SUSTAINABLE WATER RESOURCES: CONCEPT, DEFINITION, AND EXAMPLE

by

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ABSTRACT

The sustainability of water resources is a significant challenge for most countries, and specially for those that are located in arid regions. Here, we define a sustainable water resource as a **flux of water** that is **managed** with the objective of maintaining the **availability and quality** of water for as long as the **current climate** prevails. Based on this definition, we identify three main threats to sustainability of water resources: climate change, water pollution, and the adverse impacts of water resource management practices. These general concepts are illustrated using the example of Saudi Arabia. A framework for water resources management has been proposed for countries in arid regions, where the demand on water exceeds sustainable water resources. The objective of this framework is to close the gap between demand and sustainable water resource by developing new sustainable resources. The cornerstone in this framework is a water pricing system that links the price of water to the marginal cost for developing new sustainable water resource. The adoption of such a system would result in reducing demand as well as facilitating the development of new water technologies that are likely to enhance sustainable water resources.

1 INTRODUCTION

The human population density is significantly correlated to the corresponding spatial distribution of global water resources as measured by the amount of rainfall per unit area. This observation could easily be explained as due to the fact that water is one of the most important resources which determine the capacity for food production and the related potential for population growth. As a result, most of humans live within river basins or at locations that are within easy access to water supplies. However, with the evident increase in human population, and the ever increasing rates of economic growth, the demand on water is rapidly increasing and approaching the capacity of the natural water cycle to replenish this vital resource. The concept of sustainable water resources has been developed to address this clear conflict between the limited natural supply of water and the demand on water by human society that is increasing without limits.

2 DEFINITION OF SUSTAINABLE WATER RESOURCES

We define a sustainable water resource as a **flux of water** that is **managed** with the objective of maintaining **the availability and quality** of water for as long as the **current climate** prevails.

In presenting this definition, we would like to highlight four related issues:

First, we emphasize that a sustainable water resource is a flux of water that reflects the natural rate of replenishment of the water resource through the hydrological cycle. A sustainable water resource is not a stored volume of water. This distinction is particularly important when considering groundwater aquifers, natural lakes, and man-made reservoirs. The value of any groundwater aquifer as a water resource system is directly proportional to the rate of recharge to the aquifer. Here, the hydrologic concept of the aquifer as a water reservoir is indeed more relevant than the geologic concept of the aquifer as a water holding formation. Similarly, the inflow to natural lakes and man-made reservoirs is the important variable to consider in evaluating the corresponding sustainable water resource.

Second, in assessing sustainability of a water resource the quality of water is an important consideration. Water quality is as relevant as water availability. However, these two issues are not independent from each other. For example, pollution of an aquifer may limit the value of the abundant recharge to the aquifer. On the other hand, excessive pumping from an aquifer may result in degradation of the water quality to the extent of limiting the usefulness of the water resource.

Third, the sustainability of any water resource is largely a function of how we manage it. Water management practices that utilize the water stored in any reservoir without considering the corresponding rate of replenishment are not sustainable. Sound management practices should seek to maintain the quality and availability of the water resource indefinitely. This represents the only pathway towards sustainability. Any other pathway would result in compromising the quality and/or availability of water for future generations.

Fourth, the direct relationship between sustainability of water resources and climate is emphasized. One of the most important impacts of climate change is the potential for changing the distribution of sustainable water resources. A water resource that is sustainable in the current climate may not continue to be sustainable if climate changes.

The distribution of rainfall, and other related hydrological variables such as river flow and recharge, is determined by the prevailing climatic regime.

3. THREATS TO SUSTAINABILITY OF WATER RESOURCES:

Here, we would like to emphasize three main threats to the sustainability of any water resource: climate change, water pollution, and the adverse impacts of water resource management practices. These threats are identified based on the definition of sustainable water resources that has been introduced in the previous section.

3.1 Climate Change:

Rainfall is the flux of water from the atmosphere to the surface and represents an important climate variable. All other important hydrologic variables such as river flow and recharge are proportional to the rainfall rate. Any significant climate change is likely to be reflected in changing the distribution of rainfall, and then through the water cycle in modifying the distribution of all the other important hydrologic variables such as river flow and recharge to aquifers. For this reason, climate change may represent a threat to the sustainability of water resources. However, this may not be true for all possible climate change scenarios. A climate change that modifies the distribution of rainfall towards wetter conditions is likely to enhance sustainable water resources in the affected region.

Causes of climate change could be natural or anthropogenic. The two main human activities that are modifying the global environment significantly are (1) the emissions of green house gases resulting in the evident change in the chemical composition of the atmosphere; and (2) deforestation and desertification resulting in the observed change in global land cover. These two human activities could potentially result in significant climate change that may affect the distribution of sustainable water resources.

3.2 Water Pollution

All human activities that impact the quality of water within the hydrologic cycle could impose serious threats to the sustainability of water resources. Examples for such activities include:

(1) air pollution by industrial emissions which causes acid rain;

(2) pollution of surface runoff due to drainage from irrigation schemes that apply hazardous chemicals such as pesticides;

(3) pollution of aquifers and lakes due to contamination by industrial waste discharges.

Adoption of pollution prevention measures as well as development of remediation technologies that treat contaminated sites could potentially protect sustainable water resources against these threats.

3.3 Non-Sustainable Management Practices:

Any water resource management strategy that seeks to maximize short term benefits and neglects long term consequences would pose a direct threat to sustainability of that resource. Examples for these strategies include:

(1) management of ground water reservoirs that allow excessive pumping of water at rates that exceed the recharge rate resulting in significant decline of the aquifer water level;

(2) design and management of dams and reservoir systems using operating rules that maximize the benefit from water use without dealing with the accumulation of sediments and hence limiting the life of the reservoir to a finite period of time;

(3) management of irrigation schemes in a way that maximizes the short term benefits without careful consideration to salt accumulation in the top soil layer which could eventually render the soil and water resources useless.

4 EXAMPLE FROM AN ARID REGION: SAUDI ARABIA IN THE 1990s

The climate in Saudi Arabia is in general dry with desert conditions prevailing in most of the country. The average annual rainfall is less than 100 mm, though small regions in the southwestern mountains receive more than 500 mm of rainfall per year. The average potential evaporation is about 3000 mm per year which could sustain excessive evaporation from any natural or man made reservoir. Surface runoff is limited to the "wadis"; the intermittence of rainfall events and the dry soil moisture conditions favor the occurrence of Hortonian runoff production. This process occurs when and where the rainfall rate exceeds the infiltration capacity of the top soil layer. However, the high rate of potential evaporation and the significant seasonality of rainfall preclude the occurrence of any permanent lakes, streams, or rivers.

Saudi Arabia is rich in natural resources. The rate of production of oil in this country is among the highest in the world. Although the economy of Saudi Arabia is largely dependent on oil, there are significant trends towards diversification, evident in the recent development of strong industrial and agricultural sectors. The development in both of these sectors require additional water resource, however the agricultural sector is by far the main consumer of water in Saudi Arabia. During the 1980s the expansion in the agricultural sector increased the demand on water by almost one order of magnitude. This demand has been satisfied through excessive pumping from ground water aquifers. The significant expansion in the agricultural sector and the associated increase in the water consumption brought the issue of sustainable water resource to the forefront of environmental problems in Saudi Arabia.

4.1 Water Demand, and Supply in Saudi Arabia

The consumption of water in Saudi Arabia is dominated by the use of water for irrigation purposes. Figure 1 describes the demand on water by the agricultural sector, domestic needs, and industrial use in 1990. The total demand on water was about 16.3 Km^3, about 90% of this water is used for irrigation purposes, with most of the remaining 10% supplied for domestic use. The demand on water has been rising for the last two decades and will continue to rise in the coming decades. However, the most significant trend occurred during the 1980s, when the demand on water increased by about a factor of 8. Most of this increase was associated with the significant expansion in agriculture during the 1980s. Land under cultivation has grown from under 400,000 acres in 1976 to more than 8 million acres in 1993.

The main sources of water in Saudi Arabia are groundwater aquifers, surface runoff, desalination, and wastewater reuse, see Figure 2. In 1990, most of the water was supplied by pumping from groundwater aquifers. Surface runoff and desalination contribute significantly less water. Most of the groundwater comes from the deep aquifers whose recharge rates are significantly smaller than the current rate of groundwater extraction.

The definition of sustainable water resource will be applied in analyzing the situation in Saudi Arabia. Figure 3 describes estimates of sustainable water resources. The total sustainable water resource in Saudi Arabia is about 7.1 Km^3 contributed by groundwater recharge, surface runoff, desalination and wastewater reuse. The only difference between Figure 2 and Figure 3 is in the groundwater component. While the use of groundwater in 1990 is close to 15 Km^3/year, the recharge to those aquifers is estimated to be less than 4 Km^3/year. The difference of about 11 Km^3/year quantifies the gap between the demand on water and the available sustainable water resource. This was satisfied by extraction of water from deep groundwater aquifers. This practice could not be sustained indefinitely. Hence, changes in agricultural policies were advocated and implemented to address this problem.

5 A MANAGEMENT FRAMEWORK FOR SUSTAINABLE WATER RESOURCES

This section presents a framework for water resources management that is designed to provide a pathway towards sustainable water resources. The design of this framework is general and can be applied in any arid region. The central idea in this framework is simple. In order to enhance the sustainable water resources, we need to link the price of water to the marginal cost for development of a new sustainable water resource. As shown in Figure 5 (a,b), such a pricing system working in a free market economy would stimulate the development of new sustainable water resources as well as stimulating sustainable use and consumption of water. Through these two market driven processes, the dynamics of the water price assume a trajectory along which water resources are always sustainable.

Desalination is a readily available technology which produces a sustainable water resource. In arid regions where desalination is the only feasible sustainable source of additional water, the price of water has to be consistent with the high cost of desalination. From the supply side, this high price should stimulate the development of new cheaper technologies that could potentially enhance sustainable water resources. Examples for such technologies include weather modification, and other interventions with land surface hydrology that enhance surface runoff and groundwater recharge at the expense of evaporation losses. Specific ideas relevant to these technologies will be discussed in the next section. A low price of water would make development of such technologies not feasible. From the demand side, a high price of water would definitely reduce the consumption and hence the demand on water. The use of available technologies that conserve water in irrigation practices as well as domestic purposes would be enhanced under a realistic pricing system.

A trajectory that could result from applying this framework is described schematically in Figure 5 b. Initially, the demand on water falls quickly in response to the high water price, at the same time new sustainable sources of water become available. More supply and less demand should drive the price of water down, making some of the available resources not economically feasible and hence reduce supply, but at the same time enhance consumption and demand. More demand

and less supply, and the price bounces back. A series of fluctuations like this should move the system gradually towards a point where all the demand is satisfied from sustainable water sources. The final price of water would eventually be determined by the external constraints imposed by natural hydro-climatological conditions. Under this system, the price of water as well as the use of water technology would vary significantly between humid and arid regions.

Application of the proposed framework of water resources management in any country would involve significant political issues. This is particularly true in countries where the price of water may be heavily and implicitly subsidized through adoption of low prices of water. Specifying the level of subsidies for water prices is a political issue beyond the scope of this article. However, we argue that such water subsidies should be explicit, in other words if any government, for whatever political reasons, decides to subsidize the price of water, then these subsidies should be introduced explicitly by adopting a realistic price for water and then providing the consumers with payments that are designed to offset this high price. Subsidizing water this way would at least raise the value of water, and stimulate conservation of this vital resource. Such a policy would indeed be feasible only in those countries where the government has full control on the national water resources.

6 DEVELOPMENT OF NEW SUSTAINABLE WATER RESOURCE

This section presents some examples on how to develop new sustainable water resources. Such ideas are potentially feasible in arid regions, where the water price is high enough to justify investment in developing the new resource. The basic idea is to minimize losses of water through evaporation. As discussed earlier, potential evaporation in arid regions is often of large magnitude, exceeding rainfall. This fact results in tremendous loss of water through evaporation following rainfall events. If we can somehow intervene to reduce the efficiency of this process, more rainfall will be transformed into surface runoff and less water will be lost to evaporation.

Figure 6 (a) describes a general picture of the hydrologic cycle in a typical dry catchment. Rainfall is partitioned at the surface into surface runoff and infiltration. The latter is further partitioned into evaporation and groundwater recharge. Surface runoff flows over land and most of it evaporates back to the atmosphere. The simplest way to intervene with this natural system is to intercept surface runoff and keep it in surface reservoirs, see Figure 6(b). For example, such reservoirs have been built in numerous locations in Saudi Arabia. Although, some of the water would infiltrate through the bottom of these reservoirs and recharge the aquifer, most of the water would be lost through evaporation which takes place from the standing water bodies at the potential rate.

The hydrologic system of Figure 6(b) can be improved significantly if the water stored in these reservoirs is somehow transported through a network of pipelines to feed a network of recharge wells. By short-circuiting the evaporation process through a human-made system of reservoirs-pipelines-recharge wells significant gains could be achieved.

A potential design for such system is described schematically in Figure 6(c). Here, the groundwater aquifer is used as a natural reservoir that would preserve water from being lost through evaporation. However, this system would be limited by the low rates of natural surface runoff that occur in arid catchments. The final component of the proposed technology addresses this problem by enhancing the rate of surface runoff, Figure 6d. This process depends on the infiltration capacity of the soil. By modifying this soil property towards smaller infiltration capacity, some gain might be achieved by increasing the fraction of rainfall that would go into surface runoff at the expense of evaporation.

The exact nature of how these "hydrologic" technologies should be designed and implemented and how efficient they would be, remain open questions for future research. However, this example demonstrates that in regions where water is an expensive commodity, new "hydrologic" technologies could be developed to enhance the supply of sustainable water resources.

7 CONCLUSIONS

(1) A new definition is proposed to describe a *sustainable water resource*. A sustainable water resource is a **flux of water** that is **managed** with the objective of maintaining **the availability and quality** of water for as long as the **current climate** prevails. This definition emphasizes that a sustainable water resource should be measured by the flux of water that is available for society as opposed to measuring it by the volume of stored water. Sustainability of water quality is as important as that of the water flux. The link to climate and climate change is made explicit which highlights the dangers of climate change; a process that may modify the geographical distribution of sustainable water resources.

(2) The annual demand on water in Saudi Arabia in 1990 is about 20 Km^3, mainly for agricultural purposes, while the available sustainable water resource can supply about 7 Km^3. The difference was being satisfied through mining of the non-renewable water resource from deep groundwater aquifers. This is a good example for non-sustainable water resources.

(3) A general framework of water resources management has been designed to define a pathway towards development of new sustainable water resource and reduction of water consumption. The cornerstone in this framework is a water pricing system that links the price of water to the marginal cost for development of new sustainable water resource. By adding new sustainable water resources that increase the supply of water, and by stimulating a more conservative consumption of water, this framework leads towards a state in which all the demand on water is supplied through sustainable resources.

(4) Development of new sustainable water resources is a key element in the proposed framework of water resources management. Specific proposals has been made to enhance these resources in arid regions where the cost of additional sustainable water resources is relatively high. In particular, we propose to modify the natural hydrologic processes in a way which enhance surface runoff and groundwater recharge, at the expense of evaporative losses. As a result of these modifications, the groundwater aquifer can be used as a natural storage reservoir that is relatively less vulnerable to the tremendous potential evaporative losses characteristic of arid environments.

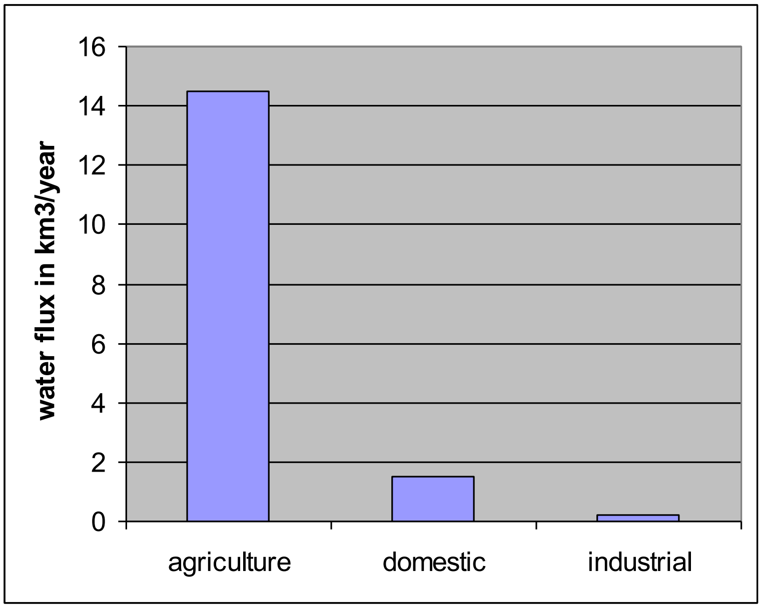


Figure-1: demand on water in Saudi Arabia in 1990

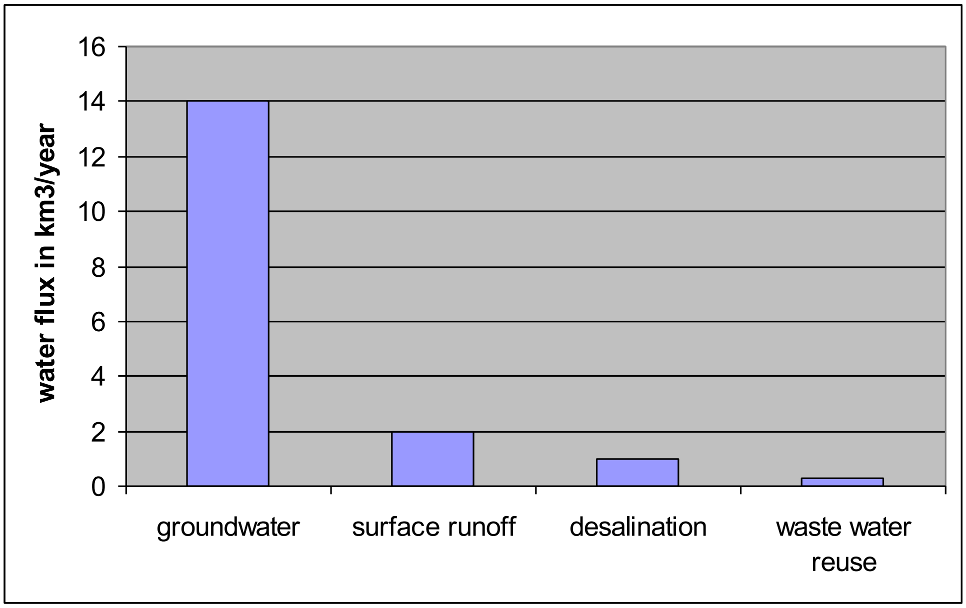


Figure-2: water supply in Saudi Arabia in 1990

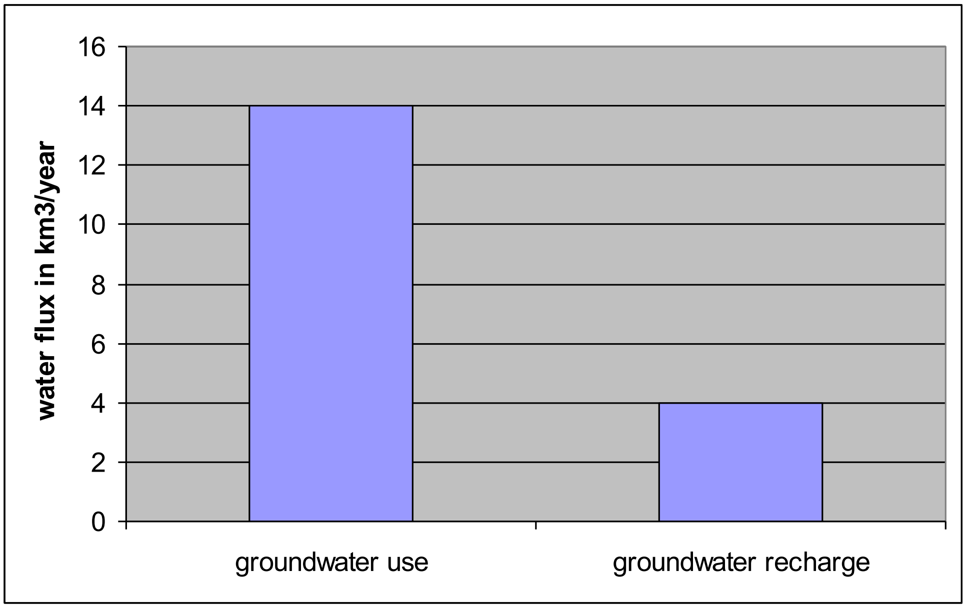


Figure-3: Comparison of groundwater discharge (pumping) and natural recharge in Saudi Arabia in 1990

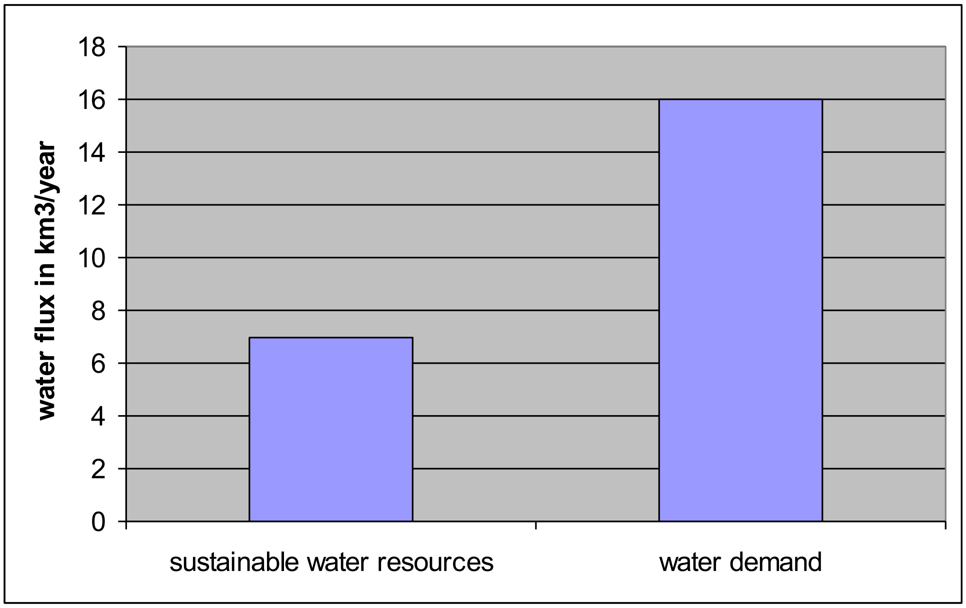


Figure-4: Comparison of sustainable water resources and water demand in Saudi Arabia in 1990

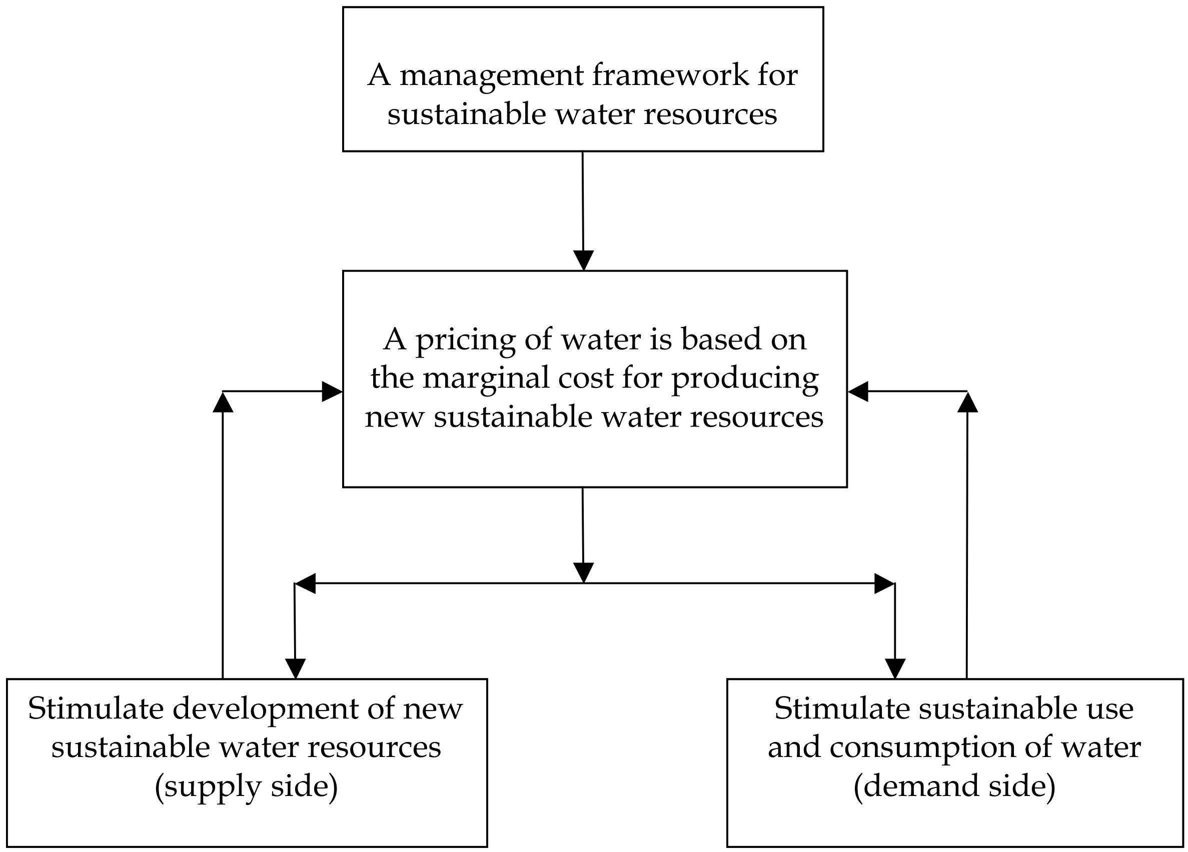


Figure-5 : A management framework for sustainable water resources

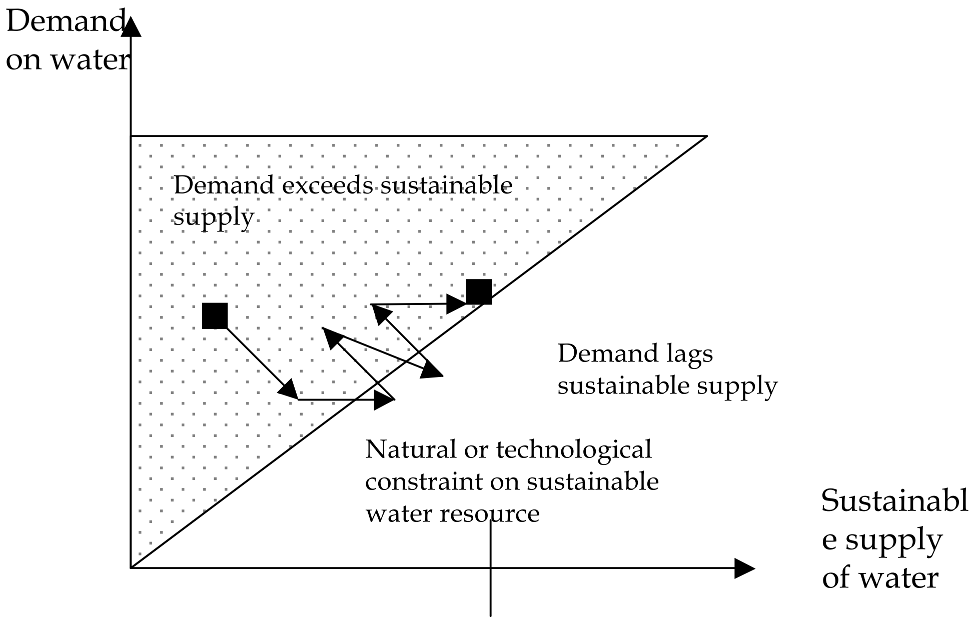
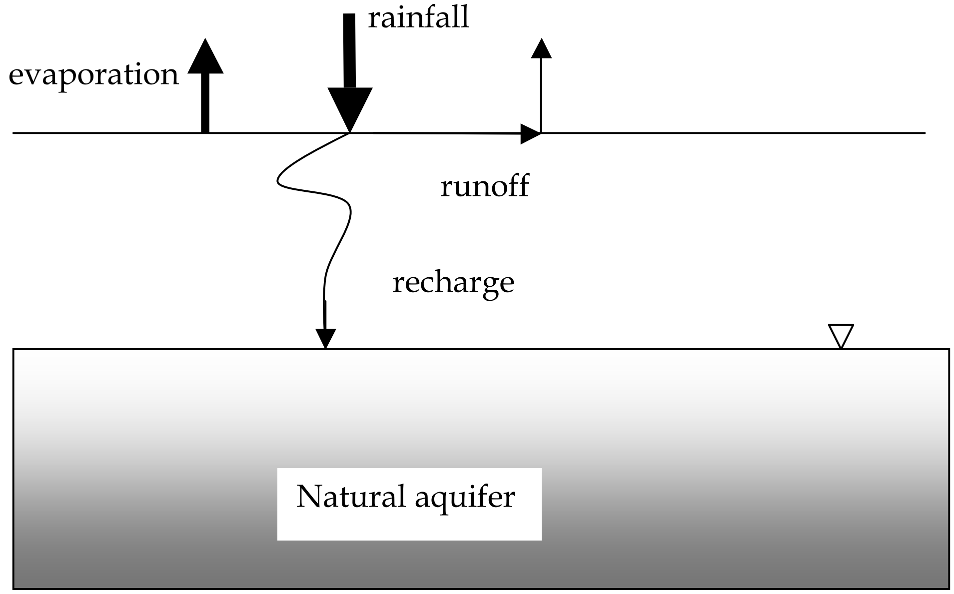
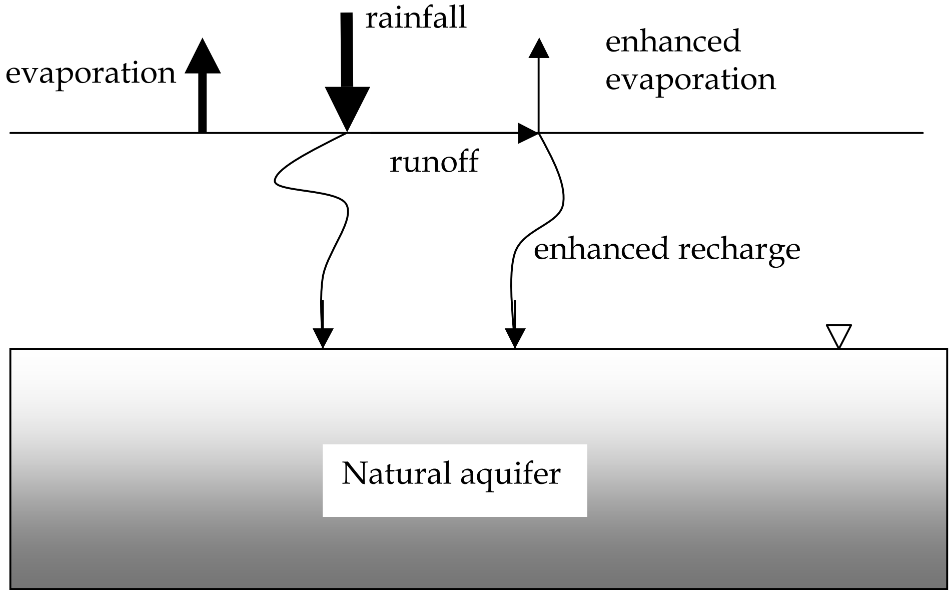


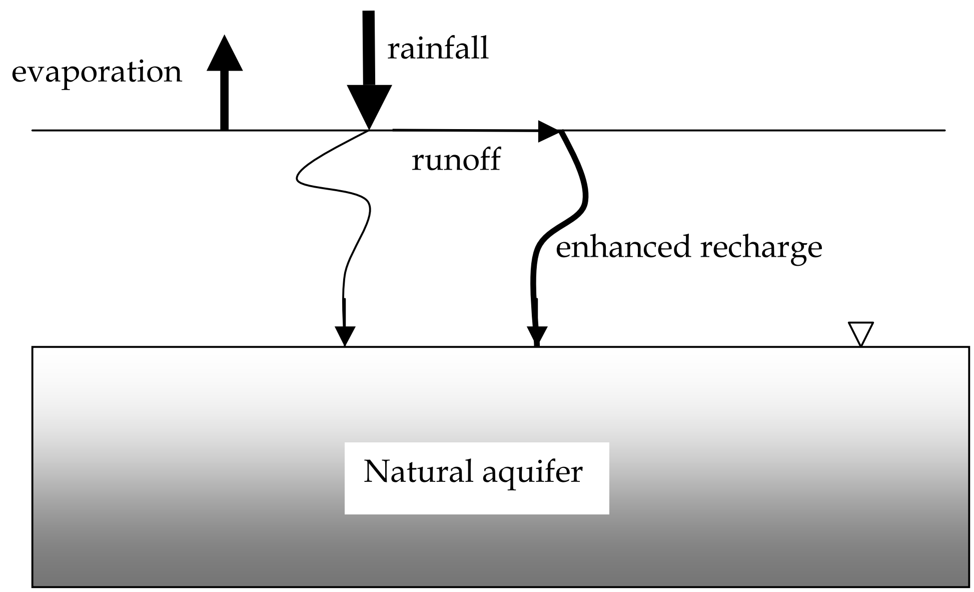
Figure 5b: A management framework for sustainable water resources



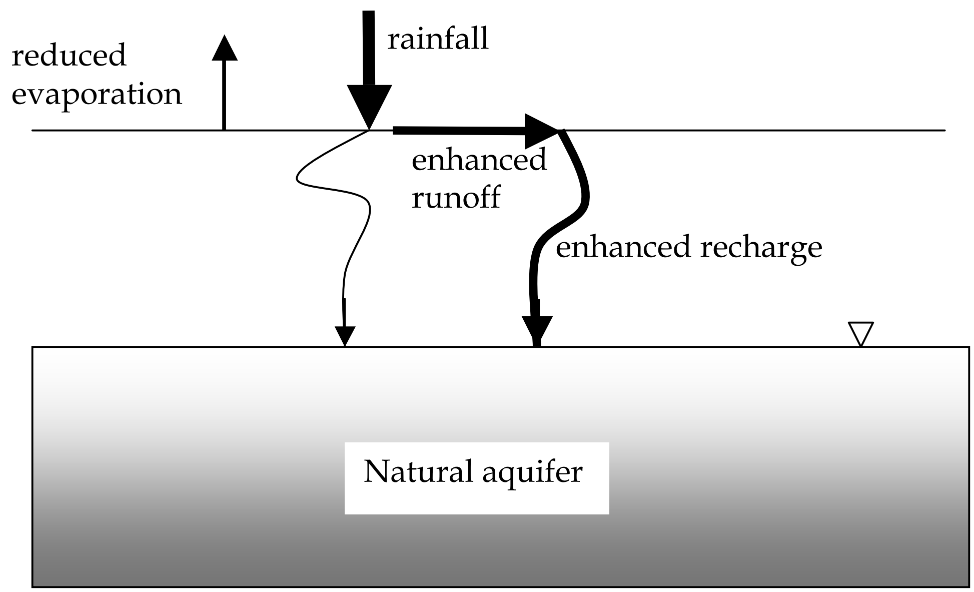
(a) natural catchment in a
dry region



(b) natural catchment in a dry
region + storage reservoirs



(c) natural catchment in a dry region + surface storage reservoirs+ network of pipelines + network of recharge wells



(d) natural catchment in a dry region + surface storage reservoirs+ reduced infiltration capacity+ network of pipelines + network of recharge wells