources and build resilience against climate change and shifting water demands. Among the internationally proposed measures to tackle the problem are groundwater recharge (GWR) and surface water harvesting. This can be conducted both naturally through rainfall and artificially through human intervention.

WH plays a key role in groundwater recharge and management. Captured surface runoff percolates into the ground, replenishing aquifers and helping maintain groundwater levels, especially in overexploited areas. By reducing reliance on groundwater for domestic, agricultural, and industrial uses, it slows groundwater depletion and supports aquifer recovery. Rainwater harvesting, in particular, offers relatively clean water for recharge, diluting contaminants and improving the groundwater quality. Integrating WH into management strategies promotes resource sustainability, supports ecosystems, and maintains stream flows and wetlands.

The effectiveness of WH for GWR depends on local hydrogeology, system design, and regional water management practices. When well-implemented, it supports integrated water resource management by enhancing groundwater availability, quality, and sustainable use.

4.1. Groundwater Recharge

Benefits of Groundwater Conservation

Groundwater conservation is essential for both the environment and society due to its far-reaching impacts on sustainable water supply, agricultural support, ecosystem conservation, and drought resilience. Additionally, it plays a critical role in preventing land subsidence, protecting water quality, adapting to climate change, preserving cultural and social values, and enhancing GWR. As a vital resource, groundwater supports numerous livelihoods, ecosystems, and communities, making its conservation a top priority in water resource management.

One of the most **effective strategies** for groundwater conservation is Groundwater Recharge (GWR), which involves replenishing aquifers to maintain their sustainability and functionality. This can occur naturally, through precipitation and infiltration, or artificially, by directing water into aquifer systems through recharge structures. The identification of **areas suitable for artificial recharge** is crucial and should be based on specific factors (among others), areas such as:

(1) declining groundwater levels,

(2) de-saturated aquifers,

(3) inadequate water supply (wells and hand pumps fail to provide sufficient water), and

(4) poor groundwater quality.

By focusing on these factors (in addition to geological and hydrogeological factors), GWR efforts can enhance

(1) the availability and quality of groundwater,

(2) support long-term environmental sustainability,

(3) mitigate subsidence, and

(4) improve human well-being.

Additionally, such measures contribute to climate change adaptation, providing resilience against the increasing challenges posed by changing precipitation patterns and water scarcity. Groundwater conservation and recharge are integral to protecting this critical resource and ensuring its availability for future generations.

4.2. **Water Sources for GWR**

GWR is a process that replenishes underground aquifers through both natural and artificial means. To ensure effective recharge, it is crucial to identify and evaluate the availability of adequate water sources. These sources serve as the foundation for designing recharge systems, particularly in regions facing water scarcity or aquifer depletion. The primary sources of water for GWR include (1) rainfall, (2) rainwater collected from rooftops, (3) surplus water from natural streams and springs, and (4) properly treated municipal and industrial wastewater.

Rainfall or precipitation is the most common natural source of GWR. Rainwater percolates through the soil and gradually replenishes aquifers, making it an integral part of the hydrological cycle. However, the effectiveness of precipitation as a recharge source depends on several factors, such as **land slope, soil type, geology, vegetation cover, and rainfall intensity**. While in situ precipitation occurs naturally at all locations, it may not always provide enough water for effective recharge, especially in arid or semi-arid regions where rainfall is infrequent or insufficient.

In urban and densely populated areas, rainwater collected from large roof surfaces can significantly contribute to GWR. Rooftop RWH systems collect and channel rainwater into recharge structures such as **pits, trenches, or wells**. This method is particularly effective in areas with limited open land for natural infiltration and helps reduce surface runoff, which often causes waterlogging and urban flooding. By utilizing roof areas, rainwater can be captured and redirected to replenish aquifers, making it a valuable strategy for urban water management.

Natural streams, rivers, and other surface water bodies are another important source of water for GWR. During periods of high flow or seasonal surpluses, water from these sources can be diverted into recharge systems like check dams, percolation tanks, or Water infiltration basins. This diverted water helps replenish aquifers while minimizing surface water wastage. However, it is essential to ensure that the **diversion of water does not violate the rights of downstream users or disrupt aquatic ecosystems.** Proper planning and stakeholder engagement are necessary to balance recharge activities with other competing water needs.

In addition to natural sources, **properly treated municipal and industrial wastewater** can be utilized for GWR. Advanced wastewater treatment processes remove harmful contaminants, making the water safe for recharge purposes. Treated wastewater can be directed into aquifers through recharge wells or basins, providing a sustainable way to reuse water and reduce pressure on freshwater resources. This approach is particularly beneficial in urban and industrial areas where water demand is high, and alternative sources are limited.

In regions where rainfall and natural water sources are inadequate for effective recharge, alternative water sources can be explored and transported to recharge sites. For example, surplus water from nearby reservoirs, rivers, or other catchments can be conveyed through pipelines or canals to areas needing recharge. While this solution enhances recharge efficiency, it requires careful infrastructure planning to minimize water losses during transportation and ensure cost-effectiveness.

4.3. **Groundwater Recharge Methods**

4.3.1. Natural Groundwater Recharge (GWR)

Natural GWR is a process through which water from precipitation and other surface sources infiltrate the ground, replenishing underground aquifers. This occurs when rainwater or melted snow seeps into the soil and permeable rock layers, gradually making its way to the groundwater table. The efficiency and rate of natural recharge are influenced by a variety of factors, including **soil type, geology, land cover, topography, depth to groundwater table, vegetation and climate** conditions. Favorable conditions for natural recharge include permeable soils, fractured rock formations, perennial rivers and streams, forest cover, and relatively level land with minimal slope, all of which enhance the infiltration of water into the subsurface.

However, natural GWR can be significantly reduced or obstructed due to a variety of factors, many of which are driven by human activities and environmental changes. **Urbanization** is one of the main contributors to reduced recharge, as the expansion of impervious surfaces such as roads, pavements, and buildings prevent water from infiltrating into the soil. Instead, water flows off these surfaces into storm drains, reducing the amount of water available for aquifer replenishment.

The presence of vegetation plays a crucial role in facilitating natural recharge. Trees and plants promote infiltration by allowing water to percolate through the soil, while their roots create pathways that enhance soil permeability. When vegetation is reduced, for example, through deforestation or land clearing, there is a significant reduction in the amount of water absorbed into the ground, leading to lower recharge rates. Similarly, certain agricultural practices, such as excessive tillage, can compact soil, decreasing its ability to absorb water. The use of chemical fertilizers and pesticides further degrades soil health and reduces permeability, impeding the natural recharge process.

In addition, excessive groundwater extraction can outpace natural recharge rates, leading to a decline in the water table. Over-extraction can also reduce the effectiveness of recharge, as deeper groundwater levels make it harder for infiltrating water to reach aquifers. Climate change further exacerbates these challenges by altering precipitation patterns and intensities. For instance, an increase in the frequency and intensity of droughts, Water along with shifts in rainfall distribution, can reduce the overall availability of water for recharge. Areas that experience heavy rainfall over short periods may see more surface runoff than infiltration, further limiting the water that reaches the aquifer.

Another critical factor affecting natural recharge is the **discharge of polluted** water into natural waterways. **Polluted water can block soil pores with impurities**, reducing the soil's infiltration capacity. Industrial discharges, untreated wastewater, and contaminated surface water flows prevent water from percolating effectively into the ground, thereby hindering natural recharge processes.

4.3.2. Artificial Groundwater Recharge (GWR)

Artificial GWR is a method of replenishing groundwater reservoirs by deliberately modifying the natural movement of surface water, treated wastewater, rainwater, etc., using appropriate civil/hydraulic engineering techniques. This process is typically implemented in situations where natural recharge is insufficient to meet groundwater demand throughout the year and store water for later use. By employing artificial recharge, water managers can enhance the sustainability of aquifers and ensure the availability of groundwater for various uses.

The primary objectives of artificial recharge techniques are to

(1) **enhance natural recharge**: replenishing aquifers by **capturing and directing** precipitation and surface runoff into the ground;

2) stabilize aquifer levels: contributing to maintaining consistent groundwater levels;

(3) control contamination of water supplies: protect groundwater quality and reduce the risk of pollutants infiltrating aquifers (recharged water quality is controlled); and

(4**) prevent freshwater degradation**: minimize saltwater intrusion in coastal areas. These techniques are especially valuable in areas with high water demand, limited natural recharge, or increasing pressure on groundwater resources due to climate change, urbanization, and population growth.

Groundwater levels can be improved through various artificial recharge methods, including **spreading, recharge/injection wells, and the induced infiltration** method. The first two methods spreading and recharge/injection wells are classified as **direct techniques**, with spreading involving the application of water directly to the surface, while recharge/injection wells operate below the surface. In contrast, the **induced infiltration** method falls under the **indirect category**, as it utilizes the natural processes of infiltration from nearby water sources to enhance GWR.

Examples of induced infiltration method **include induced recharge, aquifer modification**, and **groundwater conservation** structures.

4.3.2.1. Direct Methods

a. Surface Spreading Method

The surface spreading method is a widely used technique for artificial GWR. In this approach, water is diverted from streams or released from reservoirs into shallow basins or trenches. Recharged water then infiltrates through the bottom of these basins or trenches, percolating through the unsaturated zone (vadose zone) and gradually migrating to the water table. The rate of recharging is influenced by several factors, including

(1) the permeability of the material between the basin bottom and the water table,

(2) the depth of the water table in the basin, and

(3) the biological, geochemical, and physical changes occurring within the materials through which the water moves. For optimal recharge efficiency, the area chosen for the surface spreading method have gently sloping terrain that avoids significant gullies or ridges. Additionally, the vadose zone the soil and rock above the water table should be permeable and free from clay lenses, as these can obstruct water, Water movement and reduce infiltration. The permeability of the geological formation plays a critical role in ensuring that water easily reaches the aquifer.

Several **sub-techniques** are commonly employed within the surface spreading method. These include Flooding, Ditches and Furrows, Recharge Basins, Run-off Conservation Structures (Bench Terracing, Gully plugs, Contour bunds, Contour trenches, Percolation tanks, etc.), Stream Channel Modification, and Surface Irrigation.

The surface spreading method is particularly effective in areas with high permeability in the vadose zone and is a cost-efficient solution for enhancing groundwater resources when natural recharge is insufficient.

b. Subsurface method

The subsurface method is employed in regions where the soil exhibits low vertical permeability, which hinders natural infiltration of water into the ground. This technique involves the construction of structures such as **injection wells, recharge wells, dug wells, shafts, and pits** that are placed below the surface. These structures facilitate the direct recharge of groundwater by allowing water to be introduced into the subsurface layers, overcoming the limitations posed by the surrounding soil conditions. As a result, the subsurface method is particularly effective in areas where traditional surface recharge techniques may not be viable due to insufficient permeability.

4.3.2.2. Indirect Methods

(a) Induced Recharge

Induced recharge is an indirect method of artificial GWR that involves **pumping water from an aquifer that is hydraulically connected to surface-water sources**. By creating a flow gradient, this process encourages the surface water to infiltrate and recharge the groundwater reservoir. One of the notable benefits of induced recharge is the **natural filtration effect**: as surface water passes through the aquifer materials, its quality often improves before being discharged from the pumping well, provided the hydrogeological conditions are favorable. This natural filtration process can significantly enhance the overall quality of the groundwater. A few examples of induced recharge are described below.

Pumping Wells: An induced recharge system typically **pumping wells** strategically located near **perennial streams** that are hydraulically linked to an aquifer through permeable materials in the stream channel. A prime location for a well is often at the outer edge of a bend, where the hydrological conditions are particularly conducive to recharge. However, a critical consideration in this system is the chemical quality of the surface water source, as it directly impacts the effectiveness and safety of the recharge process.

Collector Wells: These are used to extract significant water from riverbed or lakebed deposits and waterlogged areas. In cases where the phreatic aquifer (unconfined aquifer) near the river has limited thickness, horizontal wells are often more effective than vertical wells. Collector wells equipped with horizontal laterals and infiltration galleries can considerably enhance induced recharge from the stream, making them a preferable option for maximizing water extraction in suitable locations.

Infiltration Gallery: Infiltration galleries are specialized structures designed to access groundwater reservoirs beneath riverbed strata. These galleries consist of horizontal perforated or porous pipes with open joints, enclosed in a gravel filter envelope. They are installed in permeable, saturated layers with a shallow water table and a continuous source of recharge. Typically positioned at depths of 3 to 6 m, infiltration galleries collect water through gravity flow. Key considerations when designing an infiltration gallery include the desired yield and economic feasibility of the project

(b) Aquifer Modification Techniques

Aquifer modification techniques aim to enhance the physical characteristics of aquifers, improving their ability to store and transmit water. While these methods are primarily used to augment water yield rather than serving as traditional artificial recharge structures, they are increasingly recognized as effective approaches for boosting groundwater storage within aquifers. **Bore Blasting** is an effective technique for hard crystalline and consolidated strata. Through detailed hydrogeological investigations, suitable sites are identified where aquifers are underperforming or drying up. In this method, blasting holes are drilled to the required depth of the aquifer whether it is unconfined or confined. Explosive charges are arranged in rows or circular patterns and detonated simultaneously to maximize the impact. The **controlled blasts** increase the secondary porosity and permeability of the aquifer, allowing for greater water infiltration and storage capacity.

Hydro-Fracturing is a modern alternative to traditional blasting methods, particularly in cases where blasting has yielded inconsistent results. This technique is designed to enhance secondary porosity in hard rock formations by applying hydraulic pressure to a specific zone within bore wells. **The process involves injecting high-pressure water into the borehole to initiate and expand fractures in the rock**. Additionally, it clears clogged fissures and improves connectivity with nearby water-bearing strata, significantly increasing water flow and accessibility. Hydro-fracturing is particularly effective for improving the hydraulic properties of aquifers in areas with limited natural recharge potential.

(c) Groundwater Conservation Structures

Groundwater conservation structures are essential for ensuring that artificially recharged water remains available for use when needed. Once water is recharged into the aquifer, it becomes subject to natural groundwater flow regimes, which may lead to its movement away from the desired area. Conservation techniques aim to slow or control this flow, enhancing sustainable management of groundwater resources and improving long-term water availability.

Subsurface Dams/Underground Barriers are structures built across streams, or other flow paths **to slow the natural flow** of groundwater and create subsurface storage. By impeding the movement of groundwater, these dams increase the storage capacity within the aquifer and allow water to be retained during peak usage periods. The primary objective of a subsurface dam is to prevent the outflow of groundwater from the sub-basin while simultaneously enhancing the aquifer's storage potential. This method is particularly effective in areas where aquifers experience rapid depletion or where seasonal water demand is high.

The Fracture-Sealing Cementation Technique is a specialized groundwater conservation method used in arid and semi-arid regions. In these areas, boreholes may initially provide good yields but often dry up by the end of the winter or summer due to limited groundwater storage along preferential flow paths. This method involves sealing fractures in the rock with specially formulated cement to reduce water loss through these pathways. In addition to conserving groundwater, this technique is highly effective in preventing the intrusion of saline or polluted water from known sources, thereby protecting the quality of the aquifer. It is particularly useful in regions with challenging topography or aquifer conditions where water management is critical.

4.4. **Groundwater Recharge (GWR) Estimation Techniques**

GWR estimation involves quantifying the amount of water that infiltrates into the groundwater system from various sources. This is a critical process for understanding and managing groundwater resources. A variety of methods for estimating both natural and artificial recharge are documented. The selection of an appropriate method depends on several factors, including (1) data availability, (2) local geographic and topographic conditions, (3) spatial and temporal scales required for the analysis, and (4) reliability of results for specific context.

The following are the main techniques used to estimate GWR: (1) water table fluctuation (WTF), (2) water budget, (3) Darcy's law, (4) empirical relationships, (5) tracer techniques, and (6) groundwater models. Each method has its own strengths and limitations, and the choice of technique is often influenced by the specific hydrogeological conditions of the area under study. Combining multiple methods can also improve the accuracy and reliability of recharge estimates. Brief descriptions of each method are presented below:

4.4.1. Water Table Fluctuation (WTF) Method

The WTF method is a widely used approach for estimating GWR by analyzing changes in the water table. Recharge causes the water table to rise, which increases the volume of water stored in the aquifer. This method assumes that the rise in water table is directly related to the amount of recharge entering the aquifer. However, it also accounts for lateral drainage that occurs during the recharge process, providing a more accurate assessment of how much water is stored and how it interacts with surrounding areas.

To apply the WTF method, **a hydrograph of** the water table is analyzed to observe fluctuations over time. The method is particularly effective in areas where aquifers are unconfined and where water table and specific yield data are readily available. By examining the modified rise in the water table, the method estimates both the water stored in the aquifer and the portion that contributes to discharge. This technique is commonly used because of its simplicity and reliance on readily available data, such as water table measurements and specific yield values. However, it is most effective in regions with **minimal external influences**, such as pumping or evapotranspiration, which can complicate the interpretation of WTF.

The WTF method is widely applied in various hydrogeological settings, including humid regions and fractured aquifers. However, it is often criticized for its limitations, such as its inability to account for spatial heterogeneity in aquifers or to provide accurate recharge estimates in areas with complex groundwater flow systems.

4.4.2. Water Budget Method

The Water Budget Method (WBM) is a widely used approach for estimating GWR by balancing the various components of the hydrological cycle. This method evaluates all inflows and outflows of water within a specific area over a defined time period. It involves quantifying water inputs (recharge) and outputs (discharge) in a watershed or aquifer system to determine the net change in water storage.

The parameters required for recharge estimation include precipitation, water flow into and out of the area, evapotranspiration, changes in subsurface storage, and base flow. While most of these parameters can be measured or estimated, the accuracy of the recharge calculation is highly dependent on the precision of the other components.

The infiltration of rainwater into the groundwater is influenced by factors such as soil hydraulic properties, topography, vegetation, and land use. Infiltration coefficients are used to estimate the amount of water that percolates into the ground. These coefficients vary based on surface conditions, such as built environments, vegetation, or bare soil.

For example, built areas without RWH systems typically have a very low infiltration coefficient compared to natural landscapes like meadows or forests. The effective infiltration coefficient for an area can be calculated by considering the contributions of different land cover types and their respective infiltration rates. This value helps determine the volume of water that infiltrates into the groundwater system from precipitation across various surfaces.

Surface runoff is another critical component of GWR calculations. Runoff is affected by factors such as rainfall intensity and duration, land use/cover, soil type, and topography. RWH and GWR systems can significantly reduce surface runoff by increasing the infiltration of water into the subsurface, thereby enhancing recharge potential. A commonly used model for estimating surface runoff was developed by the United States Soil Conservation Service (SCS). This method is particularly effective for assessing runoff depth across watersheds by using runoff curve numbers (CNs). The CN reflects the combined effects of soil type, vegetation, and land use on surface runoff. Higher CN values indicate greater runoff potential, while lower values suggest more infiltration and less runoff. The potential maximum retention of water in a region is closely tied to the CN value, which serves as a critical parameter for estimating how different landscapes respond to precipitation. This relationship allows for the calculation of storm runoff depth and helps quantify the portion of precipitation that contributes to surface runoff versus infiltration.

While the WBM is comprehensive, its accuracy is heavily reliant on the precision of the individual components, such as precipitation, evapotranspiration, and surface runoff estimates. Small errors in these parameters can lead to significant inaccuracies in recharge calculations. Additionally, variations in soil conditions, land use, and topography can further complicate the estimation process. Therefore, careful consideration and accurate data collection are essential for reliable results.

4.4.3. Darcy’s Law

Darcy’s law serves as a foundational principle in hydrogeology, providing critical insight into the flow of groundwater through porous media. This principle, established by Henri Darcy in the 19th century, is vital for understanding dynamics of groundwater movement and particularly significant in estimating GWR the process by which water infiltrates from the surface into the groundwater system (Figure 11).

Darcy’s Law explains how groundwater flows in response to differences in hydraulic head and the properties of the geological materials through which it moves. By analyzing the hydraulic gradient (the change in water pressure over a distance) and the **hydraulic conductivity** (which reflects the permeability of the soil or rock), the rate at which water infiltrates into aquifers can be estimated.

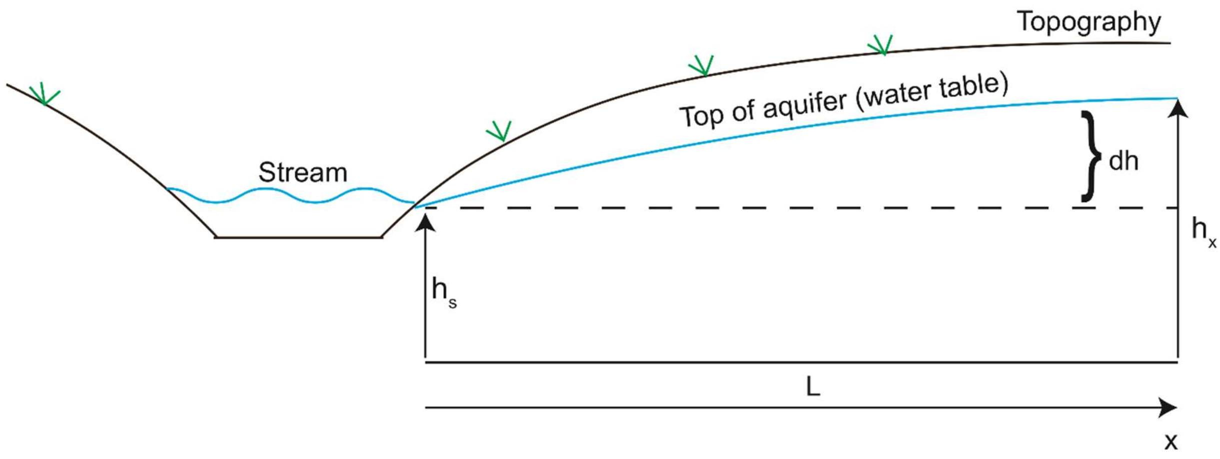

Figure 11: Water Entering an Aquifer, Darcy principle

Darcy flux:

$$q = -K\frac{dh}{L} \qquad Q = -KA\frac{dh}{L}$$

q =Darcy flux

dh= height of the aquifer/ hydraulic head (m)

L= horizontal distance (m)

K = hydraulic conductivity (m/s)

Q = discharge rate / a volume flux (m^3/s)

A = Cross sectional area of the flow media

4.4.4. Empirical Methods

Empirical relationships between groundwater recharge and rainfall are often established through seasonal groundwater balance studies. By analyzing data such as precipitation, evapotranspiration, and changes in groundwater levels across different seasons, recharge rates can be identified linking with rainfall amounts. These studies help to better understand how variations in rainfall contribute to groundwater replenishment, providing a foundation for predicting GWR under different climatic and hydrological conditions.

Such an approach enables the development of predictive models that estimate GWR based on seasonal rainfall variability. These models are particularly valuable for water resource management, as they can guide decision-making in regions where rainfall patterns directly influence aquifer sustainability. For example, explored the relationship between rainfall and recharge using empirical methods, highlighting how recharge rates vary with seasonal precipitation changes in different hydrogeological settings.

Establishing empirical relationships between rainfall and recharge is critical in regions affected by climate variability or water scarcity. By identifying and quantifying these relationships, water managers can:

• Predict the impacts of drought or changing rainfall patterns on groundwater resources.

• Design effective groundwater management and recharge enhancement strategies.

• Support sustainable groundwater extraction practices in agricultural, urban, and industrial sectors

Empirical methods for groundwater recharge use simple formulas based on rainfall (P) and regional coefficients to estimate how much water infiltrates to the aquifer, avoiding complex hydrological models, with common equations like

Recharge Coefficient Rc): The percentage of rainfall that becomes groundwater recharge, often determined from case studies (e.g., 18-20%) or derived from water table fluctuations.

- Maxey-Eakin Method: $R=P$*0.20 (using annual precipitation P, often in mm).
- Bredenkamp Formula: R=0.32*(MAP–360) (MAP = Mean Annual Rainfall in mm)
- Krishna Rao Relationship: R=0.30*(P–500) (using rainfall P in mm).

4.4.5. Tracer Techniques

Tracer techniques are widely employed in arid and semi-arid regions to estimate GWR from sources such as irrigation and rainfall. These methods rely on the use of environmental tracers to track water movement and quantify recharge rates. For instance, the chloride mass balance (CMB) method is commonly applied to assess recharge by analyzing chloride concentrations in soil and groundwater, providing insights into recharge processes under dry conditions.

Chemical Tracers (Bromide, Chloride, etc.):

Process: Inject or observe naturally occurring bromide/chloride and track its downward movement with water in soil/aquifer.

Principle: Depth of the tracer peak indicates average velocity; used for quantifying recent recharge, especially where recharge is small or irrigation is present.

Application

- Used in unsaturated zone (soil) to track infiltration and in the **saturated zone** (aquifer) to date water and map flow paths.
- Crucial for managing irrigation, assessing pollution, and understanding aquifer sustainability.

4.4.6. Groundwater Models

Field measurements of GWR often carry a significant degree of uncertainty, primarily due to the complexity of natural systems and the limitations of measurement techniques. Recharge estimation is influenced by numerous factors, including variability in precipitation, soil properties, vegetation cover, and hydrogeological conditions, all of which contribute to the challenges of obtaining precise measurements. Despite ongoing advancements in methods and technologies, reducing this uncertainty remains an active area of research in many regions.

In addition to direct field measurements, groundwater models have become essential tools in estimating recharge. These models incorporate a range of hydrological, geological, and climatic data to simulate recharge processes under various conditions. By integrating **spatial and temporal** variability, groundwater models can provide valuable insights into the distribution and dynamics of recharge over large areas and extended periods. For example, models can account for differences in recharge rates across diverse geological formations, as well as the impacts of seasonal or long-term climatic variations. Groundwater models also serve as predictive tools, enabling researchers and water resource managers to forecast recharge under changing environmental conditions, such as land use changes or climate variability. This predictive capability is crucial for sustainable water resource management, as it helps assess the resilience of aquifer systems and informs decisions on groundwater extraction and recharge enhancement strategies.

5. Soil moisture conservation practices, management, and use of residual soil moisture

Soil water plays a critical role in the life of plants. They need adequate water to develop a strong root system and to cool themselves. Irrigation is about proper timing and maintaining the available water in the appropriate amounts. When soil water drops below proper levels, crop stress develops, which leads to loss of both crop quality and yield. Over irrigation contributes to erosion, loss of nutrients, and increased input costs.

The main objective of soil moisture conservation is to minimize the amount of water lost from the soil through evaporation (water loss directly from the soil) and transpiration (water loss occurring through the plants), or combined, the evapotranspiration. Preserving soil moisture is an important means to maintain the necessary water for agricultural production and also helps minimize the irrigation needs of the crops. This is especially important in areas where rainwater and/or groundwater resources for irrigation are scarce or decreasing due to climate change or other causes.

Implementation

There is a variety of methods that can be used to conserve soil moisture. Most of these are relatively low-cost and complex approaches, primarily relying on the presence of required materials and technical capacity locally. Many of the methods rely on providing some kind of **cover** for the soil to minimize evapotranspiration and direct soil exposure to heat and sun. Generally, most methods used for **soil quality improvement and conservation** will also yield benefits to soil moisture conservation.

5.1. Soil moisture conservation practices and management

Soil moisture conservation involves practices like conservation tillage, mulching, and cover cropping to reduce evaporation and runoff, while rainwater harvesting and proper irrigation capture and store water for crops. The use of residual moisture refers to the water left in the soil after a main crop is harvested, which can be used for a second crop or to support soil health.

Agronomic practices:

- **Spreading manure or compost over the soil:** Incorporating organic matter into the soil to improve its structure and increase its ability to hold water. This minimizes evapotranspiration and also provides valuable nutrients to the soil through processes of decomposition.

- **Mulching:** Mulch is a layer of organic (or inorganic) material that is placed on the root zone of the plants and the soil surface to reduce evaporation, suppress weeds, and regulate soil temperature. Examples of mulch materials include straw, wood chips, and peat. Inorganic mulch in the form of plastic sheeting is also used. Mulching is most suited for low to medium rainfall areas, and less suited for areas with very wet conditions.

- **Conservation tillage**: Minimizing soil disturbance, as compared to conventional tilling, which helps retain soil moisture and organic matter and reduces or, in extreme cases, completely eliminates tillage to maintain healthy soil organic levels, which increases the soil's capacity to absorb and retain water. Conservation tillage is a specific type of such approach where crop residue is left on the soil to reduce evapotranspiration, and protect soil surface from wind, sun and heavy rain impacts.

- **Crop rotation and diversification**: Planting different crops in sequence to improve soil health and manage moisture needs over time, growing different types of crops every season helps improve soil structure and thus water holding capacity. Examples include rotating **deep-rooted and shallow rooted crops** that make use of previously unused soil moisture, as plants draw water from different depth levels within the soil. Crop rotation may also improve soil fertility and help control pests and diseases.

-**Cover crops:** Planting crops like legumes or grasses to protect the soil between main crop cycles, improve water infiltration, and add organic matter.

-**Weed control:** Removing weeds, especially when they are small, as they compete with crops for soil moisture.

- **Green manuring**: growing of plant materials with the sole purpose of adding to the soil for improved organic matter and nutrients. The improved soil quality then also improves water retention capacity.

- **Deep tillage**: suited for some areas and soils, deep tillage can help increase porosity and permeability of the soil to increase its water absorption capacity.

- **Mixed cropping and interplanting**: cultivating a combination of crops with different planting times and different length of growth periods.

- **Strip cropping**: growing erosion permitting crops and erosion resisting crops in alternate strips.

Soil management and landscape practices

-**Terracing:** Creating step-like ridges on slopes to slow runoff, increase water infiltration, and prevent erosion.

- **Contour farming/ploughing**: Ploughing and planting along the contour lines of a slope to create furrows that trap water. By ploughing the soil along the contour instead of up- and downward slopes, the velocity of runoff is reduced, creating even barriers, and more water is retained in the soils and distributed more equally across the cropland.

-**Tie-ridging:** A form of contour ridging where small dams are built across the ridges to hold water and increase infiltration time.

-**Ripping:** Using deep, narrow tines to break up compacted soil, creating channels for water to penetrate deeper into the soil profile.

-**Windbreaks:** Planting trees or shrubs around fields can reduce wind speed, which decreases soil evaporation.

Water harvesting and irrigation

-**Rainwater harvesting:** Constructing structures like terraces, contour bunds, or small ponds to capture and store runoff for later use.

-**In-situ moisture conservation:** Techniques like using tied ridges, planting basins, or Zai pits capture rainwater where it falls.

-**Drip irrigation:** A highly efficient method that delivers water directly to the plant roots, minimizing water loss through evaporation.

-**Retention ditches:** Digging ditches to collect and hold runoff water, allowing it to slowly seep into the soil, especially beneficial in semi-arid areas.

-**Water ponds:** Constructing small ponds or dams to capture and store rainwater for use during dry periods.

Other soil moisture conservation techniques may include **rainwater harvesting** to minimize runoff and collect water for use on site.

Environmental Benefits of Soil Moisture Conservation Techniques

- The benefits of many soil conservation methods, depending on the material used, may also include better control of weeds, provision of additional nutrients to the soil, soil temperature control and protection of soil surface from the impacts of heavy rain and wind.

- Active reuse of waste organic materials also reduces waste management needs, returning the residue crops and plants to the soil through decomposition.

Socioeconomic Benefits of Soil Moisture Conservation Techniques

- Potential to reduce water irrigation needs, increase crop productivity and improve soil quality

- By extension, reduced irrigation needs may also reduce the costs and energy requirements of water pumping for irrigation.

Opportunities and Barriers of Soil Moisture Conservation Techniques

Opportunities:

- Improved soil moisture goes hand in hand with improved soil quality thus potentially improving harvest and reducing soil degradation

- Opportunities for using existing waste materials may considerably reduce costs and needs for waste handling

- Many soil conservation methods are relatively low cost and complexity approaches, primarily relying on the presence of required materials and technical capacity locally

- May create new income and synergies between different crop variety farmers (e.g. using palm oil production residues for mulching).

Barriers:

- In some settings crop residues are not necessarily ‘residues’, and may already be used for animal fodder, thus necessitating additional investment for soil conservation purposes

- Planting of new cycle of crops through mulch or other crop residues may be difficult for non- mechanized agriculture, thus may not be suited in all locations.

5.2. Management and Use of residual moisture

- **Definition:** Residual moisture is the water left in the soil after the main crop has been harvested.

- **Management:** Farmers can manage residual moisture through careful planning, using it to support a subsequent crop, or to help the soil remain healthy through the dry season.
- **Benefits:** Maintaining good soil moisture through conservation practices can help retain more residual moisture, making it available for crops, which can lead to higher yields and improved crop water efficiency.
- **Monitoring:** Techniques like checking soil for dampness can help farmers determine the amount of residual moisture available for use.

Residual soil moisture conservation methods

Residual moisture, the water left in soil after main rains, is crucial for second cropping/off-season farming, especially in rain-fed areas, enabling farmers to grow short-duration, low-water-needs crops like legumes (chickpeas, mung beans) to boost food security, improve soil fertility (nitrogen-fixing), and enhance water use efficiency, often with practices like conservation tillage to preserve it. It's also vital in materials science (wood, concrete) to control cracking and shrinking, and in food processing (baked goods, snacks) for texture and shelf life.

Methods for conserving residual soil moisture primarily involve agricultural practices that reduce water loss through evaporation and runoff, while increasing the soil's capacity to store water. Key techniques include:

Agronomic Practices

- Mulching: Applying a layer of organic materials (e.g., straw, wood chips, compost, or crop residues) or inorganic materials (e.g., plastic sheeting) to the soil surface is highly effective. Mulch acts as a barrier to block direct sunlight and wind, significantly reducing evaporation and helping to maintain a more stable soil temperature.
- Conservation Tillage/No-Till Minimizing or eliminating soil disturbance (plowing) helps maintain soil structure, which in turn improves water infiltration and retention capacity. Leaving crop residues on the surface as part of no-till farming protects the soil from the impacts of sun, wind, and heavy rain.
- Crop Rotation and Cover Crops Rotating deep-rooted and shallow-rooted crops helps utilize moisture from different soil depths, improving soil structure over time. Planting cover crops also provides a permanent soil cover, which helps suppress weeds (reducing competition for water) and adds organic matter, further enhancing water retention.
- Adding Organic Matter Incorporating manure, compost, or other organic amendments into the soil significantly increases its water-holding capacity. Soil organic matter can absorb and hold up to 90% of its weight in water, a large portion of which is available to plants.

Physical and Mechanical Methods

- Contour Farming and Terracing Farming across the slope of the land (contouring) or creating terraces helps slow down surface water flow, which decreases runoff and allows more time for water to infiltrate the soil.
- Rainwater Harvesting/In-situ Conservation Techniques like planting basins, tie-ridging, and V-shape catchments are designed to concentrate rainwater in the root zone, preventing runoff and ensuring that moisture is captured and stored within the field for later use.
- Deep Tillage/Ripping (Context Specific) In some cases, deep tillage (subsoiling or ripping) can be used to break up compacted soil layers (pans) that impede water infiltration and root growth, allowing water to penetrate deeper into the soil profile.

These methods, often integrated as part of broader "conservation agriculture" principles, work to mitigate soil moisture stress, especially in rainfed or semi-arid regions where water scarcity is a major limitation to crop production.

In Agriculture (Soil Moisture)

- Double Cropping: Allows a second crop after the rainy season, increasing food/feed production in regions with limited irrigation.
- Crop Suitability: Ideal for short-season crops like chickpeas, mung beans, and certain pulses that need less water.
- Soil Health: Legumes grown in this way can fix nitrogen, improving soil fertility for subsequent crops.
- Water Conservation: Practices like mulching and conservation tillage help retain this moisture.

6. Climate-smart Agriculture (CSA) and water technologies

6.1. Climate-smart Agriculture (CSA) Technologies

What is climate-smart agriculture? Climate-smart agriculture (CSA) is a new approach to farming that aims to achieve **three goals** simultaneously, referred to by the FAO as the '**triple win'.**

These are:

(i) sustainably increasing agricultural **productivity and incomes**;

(ii) **adapting and building resilience t**o climate change; and

(iii) reducing and/ or removing **greenhouse gas emissions** in order to meet national food security and development goals.

CSA builds on earlier paradigms such as sustainable intensification (SI). SI was introduced to address the shortage of arable land by increasing agricultural yields without adverse environmental impact and without the conversion of additional non-agricultural land.

An important feature of CSA is the use of technology and improved agronomic practices to increase productivity on farms. Examples of this include the use of new crop varieties that are tolerant to heat and salinity and resistant to floods and drought. Another example is the use of crop diversification strategies and effective management techniques to improve water and soil quality.

CSA also allows for science-based **technology transfers, such as precision agriculture**, to developing countries. Finally, CSA goes behind agricultural practices and technology to include enabling policies, institutions and financing mechanisms to facilitate its uptake.

The third objective of CSA mentioned above acknowledges that agriculture and land use change are significant contributors to greenhouse gas (GHG) emissions. For example, agriculture, forestry and other land use contribute 24% of total anthropogenic GHG emissions, second only to the energy sector. African agriculture contributes about 15% of global agricultural GHG emissions, compared to 13% for Europe and 25% for the Americas

A set of 22 adaptation technologies are showcased. These are based primarily on the principles of agroecology, but also include scientific technologies of climate and biological sciences complemented by important sociological and institutional capacity building processes that are required for climate change to function. The technologies cover:

- Planning for climate change and variability
- Sustainable water use and management
- Soil management
- Sustainable crop management
- Sustainable livestock management
- Sustainable farming systems
- Capacity building and stakeholder organization

Table 1.1 Overview of Technologies Covered in the Guidebook

Technology Categories	Technologies
Planning for Climate Change and Variability	1. National Climate Change Monitoring System
	2. Seasonal to Interannual Prediction
	3. Decentralised Community-run Early Warning Systems
	4. Climate Insurance
Sustainable Water Use and Management	1. Sprinkler and Dripping Irrigation
	2. Fog Harvesting
	3. Rainwater Harvesting
Soil Management	1. Slow-forming Terraces
	2. Conservation Tillage
	3. Integrated Soil Nutrient Management
Sustainable Crop Management	1. Crop Diversification and New varieties
	2. New Varieties through Biotechnology
	3. Ecological Pest Management
	4. Seed and Grain Storage
Sustainable Livestock Management	1. Selective Breeding via Controlled Mating
	2. Livestock Disease Management
Sustainable Farming Systems	1. Mixed Farming
	2. Agro-forestry
Capacity Building and Stakeholder Organisation	1. Farmer Field Schools
	2. Community Extension Agents
	3. Forest User Groups
	4. Water User Associations

6.2. Climate-smart water technologies

Worldwide water management in irrigated and rain-fed agriculture is becoming more and more complex to overcome the expected water scarcity stress. In addition to this, challenges of global warming and climate change would have to be met through the judicious application of water in agriculture through climate-smart water technologies. Agriculture is an important sector in Ethiopia and many developing countries, providing huge employment opportunities to rural populations and supporting them to achieve food and nutritional security goals. An attempt has to be made to address challenges of increasing food production and improving rural livelihoods, while safeguarding critical water resources for sustainable use through adaptive measures for effective water management, particularly in drought-prone regions. An integrated approach needs to be implemented in agricultural water management through the adoption of innovations such as water harvesting, micro-irrigation, and resource conservation farming to increase water-use efficiency in agriculture and other critical services to humans and animals. This training also aims to facilitate an improved understanding of the potential implications of climate change and adaptation options for agricultural water management and thereby assist policymakers in taking up adaptation challenges and developing measures to reduce the vulnerability of the farming sector to climate change.

Climate Change and its Impacts

Climate change is a complex and pressing issue that has been affecting our planet for decades. It is a result of the increased emission of greenhouse gases, such as carbon dioxide, into the atmosphere. These gases trap heat from the sun and cause the Earth's temperature to rise, leading to a series of changes in the climate system. As a result, the Earth is experiencing rising temperatures, altered precipitation patterns, and sea level rise, among other things.

As we grapple with the complexities of climate change, it becomes increasingly clear that its impacts are not confined to any single domain. Rather, they manifest across various facets of life, from the natural world to the economy, society, and human health. Each of these areas experiences the ripple effects of climate change in unique yet interconnected ways, necessitating a comprehensive understanding and multi-pronged approach to mitigation and adaptation.

Impact on the Natural World

In the realm of the natural world, climate change is a catalyst for profound transformations. Rising temperatures and altered precipitation patterns disrupt ecosystems, leading to loss of biodiversity as plant and animal species struggle to adapt to new climatic conditions. The melting of glaciers and polar ice caps contributes to sea-level rise, which in turn leads to the loss of habitats for numerous marine and coastal species. **Forests, the lungs of the Earth**, are increasingly susceptible to wildfires, further accelerating the release of carbon dioxide into the atmosphere.

Economic Consequences

From an economic standpoint, the implications are equally terrible. Agriculture, a cornerstone of many economies, faces the brunt of unpredictable weather patterns, affecting food production and leading to market volatility. Energy sectors, particularly those reliant on hydroelectric power, are compromised as water levels in rivers and dams fluctuate. Tourism, especially in regions known for their natural beauty, suffers as landscapes are altered, and extreme weather events become more common. These economic disruptions have a cascading effect, leading to job losses and exacerbating poverty.

Social Implications

On the social front, climate change acts as a "threat multiplier," exacerbating existing inequalities and vulnerabilities. Marginalized communities, often residing in areas more susceptible to flooding, droughts, or other extreme weather events, face disproportionate challenges. These communities frequently lack the resources or social infrastructure to adapt or recover quickly, leading to increased poverty, displacement, and social unrest. Moreover, the social fabric of communities can be strained as competition for dwindling resources intensifies.

Effects on Human Health

The impacts on human health are both direct and indirect. Rising temperatures contribute to heat-related illnesses and exacerbate existing health conditions. Altered weather patterns can lead to the spread of waterborne diseases like cholera and increase the prevalence of vector-borne diseases such as malaria. Air pollution, intensified by wildfires and industrial emissions, leads to a rise in respiratory and cardiovascular diseases. Mental health is also affected, as the stress and anxiety associated with extreme weather events or gradual environmental changes take a psychological toll.

The Impacts of Climate Change on Water Resources: Quantity, Quality, and Variability

Climate change is one of the most pressing issues of our time, with far-reaching impacts on the environment, human societies, and the economy. Among the many areas affected by climate change, water resources are of particular concern, as water is a critical resource for human well-being, economic development, and ecological health.

Climate change is impacting water resources across multiple dimensions: quality, quantity, and availability.

- **Quality**: Rising temperatures can cause water to become warmer, which can lead to an increase in the growth of harmful algae and bacteria. These organisms can produce toxins that are harmful to humans, animals, and the environment. The increased frequency and severity of natural disasters, such as storms and floods, can also lead to water pollution by washing pollutants and toxic substances into rivers, lakes, and groundwater aquifers. This can result in the contamination of drinking water sources and the death of aquatic species.

- **Variability**: As temperatures rise and precipitation patterns change, water resources are becoming increasingly unpredictable. This can make it difficult for water managers to make decisions about water allocation and distribution, as they must balance the needs of different water users, including farmers, cities, and the environment. This unpredictability can also make it challenging to plan and implement water infrastructure projects, such as dams and reservoirs, which are critical to ensuring a reliable water supply.

- **Availability**: With the onset of climate change, sea levels are rising and glaciers are melting, leading to significant shifts in water availability. The intrusion of saltwater into coastal aquifers is restricting access to fresh water for local communities. Similarly, the diminishing water reserves in mountainous regions, often a vital water source for entire countries, are causing increased water scarcity. These changes are complicating existing water management efforts, making it more challenging to meet the needs of various water users.

Addressing these impacts requires a comprehensive, multi-faceted approach that involves governments, industry, and citizens working together to develop and implement effective adaptation and mitigation strategies.

Understanding Climate Change: Adaptation and Mitigation

While both adaptation and mitigation are essential strategies for addressing the impacts of climate change on water resources, they serve distinct roles and objectives.

- **Adaptation** focuses on making adjustments to existing systems and practices to minimize the adverse effects of climate change. This could involve implementing **water-saving technologies,** redesigning infrastructure to withstand extreme weather events, or altering water allocation policies to account for changing precipitation patterns.
- **Mitigation** aims to reduce the severity of climate change itself, primarily by lowering greenhouse gas emissions. In the context of water management, mitigation strategies might include transitioning to energy-efficient water treatment plants, promoting sustainable agriculture that requires less water, or protecting and restoring natural water systems like wetlands and forests that act as carbon sinks. While adaptation addresses the symptoms of climate change, mitigation tackles the root cause, and both are needed for a comprehensive approach to sustainable water resource management.

Adaptation Strategies for Water Resource Management in a Changing Climate

Adaptation strategies for water resource management in a changing climate are crucial to ensuring the sustainability and resilience of these resources in the face of changing conditions. A comprehensive and integrated approach is needed that encompasses multiple areas of intervention, including the following:

- **Improving the Resilience of Water Systems**: This can be achieved through better water management practices, such as water conservation, water reuse, and water-saving technologies, to ensure the sustainable use of water resources and reduce the impacts of droughts and floods. The development of new water infrastructure, such as dams, reservoirs, and water treatment plants, can also help to increase the resilience of water systems by improving the reliability and sustainability of water supplies.
- **Investing in New Infrastructure**: Investing in new water infrastructure, such as water treatment plants, water distribution networks, and water storage facilities, can help to improve the quality and availability of water resources and reduce the impacts of climate change. The development of new water sources, such as desalination plants and water harvesting systems, can also help to enhance the resilience of water systems and reduce the impacts of water scarcity.
- **Reducing Vulnerability of Communities**: Climate change impacts water resources differently in different regions, and communities with limited resources and infrastructure are often the most vulnerable. To address this, adaptation strategies should aim to reduce the vulnerability of communities to water-related risks by investing in water infrastructure, water education and awareness programs, and water-saving technologies.
- **Improving Water Management Practices**: Effective water management practices are essential for ensuring the sustainability and resilience of water resources in a changing climate. This includes measures such as water conservation, water reuse, and water-saving technologies, as well as the development of

water management plans that take into account the impacts of climate change and the needs of different stakeholder groups.

- **Encouraging Collaboration and Partnerships**: Addressing the impacts of climate change on water resources requires collaboration and partnerships between government, industry, and the public. By working together, these groups can identify the most effective adaptation strategies, develop and implement new water management practices, and promote public education and awareness on the importance of sustainable water resource management.

In addition to these adaptation strategies, **mitigation strategies**, such as reducing greenhouse gas emissions and improving energy efficiency, can help to slow the pace of climate change and limit its impacts on water resources. These strategies can help to reduce the overall demand for water, improve the sustainability of water supplies, and reduce the risks associated with climate change. Ultimately, an integrated and comprehensive approach that encompasses both adaptation and mitigation strategies is needed to ensure the sustainability and resilience of water resources in a changing climate.

The Role of Governments, Regulators, Industry, and Citizens in Addressing the Impacts of Climate Change on Water Resources

Addressing the impacts of climate change requires a collective effort from various stakeholders. The role of each stakeholder is critical to ensuring that we can effectively mitigate the impacts of climate change and ensure the long-term sustainability of our water resources.

- **Governments**: As the primary policy-making bodies, governments have a multi-faceted role in addressing the impacts of climate change on water resources. They are responsible for developing and implementing comprehensive policies and regulations that promote sustainable water management. This includes setting legal frameworks for water usage, quality standards, and conservation efforts. Beyond this, governments can also fund research and development initiatives aimed at discovering innovative water-saving technologies and practices. These actions align closely with the strategy of "Improving the Resilience of Water Systems." Moreover, governments have the financial capability to invest in new and existing infrastructure, such as dams, reservoirs, and water treatment plants, to improve the reliability and sustainability of water supplies, thereby contributing to "Investing in New Infrastructure."

- **Regulators**: Regulatory bodies serve as the enforcement arm of government policies, ensuring compliance with established standards and guidelines. They play a crucial role in auditing and monitoring the sector to ensure alignment with sustainable water management principles. Regulators also have the authority to set stringent standards for water quality and usage, which can include penalties for wasteful practices or incentives for water-saving initiatives. This role is directly related to the strategy of "Improving Water Management Practices." Additionally, regulators can facilitate the approval and implementation of new technologies and infrastructure projects that contribute to water sustainability, thereby aligning with the strategy of "Investing in New Infrastructure." To further bolster system resilience and sustainability, regulators can incentivize utilities to invest in innovative solutions and infrastructure upgrades. By offering financial incentives or streamlined approval processes, regulators encourage utilities to proactively contribute to the system's overall resilience, thereby enhancing its capacity to adapt to the challenges posed by climate change.

- **Industry**: Industries, particularly those that are water-intensive, have a significant role to play in sustainable water management. They can adopt and implement water-efficient practices, such as closed-loop systems that recycle and reuse water, thereby reducing overall water consumption. With their technical expertise and capital resources, industries are well-positioned to invest in research and development of new water-saving technologies. This aligns them with the strategy of "Investing in New Infrastructure." Furthermore, industries can collaborate with governments and regulators to develop best practices and standards, contributing to "Improving Water Management Practices." Their role extends beyond compliance, as they can also be pioneers in adopting renewable energy sources, thereby reducing greenhouse gas emissions and mitigating the broader impacts of climate change.

- **Citizens**: The role of individual citizens in sustainable water management is often underestimated, yet it is crucial for the success of any large-scale initiative. Citizens can adopt water-saving practices in their daily lives, such as using water-efficient appliances and fixing leaks promptly. Beyond individual actions, citizens can engage in community-based initiatives that promote water conservation and sustainable usage. By actively supporting policies and initiatives that promote sustainability, citizens can exert pressure on governments and industries to adopt more responsible practices. Their role extends to being informed voters, choosing leaders who prioritize sustainable water management, thereby indirectly influencing policy and regulation.

- **Farmers and Farmers' Consortiums**: Agriculture is one of the most water-intensive sectors, making farmers key stakeholders in the management of water resources. They can adopt water-efficient agricultural practices, such as drip irrigation and rainwater harvesting, which align with "Improving Water Management Practices." Farmers are often the first to feel the impacts of water scarcity and climate change, making them vital players in "Reducing Vulnerability of Communities." By adopting new technologies and practices, they can serve as examples for sustainable water usage in their communities. Farmers' consortiums, on the other hand, can act as advocacy groups, influencing policy at both local and national levels. These consortiums can collaborate with governments and other stakeholders to develop and implement water management plans, contributing to the strategy of "Encouraging Collaboration and Partnerships."

While in this manual, we mentioned the roles of governments, regulators, industry, and citizens, it's important to note that there are many other crucial stakeholders involved. These include Non-Governmental Organizations (NGOs), academic and research institutions, international organizations, local communities and indigenous groups, media, investors and financial institutions, utility companies, consultants and contractors.

Water resource management for climate change adaptation and mitigation:

Water resources management for climate change adaptation and mitigation involves both long-term strategies like investing in infrastructure and governance, and immediate actions like water conservation and rationing. Adaptation focuses on building resilience to climate impacts through measures like improved storage and efficient use, while mitigation involves reducing greenhouse gas emissions, such as by implementing different farming practices, and can be supported by water management strategies like conserving water to save energy.

Adaptation strategies

- **Invest in infrastructure:** Build new water treatment plants, distribution networks, and storage facilities to **improve availability and quality.**
- **Enhance storage:** Increase water storage in reservoirs, aquifers, ponds, and other natural water bodies to create a buffer against seasonal variability.
- **Implement efficient use and reuse:** Reduce waste and promote water reuse through more efficient practices and advanced modeling.
- **Develop new sources:** Explore options like desalination plants and water harvesting systems to enhance resilience and reduce scarcity.
- **Strengthen governance:** Improve coordination between stakeholders and adapt governance frameworks to different scales (e.g., watersheds, river basins) to better respond to climate hazards.
- **Use immediate coping strategies:** Employ short-term solutions like water rationing, filtration, and using alternative water sources during extreme events, while integrating them with long-term solutions.

Mitigation strategies

- **Improve farming practices:** Adopt methods like the System of Rice Intensification (SRI) to reduce methane emissions by managing water saturation and flooding in rice paddies.
- **Conserve water:** Water conservation efforts reduce energy consumption needed for water transport and treatment, contributing to overall energy and emissions reduction.

Integrate planning: Adopt an integrated planning approach that considers the connection between water conservation and energy savings at all levels.

Climate-Smart water technologies

Climate-smart water technologies are innovative approaches to water management that increase efficiency, promote sustainability, and build resilience to climate change impacts. Key examples include micro-irrigation and laser land leveling for agriculture, water harvesting, smart water meters, and solar-powered irrigation systems. These technologies aim to conserve water, reduce waste, and help communities and industries adapt to challenges like drought and inconsistent rainfall.

In agriculture

- **Micro-irrigation:** Drip and sprinkler systems deliver water directly to plant roots, reducing evaporation and saving 30-40% of water compared to traditional furrow irrigation.
- **Laser land leveling:** This technology improves field uniformity, which decreases irrigation needs and increases water efficiency.
- **Water harvesting:** Collecting and storing rainwater runoff for later use is a crucial water conservation technique.
- **Alternate wetting and drying:** A practice particularly useful for rice paddies, this method involves alternating periods of flooding and draining to reduce water use and greenhouse gas emissions.
- **Floating solar power plants:** These can be used to power pumps and other irrigation equipment, and also help reduce water loss from reservoirs through evaporation.

In water management and conservation

- **Smart meters and IoT sensors:** These devices help monitor water consumption, detect leaks in real-time, and alert users to potential problems, which promotes responsible use in both municipalities and households.
- **IoT** sensor **i**s are crucial devices that detect and measure physical changes (like temperature, light, motion, pressure, humidity, air quality) in the environment, convert them into digital data, and transmit it over a network for processing, analysis, and automation, forming the core of Internet of Things (IoT) systems in smart homes, industries, healthcare, and agriculture.

In climate adaptation

- **Greenhouse and tunnel technology:** These structures can increase agricultural production by allowing for more harvests per year, particularly for high-value crops.
- **Hydroponics and aeroponics:** These soil-less farming methods can significantly reduce water usage compared to traditional agriculture. It a system grows plants without soil, using mineral-rich water solutions, often with an inert medium like perlite or coco coir for root support, enabling faster growth, higher yields, less water use (up to 80% less), and year-round production in controlled environments, making it great for urban farming and limited spaces by delivering nutrients directly to the roots (Figure 12).
- **Climate data and forecasting:** Integrated weather stations and other technologies provide data that helps farmers and water managers make better decisions about when and how to irrigate.

Urban irrigated agriculture

Figure 12: Hydroponics system of irrigation

climate-smart irrigation options include:

- **Optimal irrigation** using minimal water to grow crops profitably while reducing water waste;
- **Deficit irrigation** to supply minimal water only at drought-sensitive growth stages;
- **Irrigation timing** to balance plant needs with different day and seasonal evapotranspiration times;
- **Balancing water use** against what can be grown in different soil fertility levels;
- **Responsive varieties and strategies** to reduce water footprint, maximizing water productivity, and avoiding climate extremes.

In conclusion, climate change is having a profound impact on water resources, with serious implications for human well-being, economic development, and ecological health. It is essential that we take action now to manage these impacts and promote a sustainable future for our planet and its people. By working together, we can help to ensure a secure and sustainable water future for generations to come.

6.3. Climate-Smart Water Management Practices

Climate-smart water management practices are essential for adapting to the impacts of climate change and ensuring water security. These practices aim to improve water use efficiency, enhance resilience to climate variability, and protect water resources while also mitigating greenhouse gas emissions.

Climate-smart water management practices encompass a wide range of approaches, including water conservation and efficiency measures (e.g., drip irrigation, leakage detection, water-efficient appliances); rainwater harvesting techniques (e.g., urban rainwater systems, farm ponds, recharge wells); integrated watershed management strategies (e.g., reforestation, afforestation, terracing, wetland restoration); flood management measures (e.g., floodplain zoning, green infrastructure, early warning systems); groundwater management practices (e.g., artificial recharge, managed aquifer recharge, groundwater mapping); nature-based solutions (e.g., riparian buffers, agroforestry, wetland restoration, urban green infrastructure); climate-adaptive agricultural practices (e.g., crop diversification, alternate wetting and drying, mulching); advanced water technologies (e.g., desalination, smart water grids, water recycling); and supportive policy and institutional mechanisms (e.g., water pricing, community-based water management, legal frameworks). Capacity building and education, including training programs, public awareness campaigns, and knowledge sharing platforms, are crucial for effective implementation and widespread adoption of these practices. Continuous monitoring and evaluation, utilizing tools such as remote sensing, water quality sensors, and data-driven decision-making, are essential to assess the effectiveness of these practices and make necessary adjustments (Figure 13).

Figure 13: Precision irrigation as climate-smart irrigation water application

7. Governance, gender, and community engagement in IWRM

7.1. Governance in IWRM

Governance in Integrated Water Resource Management (IWRM) is the framework for coordinating water, land, and related resources to ensure equitable, sustainable, and efficient use. It involves establishing rules for water use, managing conflicting demands among users like agriculture and industry, and ensuring ecological sustainability. Key aspects include participatory decision-making, collaboration across different levels of government and policy sectors, and implementing mechanisms for enforcement.

Core principles and goals

- **Economic efficiency:** Manages water resources to maximize economic and social welfare.
- **Social Equity:** Ensures basic human needs, especially for water and sanitation, are met.
- **Ecological sustainability:** Considers the long-term health of ecosystems and ensures the resource isn't compromised for future generations.
- **Human right to water:** Recognizes water as a fundamental right for all.

Key components of IWRM governance

- **Coordination:** IWRM requires intensive coordination both vertically (across government levels) and horizontally (across sectors like agriculture, industry, and energy).
- **Participation:** A participatory approach involving users, planners, and policymakers at all levels is crucial for effective decision-making.

- **Inclusivity:** Includes all stakeholders, such as farmers, factories, and communities, in the decision-making process.
- **Holistic approach:** Considers the interconnectedness of water with land and other resources, and factors like climate change, population growth, and economic development.
- **Enforcement and mechanisms:** Water governance refers to the mechanisms that establish and enforce the rules that guide water-related actions and plans.
- **Decentralization:** Decentralizing management functions to catchment or local levels can create new political spaces for contestation and resource management, with local governments playing a key role in service delivery.

7.2. Gender Roles and Responsibility in Water Management

Gender and water have a particularly strong link. For sustainable water resources management, ensuring meaningful participation of all stakeholders is critical.

7.2.1. Domestic Water Use

Domestic water use and management are areas where gender roles are Gender Perspectives in Integrated Water Resource Management. Gender Perspectives in Integrated Water Resource Management are particularly pronounced (Figure 14). In many cultures, women and girls are primarily tasked with fetching and managing household water. This responsibility includes ensuring water quality, cleanliness, and proper storage. The gendered division of labor in water-related tasks has a significant impact on the daily lives of women and girls, affecting their health, education, and economic opportunities. Collecting water can impose a significant time and labor burden on women and girls, particularly in regions where water sources are distant or unreliable. In many rural areas, women may spend several hours daily walking to and from water sources, reducing the time for other productive activities, such as education, income-generating work, and leisure. This labor-intensive task can also lead to physical health issues, including musculoskeletal problems and fatigue. Women are crucial in maintaining household health and hygiene through water management.

They are typically responsible for cooking, cleaning, and caring for children, which requires access to safe and sufficient water. Limited access to clean water can cause health problems, like waterborne diseases, with women and children being the most affected. Women's knowledge and practices regarding water, sanitation, and hygiene are vital in preventing disease outbreaks and ensuring community health. The time and effort required for water collection can have significant educational and economic impacts, particularly on girls.

In many cases, girls are taken out of school to help with water-related tasks, which limit their educational attainment and future opportunities. Women's economic activities are also affected, as time spent on water collection reduces the time available for other income-generating activities. This perpetuates the cycle of poverty and limits the economic development of communities. Despite the challenges, women possess extensive knowledge and expertise in water management that can be leveraged for community benefit. Their firsthand experience with water use and needs makes them invaluable participants in water management decision-making processes.

Encouraging women's leadership and participation in water committees and local governance structures can lead to more effective and sustainable water management practices that address the needs of all community members. Addressing gender disparities in domestic water use and management requires targeted policy interventions and programs. Governments and organizations should prioritize gender-sensitive approaches that recognize and address women and girls' unique challenges. This includes investing in infrastructure to reduce water collection time and labor burden, promoting women's education and economic opportunities, and ensuring women's active participation in water governance. By empowering women and integrating gender perspectives into water management policies, communities can achieve more equitable and sustainable outcomes.

Figure 14: The role of women on water use in pastoral areas, Afar.

7.2.2. Agricultural Water Use

Agriculture is a sector where water use and management are crucial, and gender roles significantly influence these practices. In the field of agriculture, there exists a notable distinction between the roles and resource access of women and men, which significantly influences their respective experiences and challenges concerning water usage. Women play a crucial role in agricultural water management, especially within small-scale and subsistence farming contexts. They are often responsible for essential tasks such as planting, weeding and harvesting, all of which necessitate considerable water consumption. However, despite their significant contributions, women often face limited access to water resources and irrigation infrastructure compared to men due to cultural norms.

7.2.3. Fisheries and Aquaculture Water Use

Fisheries and aquaculture are vital for food security, nutrition, and livelihoods, particularly in coastal and inland communities, with distinct gender roles across the sectors. Women hold vital yet frequently underappreciated roles in post-harvest activities, including the processing, marketing, and sale of fish. These activities are essential for enhancing the value of fish products and ensuring the economic sustainability of fishing communities. Their contributions are integral to the success and resilience of these communities.

Despite their significant contributions, women frequently face challenges related to access to resources and decision-making, often having limited access to fishing grounds, boats, gear, and aquaculture inputs compared to men. Furthermore, women are typically under-represented in formal decision-making bodies and fishery management organizations, leading to policies that may not adequately address their needs and contributions. The economic and social impacts of these gender disparities are profound, limiting women's economic opportunities and exacerbating poverty and vulnerability.

Nevertheless, women possess valuable knowledge and expertise in fisheries and aquaculture that can enhance resource management and sustainability. Promoting women's leadership and participation in fishery management and aquaculture development is essential for creating more inclusive and resilient systems. Addressing these gender disparities requires targeted policies and interventions, such as enhancing women's access to resources, providing capacity-building and training programs, encouraging representation in management organizations, supporting women's networks and developing gender-sensitive policies. By implementing these measures, the fisheries and aquaculture sectors can become more equitable and sustainable, benefiting both men and women and enhancing overall community resilience and prosperity.

7.2.4. Gender-Specific Challenges in Water Management

7.2.4.1. Access to and Control over Water Resources

Recognizing the gender dynamics within water management is vital, as men and women frequently have distinct roles and differing needs related to the access and utilization of water resources. This understanding is essential for developing equitable and effective water management strategies. Generally, it is observed that women tend to use and need more water than men for various purposes. However, despite the essential nature of water for all activities, only a minority of women globally enjoys complete access to and control over water resources.

Access to water resource management is indispensable for ensuring fair and sustainable water distribution. However, entrenched gender-specific challenges impede women and girls' full participation and benefit in this critical domain. The underrepresentation of women in decision-making bodies governing water resources, deeply rooted in societal norms and cultural expectations, sidelines their unique perspectives and needs.

Consequently, water management decisions may fail to account for women's diverse experiences and requirements, perpetuating gender discrimination in access to water resources. Moreover, the inequitable access to training and resources further exacerbates the marginalization of women in water management. Limited opportunities for women to acquire technical skills and knowledge essential for effective engagement in water management initiatives restrict their ability to contribute meaningfully to decision-making processes. Additionally, **disparities in access to financial resources** hinder women's capacity to invest in water infrastructure or implement sustainable water management solutions in their communities. These barriers hinder women's agency and perpetuate their exclusion from key roles in shaping water resource management strategies.

7.2.4.2. Participation in Decision-Making

Many challenges hinder gender participation in decision-making for water management, each deeply rooted in socio-cultural norms, institutional barriers, power dynamics and resource constraints. These obstacles collectively undermine women's meaningful involvement and representation in shaping water governance, perpetuating gender inequality in access to and management of water resources. Socio-cultural norms play a significant role in dictating male dominance in decision-making spheres related to water management. Traditional gender roles frequently assign women to domestic responsibilities, while men are typically viewed as the main decision-makers within community governance structures. As a result, women's voices are marginalized and their perspectives on water-related issues are often overlooked or undervalued. Limited access to education and training opportunities further exacerbates gender disparities in water resource management. Women and girls may face barriers in accessing technical skills and knowledge essential for effective participation in decision-making processes. Without adequate education and training, women are ill-equipped to contribute meaningfully to the development and implementation of water management policies and strategies, perpetuating their underrepresentation in water governance. Institutional barriers, such as male-dominated leadership structures and a lack of gender-sensitive policies, impede women's meaningful involvement in decision-making processes.

Women often encounter resistance and discrimination in male-dominated environments, hindering their access to decision-making roles. Additionally, the absence of gender-sensitive policies fails to address the specific needs and priorities of women, perpetuating their underrepresentation and sidelining their diverse perspectives. Power dynamics within communities further marginalize women and constrain their influence in shaping water policies and practices. Patriarchal structures prioritize men's interests, relegating women to subordinate roles and limiting their participation in decision-making processes. As a result, women's voices are often silenced and their contributions to water governance are undervalued, exacerbating gender disparities in access to water resources.

Resource constraints, including limited access to financial resources and infrastructure, present additional barriers to women's participation in decision-making for water management. Without adequate support and resources, women are unable to advocate for their needs and rights in water-related discussions and negotiations.

Integrated Water Resources Management (IWRM) systematically addresses water challenges, emphasizing sustainability, equity and community participation. Despite its significance, gender perspectives in IWRM are often overlooked. Principle 3 of IWRM highlights women's roles in providing, managing and safeguarding water, emphasizing the need to integrate gender perspectives into IWRM. However, translating this principle into actionable strategies has been sluggish, with few countries implementing gender-responsive measures.

This chapter highlights the significance of blending gender perspectives into Integrated Water Resources Management (IWRM) to improve **efficiency, effectiveness, equity and equality** -collectively referred to as the 4Es - in the pursuit of sustainable water management.

Empowering women not only promotes gender equity but also fosters resilient water management solutions. Women's roles in domestic water use, agriculture, fisheries and aquaculture highlight the need for targeted interventions, such as infrastructure investments and education. Policies must prioritize women's access to affordable water resources and their participation in decision-making. **Gender-responsive and transformative approaches** are essential to addressing gender-specific challenges in IWRM, including access, affordability, climate impacts and technological barriers. These approaches promote uniform opportunities for men and women to contribute to and benefit from water-related initiatives, fostering sustainability and inclusivity. Tailored gender policies, sensitive institutions and gender-friendly technologies are pivotal for creating a facilitating environment for women's participation and leadership in water governance. By embracing gender perspectives, communities can unlock the full potential of water resources, advancing social equity, environmental sustainability and economic prosperity for all. This approach ensures a balanced and inclusive future for water management practices globally.

7.2.4.3. Gender and Climate Change Challenges in IWRM

Climate change presents considerable obstacles to water management, with women and marginalized communities bearing a disproportionate burden of its impacts. As primary caretakers and water managers in many societies, women face heightened risks from climate-induced changes such as water scarcity, flooding, and waterborne diseases. These challenges are compounded by the intersection of gender and socio-economic factors, deepening existing vulnerabilities and creating new obstacles in accessing and managing water resources. One of the most pressing issues exacerbated by climate change is water scarcity, which amplifies the burden on women responsible for water collection and household management. As water sources dwindle or become contaminated due to changing precipitation patterns and rising temperatures, women often travel longer distances to fetch water, spending more time and energy on water-related tasks. This increased workload not only limits women's opportunities for education, income generation and participation in decision-making processes but also perpetuates gender disparities and hampers community development efforts. Moreover, climate-induced disruptions in water availability and agriculture exacerbate economic disparities, particularly affecting women in rural areas who rely on agriculture for their livelihoods. Decreased water availability and crop yields can lead to food insecurity, loss of income and increased poverty among women-headed households and marginalized communities. The lack of access to financial resources, climate-resilient infrastructure, and water-saving technologies further exacerbates their vulnerability, impeding their ability to adapt to changing water conditions and build resilience. Additionally, women's limited access to resources and underrepresentation in decision-making processes exacerbate their marginalization and hinder their capacity to cope with climate change impacts. Male-dominated leadership structures and cultural norms often marginalize women's voices and perspectives in water management and climate adaptation strategies, resulting in policies and initiatives that fail to address their specific needs and vulnerabilities.

To address these challenges, gender-responsive approaches are essential, prioritizing women's participation, equitable access to resources and the integration of gender considerations in water management and climate adaptation strategies. Promoting women's leadership and involvement in decision-making processes, ensuring equal access to education, training **Gender Perspectives in Integrated Water Resource Management** and technology and challenging harmful gender norms and stereotypes are crucial steps towards building more inclusive and sustainable water systems. By recognizing and addressing the gender dimensions of climate change, communities can foster resilience and empower women to become agents of change in building more equitable and sustainable water management systems that benefit everyone, regardless of gender or socio-economic status. Through collaborative initiatives and inclusive policies, we can foster a future where water resources are managed with integrity and the effects of climate change are addressed effectively, ensuring the well-being of all stakeholders involved.

7.2.4.4. Gender and Technological Challenges

Gender and technological challenges significantly influence water management, affecting access, efficiency and sustainability in water-related activities. Women and marginalized communities often encounter barriers in accessing water-related technologies, stemming from limited financial resources, technical skills and cultural norms. This impediment hinders their capacity to adopt technologies facilitating water collection, purification and distribution. Moreover, technological solutions may not align with women's preferences and needs, leading to the adoption of systems ill-suited for their usage, particularly in rural areas where women bear the brunt of water collection responsibilities. The design of water-related technologies often reflects biases towards male users, overlooking ergonomic considerations crucial for women's comfort and effectiveness in usage. Additionally, the under-representation of women in technological development leads to solutions that often fail to address their needs, further reinforcing gender disparities in water management. The digital divide exacerbates these challenges, particularly in rural and low-income communities, where women lack access to **essential digital tools** for effective water resource management. Addressing these hurdles necessitates a gender-responsive approach, involving women in designing and developing water-related technologies to ensure inclusivity and user-friendliness. Targeted training programs must be implemented to enhance women's technical skills and empower them to utilize water-related technologies effectively. Furthermore, adopting gender-sensitive technologies tailored to address women's specific challenges is crucial, alongside investment in infrastructure and policies bridging the digital gap to ensure equitable access to technology for women and marginalized communities. Through addressing these gender and technological challenges in water management, communities can enhance access to clean water, improve efficiency in water distribution and promote sustainable utilization of water resources for the collective benefit of all.

7.2.5. Policy Frameworks and Recommendations

7.2.5.1. Gender Mainstreaming in Policies

The integrated management of water resources is essential for sustainable development, economic growth and social well-being. However, Gender Perspectives in Integrated Water Resource Management disparities in access, control and decision-making related to water resources persist, limiting the effectiveness and equity of water management practices. To address these disparities, gender mainstreaming in IWRM is crucial. This policy outlines strategies to incorporate gender perspectives into all aspects of water resource management, ensuring that both women and men can equally contribute to and benefit from water-related initiatives. The objectives of this policy are multifaceted and aim to foster an inclusive approach to water resource management. Firstly, promoting gender equality is a core objective, ensuring that women and men have equal opportunities to participate in and benefit from water resource management. This is crucial because water management decisions affect all aspects of community life, from health and hygiene to economic activities and environmental sustainability. Enhancing women's participation is another key objective, aiming to increase women's representation and influence in decision-making processes related to water management. Historically, women have been underrepresented in these areas, which have led to a lack of consideration for their specific needs and perspectives. **Improving resource allocation** is also essential, ensuring that water resources and related services are distributed in a manner that meets the needs of both women and men. This involves understanding and addressing the different ways in which men and women use and prioritize water resources**. Strengthening capacity building** is another critical objective, involving the provision of training and resources to empower both women and men with the knowledge and skills necessary for effective water management. Finally, **monitoring and evaluation** are vital for establishing mechanisms to track the impacts of gender mainstreaming in IWRM, ensuring continuous improvement and accountability.

To achieve these objectives, a series of policy actions are proposed. **Establishing an institutional framework** is the first step, which includes creating dedicated gender units within water management institutions to oversee the implementation of gender mainstreaming policies. These units would be responsible for developing gender action plans that outline specific goals, activities and indicators to promote gender equality in water management. Participation and decision-making processes must be reformed to ensure equal representation. This can be achieved by mandating the inclusion of women in water management committees, boards and decision-making bodies at all levels.

Supporting women's leadership is also crucial, which can be facilitated through **leadership training and mentorship programs** designed to encourage and support women in taking on leadership roles in water management. Capacity building is another essential component, involving the organization of regular gender sensitivity and **capacity-building workshops** for water management staff and community members. These workshops would focus on the importance of gender equality in water resource management and provide practical training on how to implement gender-sensitive approaches.

Promoting education and awareness is equally important, with campaigns to highlight the significance of gender equality in water resource management and to challenge traditional gender norms that may hinder women's participation.

Resource allocation and Gender Perspectives in Integrated Water Resource Management access must be addressed to ensure equitable distribution. This involves ensuring that water resources, infrastructure and services are distributed equitably, taking into account the specific needs of women and marginalized groups. Supporting women's projects by providing financial and technical support for water-related initiatives led by women can also promote gender equality.

Monitoring and evaluation are critical for tracking progress. This requires developing and using gender-sensitive indicators to measure the impact of gender mainstreaming efforts in water management and conducting regular assessments and audits to evaluate the effectiveness of these policies and make necessary adjustments.

The **implementation strategy for this policy** involves several key components. **Stakeholder** engagement is vital, involving government agencies, non-governmental organizations, community groups and the private sector in collaborative efforts towards gender equality in water management. **Policy integration** is also essential, ensuring that gender perspectives are incorporated into national and local water policies, plans and programs, aligning with broader gender equality and sustainable development goals.

Resource allocation must be sufficient to support the implementation of gender mainstreaming activities in water resource management, requiring both financial and human resources. **Capacity** development is another critical aspect, investing in the development of all stakeholders to emphasize the importance of gender equality and equip them with the tools to implement gender-sensitive approaches effectively. **Gender mainstreaming in Integrated Water Resource Management (IWRM)** is vital for achieving sustainable and equitable water management. By addressing gender disparities and promoting the active participation of both women and men in water-related decision-making processes, this policy aims to enhance the effectiveness of water management practices and ensure the equitable distribution of benefits derived from water resources.

The **successful implementation of this initiative requires continuous monitoring** and adaptive management, which can significantly contribute to broader goals of social justice, economic development and environmental sustainability. This policy emphasizes the necessity of a holistic and inclusive approach to water management, recognizing the critical role of women's involvement and the integration of gender perspectives in the success and sustainability of water resource management initiatives. By fostering an environment that encourages equal participation and benefits for both women and men in water management, communities can develop more resilient, equitable and sustainable water systems that support overall well-being and development.

7.2.6. GENDER MAINSTREAMING IN WATER RESOURCES MANAGEMENT: BENEFITS (WORLD WATER VISION, 1999)

Gendered Water Resources Management will lead to greater:

- **effectiveness:** the infrastructure, as well as valuable water resources, will be more widely and optimally used and sustained by all user groups.
- **efficiency:** the presence of limited water resources means the sector agency can reach more individuals.
- **development**: the service and its social process will not only bring water; it will increase consumption, production, income, environmental security, health, and overall family welfare.
- **Sustainable use in freshwater ecosystem:** women 's and men's direct and fair participation in research and project implementation can increase the potential flexibility and creativity in responding to environmental insecurity and changes in the resource system.
- **equity:** burdens and benefits will be shared more equitably between women and men in the community at large, as well as in the household level.

7.3. Community engagement in IWRM

Community engagement is essential for Integrated Water Resource Management (IWRM) because it integrates local knowledge, promotes equitable outcomes, and builds ownership, leading to more sustainable and effective water management. It involves various activities, from data collection and decision-making to implementation and monitoring, ensuring that IWRM initiatives meet the needs of all users and stakeholders, including marginalized groups and those with a direct dependency on water resources.

Key components of community engagement in IWRM

- **Leveraging local knowledge:** Communities have valuable on-the-ground knowledge about their local water resources, which is crucial for effective management and conservation. Engaging them ensures that decisions are made by practical experience.
- **Fostering ownership and responsibility:** Involving communities in the management process creates a sense of ownership, which increases their commitment to the long-term sustainability of water projects and the protection of water sources.
- **Promoting social equity:** IWRM with community engagement ensures that water is managed equitably, giving all users, especially vulnerable groups, a voice in decision-making and access to resources. This is particularly important in areas with water scarcity or high potential for conflict.
- **Improving adaptive capacity:** Communities can be supported to understand how changing conditions, such as climate change, affect water availability and can develop community-based strategies to adapt to these risks.
- **Ensuring accountability:** Transparency and community involvement can hold institutions accountable for their actions and performance and allow communities to voice their needs and set expectations for other parties.

8. Conclusion and recommendation

The training on IWM solutions highlights the critical importance of adopting holistic, climate-resilient, and inclusive approaches to water resource management in the face of increasing water scarcity and climate variability. By integrating the principles of Integrated Water Resources Management (IWRM) with practical interventions such as water harvesting and storage, groundwater recharge, soil moisture conservation, and climate-smart water technologies, the training emphasizes solutions that enhance water availability, productivity, and resilience at household and community levels. The participatory and experiential learning approach adopted in this training enables participants to draw on their own knowledge and field experience while strengthening their technical and analytical capacities. The focus on bundled solutions underscores the value of combining multiple, complementary interventions to maximize impact rather than implementing isolated measures. Furthermore, the integration of governance, gender, and community engagement considerations reinforces the understanding that sustainable water management outcomes depend not only on technical solutions but also on inclusive institutions, equitable access, and collective action. Overall, the training equips participants with the skills and perspectives needed to design and implement integrated water management interventions that are context-specific, socially inclusive, and environmentally sustainable.

Accordingly, the following recommendations are proposed:

- Promote integrated and bundled approaches to water management that combine surface water, groundwater, soil moisture, and climate-smart technologies to address multiple challenges simultaneously.
- Strengthen participatory planning and implementation, ensuring meaningful engagement of communities, women, and marginalized groups in decision-making processes.
- Enhance capacity building and knowledge sharing through continued learning, peer exchange, and practical field-based applications beyond the training period.
- Embed governance and institutional considerations into water management interventions to improve coordination, accountability, and long-term sustainability.
- Scale context-appropriate solutions by documenting best practices, lessons learned, and evidence of impact to inform policy, investment, and replication.
- Support monitoring, learning, and adaptation to ensure that integrated water management interventions remain responsive to changing climatic, environmental, and socio-economic conditions.

Implementing these recommendations will contribute to more resilient water systems, improved livelihoods, and sustainable management of water resources across diverse agro-ecological and socio-institutional contexts.

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Partial view of the trainees

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The CGIAR Sustainable Farming Science Program will address key challenges in agrifood systems by fostering efficient production of nutritious foods and safeguarding the environment to create fair employment opportunities, as we simultaneously tackle climate change, soil degradation, pests, diseases, and desertification.

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