Basics of Water Resources - Course Book

WaterNet, CCR, ISRI, Catalic, UNESCO-IHE Delft, UZ
1. Frederick M. Lorentz, The protection of water facilities under international law, UNESCO-IHP, 46 p.
2. Sergei Vinogradov, Patricia Wouters and Patricia Jones, Transforming potential conflict into cooperation potential: The role of international water law, UNESCO-IHP, 106 p.
11. Viktor Dukhovnyy and Vadim Sokolov, Lessons on cooperation building to manage water conflicts in the Amul sea basin, UNESCO-IHP, 50 p.
13. Peter Nachtnebel, Danube case study, UNESCO-IHP (to be published)
17. Ira D. Fijters and Jan Leerwaar, Rhine case study, UNESCO-IHP, 33 p.
WaterNet, in collaboration with the Centre of Conflict Resolution CCR (South Africa), the Instituto Superior de Relações Internacionais ISRI (Higher Institute of International Relations) (Mozambique), Catalic (The Netherlands/Mozambique), UNESCO-IHE Delft (The Netherlands) and the University of Zimbabwe (Zimbabwe), has developed a 3 day course on

Basics of Water Resources

The aim of the course is to introduce the basics of water resources to non-water managers, in order for them to be able to communicate more meaningfully with water engineers, hydrologists etc.

The specific objectives of the course are:

a. to introduce the basics of water resources
b. to improve communication between non-water professionals and water professionals.

The subjects addressed include:

- Concepts and definitions
- Water resources
- Water allocation principles
- Urban water demand
- Agricultural water demand
- Environmental water requirements

The course is targeting non-water professionals and stakeholder representatives.

The course has been developed under the UNESCO and Green Cross programme "From Potential Conflict to Cooperation Potential: Water For Peace", which forms part of the World Water Assessment Programme WWAP.

The course materials consist of a course book.
Course A

Basics of Water Resources

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1. Concepts and definitions

1.1 The water cycle

Water is finite on earth. There is a fixed amount of water which neither decreases or increases. Fresh water is a renewable resource because of the water cycle. From a human perspective the source of freshwater is rainfall. Most of this rainfall is used directly for vegetative growth, such as natural vegetation, pasture, rain-fed maize etc. This process, known as transpiration, is highly productive and produces in Southern Africa the bulk of food crops.

![Image of the water cycle](image_url)

**Figure 1.1** The water cycle (Pallett, 1997:20)

Only a small portion of the rainfall flows into rivers as surface water and recharges groundwater (Figure 1.2). This water is used for domestic water supply, industrial production, irrigated agriculture etc. This is the water that we tend to harness through infrastructure development (e.g. dams, wells) and that we tend to pollute.

If we talk about Integrated Water Resources Management, we mean to consider the entire water cycle. This means that we also look at rain-fed agriculture production, soil and water conservation within the watershed, rainwater harvesting techniques etc.

To facilitate the comprehensive thinking in terms of the entire water cycle, three types of water can be distinguished, together forming the 'rainbow' of water.
Figure 1.2 Schematic water balance for Southern Africa, showing the average partitioning of rainfall (Pallett 1997: 22)
A rainbow of water

The rainbow of water distinguishes three types of water depending on their occurrence in the water cycle (Figure 1.3).
- ‘white’ water = rainfall and that part of rainfall which is intercepted and immediately evaporates back to the atmosphere
- ‘blue’ water = water involved in the runoff (sub-)cycle, consisting of surface water and groundwater (below the unsaturated zone)
- ‘green’ water = water stemming directly from rainfall, that is transpired by vegetation (after having been stored in the unsaturated zone) (Falkenmark, 1995)

Figure 1.3 The hydrological cycle, with ‘white’, ‘green’ and ‘blue’ water, and the two partitioning points
**Water use**

There are a large number of types of water use. Among these are:
- Rainfed agriculture
- Irrigation
- Domestic use in urban centres and in rural areas
- Livestock
- Industrial and commercial use
- Institutions (e.g. schools, hospitals, government buildings, sports facilities etc.)
- Waste and wastewater disposal
- Cooling (e.g. for thermal power generation)
- Hydropower
- Navigation
- Recreation
- Fisheries
- The environment (wildlife, nature conservation etc.)

![Figure 1.4 Water use in Southern Africa in 1995 (Pallett, 1997:38)](image)

**Demand for, and use of water**

*Demand* for water is the amount of water required at a certain point. The *use* of water refers to the actual amount reached at that point.

We can distinguish *withdrawal uses* and *non-withdrawal* (such as navigation, recreation, waste water disposal by dilution) uses; as well as *consumptive* and *non-consumptive* uses. Consumptive use is the portion of the water withdrawn that is no longer available for further use because of evaporation, transpiration, incorporation in manufactured products and crops, use by human beings and livestock, or pollution.

The terms “consumption”, “use” and “demand” are often confused. The amount of water actually reaching the point where it is required will often differ from the amount required. Only a portion of the water used is actually consumed, i.e. lost from the water resource system.

A similar confusion exists when talking about *water losses*. It depends on the scale whether water is considered a loss or not. At the global scale, no water is ever lost. At the scale of an irrigation scheme, a water distribution efficiency of 60% indeed means that slightly less than half of the water is lost. Part of this water, however, may return to the river and be available to a downstream user. At the scale of the catchment, therefore, it is the transpiration of crops (60% in this example) that can be considered a loss!
While the total available freshwater is limited (finite), demand grows. Hence the importance of water resources management.

**The value of water**

The various uses of water in the different sectors of an economy add value to these sectors. Some sectors may use little water but contribute significantly to the gross national product (GNP) of an economy (see Table). Other sectors may use a lot of water but contribute relatively little to that economy. The added value of some uses of water are difficult, if not impossible to measure. Consider for instance the domestic use of water: how to quantify the value of an adequate water supply to this sector?

<table>
<thead>
<tr>
<th>Sector</th>
<th>Water use (Mm³ yr⁻¹)</th>
<th>Contribution to GNP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation</td>
<td>107</td>
<td>43.0</td>
</tr>
<tr>
<td>Livestock</td>
<td>63</td>
<td>25.3</td>
</tr>
<tr>
<td>Domestic</td>
<td>63</td>
<td>25.3</td>
</tr>
<tr>
<td>Mining</td>
<td>8</td>
<td>3.2</td>
</tr>
<tr>
<td>Industry &amp; Commerce</td>
<td>7</td>
<td>2.8</td>
</tr>
<tr>
<td>Tourism</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>249</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

The damage to an economy by water shortage may be immense. It is well known, for instance, that a positive correlation exists between the Zimbabwe stock exchange index and rainfall in Zimbabwe. The drought of 1991/92 had a huge negative impact on the Zimbabwean economy (see box 1.1).

**Box 1.1: The impact of drought in Zimbabwe**

During the drought of 1991/92, the country’s agriculture production fell by 40% and 50% of its population had to be given relief food and emergency water supplies, through massive deep drilling programmes, since many rural boreholes and wells dried up. Urban water supplies were severely limited with unprecedented rationing. Electricity generation at Kariba fell by 15% causing severe load shedding. As a result its GDP fell by 11%...
1.2 Three characteristics of water

Water has at least three important physical attributes with a bearing on management:

- Fresh water is *vital* to sustain life, for which there is no substitute. This means that water has a (high) *value* to its users.

- Although water is a renewable resource, it is practically speaking *finite*. The use of water is therefore *subtractible*, meaning that the use by somebody may preclude the use by somebody else.

- Water is a *fugitive* resource. It is therefore difficult to assess the (variations in) *stock* and *flow* of the resource, and to define the *boundaries* of the resource, which complicate the planning and monitoring of withdrawals as well as the *exclusion* of non-members.

The vital nature of water gives it characteristics of a *public good*.

Its finite nature confers to it properties of a *private good*, as it can be privately appropriated and enjoyed.

The fugitive nature of water, and the resulting high costs of exclusion, confers to it properties of a *common pool resource*.

Water resources management aims to reconcile these various attributes of water. This is obviously not a simple task. The *property regime* and *management arrangements* of a water resources system are therefore often complex.

1.3 Integrated water resources management

There is growing awareness that comprehensive water resources management is needed, because:

- fresh water resources are limited;
- those limited fresh water resources are becoming more and more polluted, rendering them unfit for human consumption and also unfit to sustain the ecosystem;
- those limited fresh water resources have to be divided amongst the competing needs and demands in a society
- many citizens do not as yet have access to sufficient and safe fresh water resources
- techniques used to control water (such as dams and dikes) may often have undesirable consequences on the environment
- there is an intimate relationship between groundwater and surface water, between coastal water and fresh water, etc. Regulating one system and not the others may not achieve the desired results.

Hence, engineering, economic, social, ecological and legal aspects need to be considered, as well as quantitative and qualitative aspects, and supply and demand. Moreover, also the ‘management cycle’ (planning, monitoring, operation & maintenance, etc.) needs to be consistent.
Integrated water resources management, then, seeks to manage the water resources in a comprehensive and holistic way. It therefore has to consider the water resources from a number of different perspectives or dimensions. Once these various dimensions have been considered, appropriate decisions and arrangements can be made.

Due to the nature of water, integrated water resources management has to take account of the following four dimensions:

1. the water resources, taking the entire hydrological cycle in account, including stock and flows, as well as water quantity and water quality; distinguishing for instance white, green, grey and blue water

2. the water users, all sectoral interests and stakeholders

3. the spatial scale, including
   3.1 the spatial distribution of water resources and uses
   3.2 the various spatial scales at which water is being managed, i.e. individual user, user groups (e.g. user boards), watershed, catchment, (international) basin; and the institutional arrangements that exist at these various scales

4. the temporal scale; taking into account the temporal variation in availability of and demand for water resources, but also the physical structures that have been built to even out fluctuations and to better match the supply with demand.

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**Figure 1.5 Three of the four dimensions of Integrated Water Resources Management**

(Savenije, 2000)
Integrated Water Resources Management can now be defined as:

Integrated Water Resources Management (IWRM) is a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

This is the definition proposed by the Global Water Partnership.

Integrated Water Resources Management therefore acknowledges the entire water cycle with all its natural aspects, as well as the interests of the water users in the different sectors of a society (or an entire region). Decision-making would involve the integration of the different objectives where possible, and a trade-off or priority-setting between these objectives where necessary, by carefully weighing these in an informed and transparent manner, according to societal objectives and constraints. Special care should be taken to consider spatial scales, in terms of geographical variation in water availability and the possible upstream-downstream interactions, as well as time scales, such as the natural seasonal, annual and long-term fluctuations in water availability, and the implications of developments now for future generations.

To accomplish the integrated management of water resources, appropriate legal, institutional and financial arrangements are required that acknowledge the four dimensions of IWRM. In order for a society to get the right arrangements in place, it requires a sound policy on water.

1.4 Policy principles

For a country to change its water management towards a more holistic and integrated management system, it will require to review its water policy. This is currently on-going in many countries in Southern Africa, or has been recently concluded. A water policy often starts with the definition of a small number of basic principles and objectives, such as the need for sustainable development and desirable socio-economic development.

Three key policy principles are known as the three 'E's as defined by Postel (1992):

a) **Equity**: Water is a basic need. No human being can live without a basic volume of fresh water of sufficient quality. Humans have a basic human right of access to water resources (see Gleick, 1999). This policy principle is related to the fact that water is often considered a public good. Water is such a basic requirement for human life and survival that society has to defend the uses of the water resources in the public interest. From here a number of other issues can be derived, such as security (protection against floods, droughts, famine and other hazards).

b) **Ecological integrity**: Water resources can only persist in a natural environment capable of regenerating (fresh) water of sufficient quality. Only sustainable water use can be allowed such that future generations will be able to use it in similar ways as the present generation.

c) **Efficiency**: Water is a scarce resource. It should be used efficiently; therefore,
institutional arrangements should be such that cost recovery of the water services should be attained. This will ensure sustainability of infrastructure and institutions, but should not jeopardise the equity principle. Here comes in the issue of water pricing, and whether or not water should be priced according to its economic value.

Much of water resources management deals with finding suitable compromises between these policy principles that sometimes are conflicting.

The Southern Africa Vision for Water has been formulated as a desired future characterised by:

Equitable and sustainable utilisation of water for social, environmental justice, regional integration and economic benefit for present and future generations.

And the South Africa white paper on water resources has been succinctly summarised as follows:

"Some (water) for all for ever."

1.5 Sustainability of water resources (Savenije, 2000)

Since the appearance of the Brundtland report "Our Common Future" (WCED, 1987), sustainable development has been embraced as the leading philosophy that would on the one hand allow the world to develop its resources and on the other hand preserve unrenewable and finite resources and guarantee adequate living conditions for future generations.

Presently the definition most often used of sustainable development is: the ability of the present generation to utilise its natural resources without putting at risk the ability of future generations to do likewise. The president of Botswana K. Masire stated:

"Our ideals of sustainable development do not seek to curtail development. Experience elsewhere has demonstrated that the path to development may simply mean doing more with less (being more efficient). As our population grows, we will certainly have less and less of the resources we have today. To manage this situation, we need a new ethic, one that emphasises the need to protect our natural resources in all we do." (cited in Savenije, 2000)

Sustainable development is making efficient use of our natural resources for economic and social development while maintaining the resource base and environmental carrying capacity for coming generations. This resource base should be widely interpreted to contain besides natural resources: knowledge, infrastructure, technology, durables and human resources. In the process of development natural resources may be converted into other durable products and hence remain part of the overall resource base.
Water resources development that is not sustainable is ill-planned. In many parts of the world, fresh water resources are scarce and to a large extent finite. Although surface water may be considered a renewable resource, it only constitutes 1.5% of all terrestrial fresh water resources; the vast majority is groundwater (98.5%) part of which - at a human scale - is virtually unrenewable. Consequently, there are numerous ways to jeopardise the future use of water either by overexploitation (mining) of resources or by destroying resources for future use (e.g. pollution).

**Physical sustainability**

Physical sustainability means closing the resource cycles and considering the cycles in their integrity (water and nutrient cycles). In agriculture this implies primarily closing or shortening water and nutrient cycles so as to prevent accumulation or depletion of land and water resources: Water depletion results in desertification. Water accumulation into water logging. Nutrient depletion leads to loss of fertility, loss of water holding capacity, and in general, reduction of carrying capacity. Nutrient accumulation results in eutrophication and pollution. Loss of top-soil results in erosion, land degradation and sedimentation elsewhere. Closing or shortening these cycles means restoring the dynamic equilibria at the appropriate temporal and spatial scales. The latter is relevant, since at a global scale all cycles close. The question of sustainability has to do with closing the cycles within a human dimension.

**Economic sustainability**

The economic sustainability relates to the efficiency of the system. If all societal costs and benefits are properly accounted for, and cycles are closed, then economic sustainability implies a reduction of scale by short-cutting the cycles. Efficiency dictates that cycles should be kept as short as possible. Examples of short cycles are: water conservation, to make optimum use of rainfall where it falls (and not drain it off and capture it downstream to pump it up again); water recycling at the spot instead of draining it off to a treatment plant after which it is conveyed or pumped back over considerable distances etc.

Strangely enough, economic sustainability is facilitated by an enlargement of scale through trade in land- and water-intensive commodities (the "virtual" water concept). The use of virtual water is an important concept in countries where the carrying capacity of a society is not sufficient to produce land and water intensive products itself.

The closing of cycles should be realised at different spatial scales:

- The rural scale, implying water conservation, nutrient and soil conservation, prevention of over-drainage and the recycling of nutrients and organic waste.
- The urban scale, both in towns and mega-cities, implying the recycling of water, nutrients and waste.
- The river basin scale, implying: soil and water conservation in the upper catchment, prevention of runoff and unnecessary drainage and enhancement of infiltration and recharge, flood retention, pollution control and the wise use of wetlands.
• The global scale, where water, nutrient and basic resource cycles are integrated and closed. The concept of virtual water is a tool for an equitable utilisation of water resources. This requires an open and accessible global market and the use of resource-based economic incentives such as resource taxing ("Green tax" which taxes the use of non-renewable or finite resources), as opposed to taxing renewable resources such as labour, which is the general practice today.

1.6 Institutional aspects of Integrated Water Resources Management

The growing complexity of water management induces a need for management at the lowest appropriate level (also known as the ‘subsidiary principle’), resulting in central government delegating functions to the decentralised organisational (regulatory) and operational levels. In general, the organisational (or regulatory) level may have a mandate over a river basin, while at the operational level concessions may have been delegated to sub-catchment areas or to user groups (municipalities, irrigation districts).

Thus, in managing the resource, a functional differentiation is made between constitutional issues (related to property rights, security, arbitration), organisational issues (regulation, supervision, planning, conflict management), and operational issues (water provision etc.) (World Bank 1993).

These issues will then be handled at three different levels:

• Constitutional level: the activities being governed by conventions of international organisation, bilateral or multilateral treaties and agreements, the national constitution, national legislation or national policy plans.

• Organisational level: activities at this level are defined by (federal) state regulation, ministerial regulation, regulation or plan of functional public body (national water authority, (sub) catchment authority), provincial regulation or plan.

• Operational level: activities being governed by subcatchment-, district-, town regulations, bye-laws of semi-public or private water users organisations etc.

The most important issue in dealing with water resources is to ensure an institutional structure that can coordinate activities in different fields that all have a bearing on water. Linking structures are crucial.

Through a process of vertical and horizontal coordination it is possible to integrate different aspects of the water issue at different levels. Linking can be facilitated if a country’s water is managed following hydrological boundaries (river basins, which may be subdivided into catchment areas and sub-catchments).

Once agreement exists over what type of functions and decisions can best be made at what level, a next policy option is that of privatisation. Operational functions often involve the provision of specific services in water sub-sectors, such as irrigation and drainage, water supply and sanitation, and energy. The production function may, in principle, be privatised; but only if the nature of the good (or service) is fit for it, and if government’s
regulatory capacity is strong enough to prevent monopoly formation or other market failures.

*Financial and economic arrangements* are complex issues. The maxim ‘water is an economic good and should be priced according to the principle of opportunity costs’, as well as the ‘users pays and polluter pays’ principles carry within them a danger, especially in countries lacking sufficient resources and with a skewed distribution of wealth. In such countries the ‘user pays’ principle may boil down to ‘who can pay is allowed to use or pollute water’. Because of historically grown inequities in society, this may result in a large group of the population having limited access to water resources. This often creates severe social problems, and should be considered unconstitutional, as it violates a first order principle (equity).

Therefore a balance has to be found between water pricing which ensures economic sustainability on the one hand, and the social requirement of sufficient access to clean water, on the other (i.e. efficiency versus equity).

Instruments that may assist in achieving a balance between efficiency and equity include:

- recovery of real costs by functional (catchment) agencies;
- financial independence (and accountability) of implementing agencies;
- water pricing by means of increasing block tariffs, and other forms of cross-subsidies.

A wider concept than water pricing and cost recovery is *demand management*, which is the use of economic and legal incentives in combination with awareness raising and education to achieve more desirable consumption patterns, both in terms of distribution between sectors and quantities consumed, coupled with an increased reliability of supply.

In fact, good water management should mean a continuous process of *integrated demand and supply management*, which would seek to match supply with demand through reducing water losses, increasing water yield and decreasing water demand (Savenije and Van der Zaag, 2000).

Environmental sustainability need not conflict with the principle of economic sustainability in a sense that uneconomic activities often waste water resources, if not the resource base itself. In addition, environmental costs or ‘environmental externalities’ should be clearly accounted for in economic impact assessments, although this is often not properly done. This points to the need for integrating the assessment tools, as suggested by UNEP (1997): assessments have to be carried out of the likely environmental, economic, and equity impacts of any water resources measure or development, the so-called **EIA**.

The vital inclusion of land use appraisal in water management assessment studies is often also omitted. Experiences in the field of environmental protection or environmental reconstruction show that positive incentives (e.g. subsidies) for practices that restore the ecology are rendering more effect than negative incentives (sanctions, fines) on practices that damage the environment.

Another prerequisite for success is the involvement and participation of water users and other stakeholders. Control without consensus is hard, if not impossible, to reach. The basic premise should be: those who have an interest in the water resource and benefit from it have the duty to contribute to its management and upkeep (in money and/or in kind) and
have the concomitant right to participate in decision-making. This leads to the maxim of
the water boards in The Netherlands: *interest - taxation – representation*.

Moreover, the wider public may play an important role in the difficult process of
monitoring this fluid and fugitive resource. Formalising the role of interest groups can be
realised by applying a comprehensive system of integrated planning at various levels, but
at least at the organisational level.

Even a perfect legal and institutional framework (provided that this may ever exist) cannot
function without motivated people with sufficient awareness, know-how and skills. Human
resources are scarce. It requires investment in (further) training to build up and maintain
the resource.

### 1.7 Strategic issues in water resources management

Current thinking on the crucial strategic issues in water resources is heavily influenced by
the so-called Dublin Principles, which were formulated during the International
Conference on Water and the Environment in Dublin, 1992, as a preparation for the UN
Conference on Environment and Development (UNCED) in Rio de Janeiro the same year.
During the Rio conference, the concepts of Integrated Water Resources Management were
widely discussed and accepted (Table 2.1).

**Table 1.2: Dublin Principles (ICWE, 1992)**

- Water is a finite, vulnerable and essential resource which should be managed in an
  integrated manner
- Water resources development and management should be based on a participatory
  approach, involving all relevant stakeholders
- Women play a central role in the provision, management and safeguarding of water
- Water has an economic value and should be recognised as an economic good, taking
  into account affordability and equity criteria.

**Associated key concepts:**

- Integrated water resources management, implying:
  - An inter-sectoral approach
  - Representation of all stakeholders
  - Consideration of all physical aspects of the water resources
  - Considerations of sustainability and the environment
- Sustainable development, sound socio-economic development that safeguards the
  resource base for future generations
- Emphasis on demand driven and demand oriented approaches
- Decision-making at the lowest possible level (subsidiarity)
Consensus over several issues have emerged in the last few years:
- In terms of water allocation, basic human needs have priority; other uses should be prioritised according to societal needs and socio-economic criteria
- The river basin is the logical unit for water resources management
- Participatory approaches in decision-making, and the crucial role of women.

There are a number of important outstanding issues of debate:
- Privatisation, and more generally the role of the private sector in water management
- The value of water (the social, economic and ecological value)
- The pricing of water (whether we should price basic needs, and if so, how we can safeguard access to water by the poor)
- Water for food (potential conflict between irrigation and ecological water demands and the scope for improving rainfed-agriculture)
- Non-water borne sanitation or traditional water borne end-of-pipe sanitation

It is obvious that these remaining issues are very important strategically. Countries are currently dealing with them individually. It is sometimes feared that outside pressure may in cases lead to countries making the wrong decision, and by so doing jeopardising fundamental policy principles. This may, for instance, be the case when a water utility is privatised without the country having an effective regulatory body to supervise the operations of the privatised utility.
1.8 Exercises

1a What are in your opinion the main policy issues for the water sector in your country?
1b Which objectives for the management of water resources can be derived from that?
1c What would be suitable performance criteria for these objectives?
1d Which institutions should be responsible for the implementation of these objectives?
1e Which should the tasks and responsibilities be for these institutions?

2 Sketch the debate between professionals who promote water borne sanitation versus the ones that promote non-water borne sanitation.

3 Sketch the debate between those professionals and stakeholders that promote privatisation versus the ones that are against it.
1.9 References


Savenije, H.H.G., 2000, Water resources management: concepts and tools. Lecture note. IHE, Delft and University of Zimbabwe, Harare


UNEP, 1997, The fair share water strategy for sustainable development in Africa. UNEP, Nairobi


2. Water resources (Savenije, 2000)

The origin of water resources is rainfall. As rainfall reaches the surface it meets the first separation point. At this point part of the rainwater returns directly to the atmosphere, which is called evaporation from interception I. The remaining rainwater infiltrates into the soil until it reaches the capacity of infiltration. This is called infiltration F. If there is enough rainfall to exceed the interception and the infiltration, then overland flow (also called surface runoff) Qs is generated. The overland flow is a fast runoff process, which generally carries soil particles. A river that carries a considerable portion of overland flow has a brown muddy colour and carries debris.

The infiltration reaches the soil moisture. Here lies the second separation point. From the soil moisture part of the water returns to the atmosphere through transpiration T. If the soil moisture content is above field capacity (or if there are preferential pathways) part of the soil moisture percolates towards the groundwater. The reverse process of percolation is capillary rise. The percolation feeds the groundwater and renews the groundwater. On average the percolation minus the capillary rise equals the seepage of groundwater Qg to the surface water. The seepage water is clean and does not carry soil particles. A river that has clear water carries water that stems from groundwater seepage. This is the slow component of runoff. During the rise of a flood in a river when the water colour is brown, the water stems primarily from overland flow. During the recession of the flood, when the water is clear, the river flow stems completely from groundwater seepage.

The water that is consumed by the vegetation through transpiration is called "green water". It is an important water resource for agriculture, nature and livestock. The surface water and groundwater which are intimately intertwined are the "blue water". Although the groundwater and surface water cannot be separated and although surface water consists to a large extent of groundwater, they are often dealt with separately. This is because they have quite different characteristics (time scales, quantities, availability) and because they obey different laws of motion.

2.1 The water balance

In the field of hydrology the budget idea is widely used. Water balances are based on the principle of continuity. This can be expressed with the equation:

\[ I(t) - O(t) = \frac{\Delta S}{\Delta t} \]  

(2.1)

where I is the inflow in [L^3/T], O is the outflow in [L^3/T], and \( \Delta S/\Delta t \) is the rate of change in storage over a finite time step in [L^3/T] of the considered control volume in the system. The equation holds for a specific period of time and may be applied to any given system provided that the boundaries are well defined. Other names for the water balance equation are Storage Equation, Continuity Equation and Law of Conservation of Mass.
Several types of water balances can be distinguished, including:

- the water balance of the earth surface;
- the water balance of a drainage basin;
- the water balance of the world oceans;
- the water balance of the water diversion cycle (human interference);
- the water balance of a local area like a city, a forest, or a polder.

The water balance of the earth is given in tables 2.1 and 2.2. The water balance of some rivers is given in table 2.3.

**Table 2.1 Amount of water on earth** (Savenije, 2000)

<table>
<thead>
<tr>
<th>Water occurrence</th>
<th>$10^{12}$ m$^3$</th>
<th>Amount of water</th>
<th>% of all water</th>
<th>% of fresh water</th>
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<td>Polar ice</td>
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<td>.035</td>
<td></td>
</tr>
<tr>
<td>Water in organisms</td>
<td>1</td>
<td>.000</td>
<td>.003</td>
<td></td>
</tr>
<tr>
<td>Fresh water lakes</td>
<td>123</td>
<td>.009</td>
<td>.335</td>
<td></td>
</tr>
<tr>
<td>Water courses</td>
<td>1</td>
<td>.000</td>
<td>.003</td>
<td></td>
</tr>
<tr>
<td>Unsaturated zone</td>
<td>65</td>
<td>.005</td>
<td>.18</td>
<td></td>
</tr>
<tr>
<td>Saturated zone</td>
<td>8,000</td>
<td>.6</td>
<td>21.8</td>
<td></td>
</tr>
<tr>
<td>Total fresh water</td>
<td>36,700</td>
<td>2.77</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Total water</td>
<td>1,337,000</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.2 Annual water balance of the earth** (Savenije, 2000)

<table>
<thead>
<tr>
<th>Area</th>
<th>Storage</th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{12}$ m$^3/a$</td>
<td>$10^{12}$ m$^3/a$</td>
<td>$10^{12}$ m$^3/a$</td>
<td>$10^{12}$ m$^3/a$</td>
</tr>
<tr>
<td>Oceans</td>
<td>361</td>
<td>1,328,500</td>
<td>403</td>
<td>449</td>
</tr>
<tr>
<td>Continents</td>
<td>149</td>
<td>8,190</td>
<td>107</td>
<td>61</td>
</tr>
</tbody>
</table>

**Table 2.3 Indicative average annual water balances for the drainage basins of some of the great rivers**

<table>
<thead>
<tr>
<th>River</th>
<th>Catchment size</th>
<th>Rainfall</th>
<th>Evapotranspiration</th>
<th>Runoff</th>
<th>Runoff Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile</td>
<td>2,803</td>
<td>220</td>
<td>190</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>Mississippi</td>
<td>3,924</td>
<td>800</td>
<td>654</td>
<td>142</td>
<td>558</td>
</tr>
<tr>
<td>Parana</td>
<td>975</td>
<td>1,000</td>
<td>625</td>
<td>382</td>
<td>372</td>
</tr>
<tr>
<td>Orinoco</td>
<td>850</td>
<td>1,150</td>
<td>420</td>
<td>935</td>
<td>795</td>
</tr>
<tr>
<td>Mekong</td>
<td>646</td>
<td>1,500</td>
<td>1,000645</td>
<td>382</td>
<td>325</td>
</tr>
<tr>
<td>Rhine</td>
<td>200</td>
<td>850</td>
<td>500</td>
<td>350</td>
<td>70</td>
</tr>
</tbody>
</table>

WaterNet / CCR / ISRI / Catalic / UNESCO-IHE Delft / UZ for UNESCO
Water balance of a drainage basin

The water balance is often applied to a river basin. A river basin (also called watershed, catchment, or drainage basin) is the area contributing to the discharge at a particular river cross-section. The size of the catchment increases if the point selected as outlet moves downstream. If no water moves across the catchment boundary indicated by the broken line, the input equals the precipitation $P$ while the output comprises the evapotranspiration $E$ and the river discharge $Q$ at the outlet of the catchment. Hence, the water balance may be written as:

$$P - E - Q = \frac{\Delta S}{\Delta t}$$

where $\Delta S$ is the change of storage over the time step $\Delta t$.

In this formula, care should be taken to use the same units for all parameters, e.g. mm/month or m$^3$/month.

$\Delta S$, the change in the amount of water stored in the catchment, is difficult to measure. However, if the ‘account period’ for which the water balance is established is taken sufficiently long, the effect of the storage term becomes less important, as precipitation and evapotranspiration accumulate while storage varies within a certain range. When computing the storage equation for annual periods, the beginning of the balance period is preferably chosen at a time that the amount of water in store is expected not to vary much for each successive year. These annual periods, which do not necessarily coincide with the calendar years, are known as hydrologic - or water years. The storage equation is especially useful to study the effect of a change in the hydrologic cycle.

If $\Delta S/\Delta t$ may be neglected, equations 2.1 and 2.2 may be re-written as:

$$I(t) = O(t)$$

and

$$P - E = Q$$

If the evaporation term $E$ consists of Interception $I$ and Transpiration $T$, then

$$E = I + T$$

and

$$P - I - T = Q$$

How to determine the blue and green water on an annual basis?

Precipitation ($P$) and the blue water ($Q$) can be determined through measurement. The difficulty lies with the green water ($T$). We first concentrate on the interception term ($I$).
The white water \((I)\) consists of the direct evaporation from small stagnant pools, bare soil evaporation and interception. Savenije (1997) showed that under the assumption that the soil moisture storage variation at a monthly or annual time step is small, the value for interception can be computed as:

\[ I = \text{Min}(P, D) \]  
(2.7)

where: \(D\) is the threshold evaporation (from interception) on a monthly or annual basis

The effective precipitation can now be defined as the remainder of the rainfall after interception has occurred:

\[ P_{\text{eff}} = \text{Max}( P - D, 0 ) \]  
(2.8)

After interception has occurred, water will either become blue water (through groundwater or surface flow), or become green water.

From gauged data of \(Q\) and \(P\), and given the threshold value \(D\), the effective runoff coefficient \(c\), on a water year basis, can be calculated as follows:

\[ c = \frac{Q}{P_{\text{eff}} = \frac{Q}{P - D}} \]  
(2.9)

where \(P\) and \(Q\) are the annual rainfall and runoff on a water year basis.

The runoff coefficient indicates the part of the effective precipitation that will become blue water. Thus, blue water can now be defined as:

\[ Q = c P_{\text{eff}} = c \text{Max}( P - D, 0 ) \]  
(2.10)

Transpiration must now be the balance between the effective precipitation and blue water:

\[ T = (1 - c) P_{\text{eff}} = (1 - c) \text{Max}( P - D, 0 ) \]  
(2.11)

Equations 2.7, 2.10 and 2.11 complete the "rainbow of water" (see Figure 1.3). Equation 2.7 accounts for the white water; eq. 2.11 for the green water, and eq. 2.10 for the blue water.

To find adequate values for \(I\) and \(T\) now depends on finding an appropriate value for \(D\).

Figure 2.1 presents the distribution of monthly values of rainfall \(P\), direct evaporation from interception \(I\), transpiration \(T\), and runoff \(R\) the total evaporation \(E\) over time in the Pungwe catchment in Mozambique. Of the total rainfall, only the evaporation from interception is a loss to the water resources in the catchment. The remainder is the green water and the blue water.
2.2 Groundwater resources

Groundwater can be split up into fossil groundwater and renewable groundwater. Fossil groundwater should be considered a finite mineral resource, which can be used only once, after which it is finished. Renewable groundwater is groundwater that takes an active part in the hydrological cycle. The latter means that the residence time of the water in the subsurface has an order of magnitude relevant to human planning and considerations of sustainability. The limit between fossil and renewable groundwater is clearly open to debate. Geologists, that are used to working with time scales of millions of years would only consider groundwater as fossil if it has a residence time over a million years. A hydrologist might use a time scale close to that. However, a water resources planner should use a time scale much closer to the human dimension, and to the residence time of pollutants.

![Diagram of groundwater resources](image)

**Figure 2.2** Blue water is surface runoff plus seepage from renewable groundwater

In our definition, the renewable groundwater takes active part in the hydrological cycle and hence is "blue water". Groundwater feeds surface water and vice versa. In the Mupfure catchment in Zimbabwe, Mare (1998) showed that more than 60% of the total runoff of the catchment originated from groundwater. Hence most of the water measured at the outfall was groundwater. One can say that all renewable groundwater becomes surface water and
most of the surface water was groundwater.

Two zones can be distinguished in which water occurs in the ground:
- the saturated zone
- the unsaturated zone.

For the hydrologist both zones are important links and storage devices in the hydrological cycle: the unsaturated zone stores the "green water", whereas the saturated zone stores the "blue" groundwater. For the engineer the importance of each zone depends on the field of interest. An agricultural engineer is principally interested in the unsaturated zone, where the necessary combination of soil, air and water occurs for a plant to live. The water resources engineer is mainly interested in the groundwater which occurs and flows in the saturated zone.

The type of openings (voids or pores) in which groundwater occurs is an important property of the subsurface formation. Three types are generally distinguished:
1. Pores: openings between individual particles as in sand and gravel. Pores are generally interconnected and allow capillary flow for which Darcy’s law (see below) can be applied.
2. Fractures, crevices or joints in hard rock which have developed from breaking of the rock. The pores may vary from super capillary size to capillary size. Only for the latter situation application of Darcy’s law is possible. Water in these fractures is known as fissure or fault water.
3. Solution channels and caverns in limestone (karst water), and openings resulting from gas bubbles in lava. These large openings result in a turbulent flow of groundwater which cannot be described with Darcy’s law.

The porosity $n$ of the subsurface formation is that part of its volume which consists of openings and pores:

$$\eta = \frac{V_p}{V}$$  \hspace{1cm} (2.12)

where: $V_p$ is the pore volume and $V$ is the total volume of the soil

When water is drained by gravity from saturated material, only a part of the total volume is released. This portion is known as specific yield. The water not drained is called specific retention and the sum of specific yield and specific retention is equal to the porosity. In fine-grained material the forces that retain water against the force of gravity are high due to the small pore size. Hence, the specific retention of fine-grained material (silt or clay) is larger than of coarse material (sand or gravel).

Groundwater is the water which occurs in the saturated zone. The study of the occurrence and movement of groundwater is called groundwater hydrology or geohydrology. The hydraulic properties of a water-bearing formation are not only determined by the porosity but also by the interconnection of the pores and the pore size.

An aquifer is a water-bearing layer for which the porosity and pore size are sufficiently large to allow transport of water in appreciable quantities (e.g. sand deposits).
Groundwater flow

The theory on groundwater movement originates from a study by the Frenchman Darcy, first published in 1856. From many experiments he concluded that the groundwater discharge \( Q \) is proportional to the difference in hydraulic head \( \Delta H \) and cross-sectional area \( A \) and inversely proportional to the length \( \Delta s \), thus

\[
Q = A^*v = A^*k^*\frac{\Delta H}{\Delta s}
\]

(2.13)

where \( k \), the proportionality constant, is called the hydraulic conductivity, expressed in m/d; and \( v \) is the specific discharge, also called the filter velocity. Since the hydraulic head decreases in the direction of flow, the filter velocity has a negative sign.

Groundwater as a storage medium

For the water resources engineer groundwater is a very important water resource for the following reasons:

- it is a reliable resource, especially in climates with a pronounced dry season
- it is a bacteriologically safe resource, provided pollution is controlled
- it is often available in situ (wide-spread occurrence)
- it may supply water at a time that surface water resources are limited
- it is not affected by evaporation loss, if deep enough.

It also has a number of disadvantages:

- it is a limited resource, extractable quantities are often low as compared to surface water resources
- groundwater recovery is generally expensive as a result of pumping costs
- groundwater, if phreatic, is very sensitive to pollution
- groundwater recovery may have serious impact on land subsidence or salinisation
- groundwater is often difficult to manage.

Especially in dry climates the existence of underground storage of water is of extreme importance. The water stored in the subsoil becomes available in two ways. One way is by artificial withdrawal (pumping), the other is by natural seepage to the surface water.

The latter is an important link in the hydrological cycle. Whereas in the wet season the runoff is dominated by surface runoff, in the dry season the runoff is almost entirely fed by seepage from groundwater (base flow). Thus the groundwater component acts as a reservoir which retards the runoff from the wet season rainfall and smoothens out the shape of the hydrograph.

The way this outflow behaves is generally described as a linear reservoir, where outflow is considered proportional to the amount of storage:

\[
Q = K S
\]

(2.14)

where \( K \) is a conveyance factor of the dimension s\(^{-1}\). Eq. 2.14 is an empirical formula which has some similarity with the Darcy equation (Eq. 2.13). In combination with the water balance equation, and ignoring the effect of rainfall \( P \) and evaporation \( E \), Eq. 2.14
yields an exponential relation between the discharge $Q$ and time $t$.

$$\frac{\Delta S}{S} = -K \Delta t$$

hence:

$$S = S(t_0) e^{-K(t-t_0)}$$

and hence, using Eq.(2.14):

$$Q = Q(t_0) e^{-K(t-t_0)}$$

Eq. (2.16) is useful for the evaluation of surface water resources in the dry season.

Fig. 2.3 gives a typical hydrograph, indicating flow from surface runoff and groundwater. The depletion curve has the shape of a negative exponential function, in keeping with the Darcy equation. Compare with the hydrograph of the Pungwe river (Fig. 2.4).
2.3 Surface water

Surface water resources are water resources that are visible to the eye. They are mainly the result of overland runoff of rain water, but surface water resources can also originate from groundwater, as was stated in Section 4.1. As Mare (1998) pointed out, more than 60% of the surface water in the Mupfure basin stemmed from groundwater, a resource hitherto disregarded. Surface water is linked to groundwater resources through the processes of infiltration (from surface water to groundwater) and seepage (from groundwater to surface water). Surface water occurs in two kinds of water bodies:
- water courses, such as rivers, canals, estuaries and streams;
- stagnant water bodies, such as lakes, reservoirs, pools, tanks, etc.

The first group of water bodies consists of conveyance links, whereas the second group consists of storage media. Together they add up to a surface water system.

The amount of water available in storage media is rather straightforward as long as a relation between pond level and storage is known. The surface water available in channels is more difficult to determine since the water flows. The water resources of a channel are defined as the total amount of water that passes through the channel over a given period of time (e.g. a year, a season, a month). In a given cross-section of a channel the total available amount of surface water runoff over a time step $\Delta t$ is defined as the average over time of the discharge.

$$R = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} Q \, dt$$  \hspace{1cm} (2.17)

The discharge $Q$ is generally determined on the basis of water level recordings in combination with a stage discharge relation curve, called a rating curve. A unique relationship between water level and river discharge is usually obtained in a stretch of the river where the river bed is stable and the flow is slow and uniform, i.e. the velocity pattern does not change in the direction of flow. Another suitable place is at a calm pool, just upstream of a rapid. Such a situation may also be created artificially in a stretch of the river (e.g. with non-uniform flow) by building a control structure (threshold) across the river bed. The rating curve established at the gauging station has to be updated regularly, because scour and sedimentation of the river bed and river banks may change the stage discharge relation, particularly after a flood.

The rating curve can often be represented adequately by an equation of the form:

$$Q = a(H - H_0)^b$$  \hspace{1cm} (2.18)

where $Q$ is the discharge in $\text{m}^3/\text{s}$, $H$ is the water level in the river in $\text{m}$, $H_0$ is the water level at zero flow, and $a$ and $b$ are constants. The value of $H_0$ is determined by trial and error. The values of $a$ and $b$ are found by a least square fit using the measured data, or by a plot on logarithmic paper and the fit of a straight line (see Fig. 2.2).
Fig. 2.5 shows the rating curve of the Limpopo river at Sicacate; the value of $b$ equals 1.90. The Limpopo is an intermittent river which falls dry in the dry season and can have very high flash floods during the flood season. The station of Sicacate has a value of $H_0$ equal to 2.1 m. In Fig. 2.4 a clear flood branch can be distinguished which is based on peak flows recorded during the floods of 1981, 1977 and 1978 in the Limpopo river. The gradient of a flood branch becomes flat as the river enters the flood plain; a small increase in water level then results in a large increase in discharge.

To illustrate the trial and error procedure in determining the value of $H_0$, a plot of data with $H_0=0$ has been added. It can be seen that the value of $H_0$ particularly affects the determination of low flow.

2.4 Catchment yield

Water resources engineers are primarily concerned with catchment yields and usually study hydrometric records on a monthly basis. For that purpose short duration rainfall should be aggregated. In most countries monthly rainfall values are readily available. To determine catchment runoff characteristics, a comparison should be made between rainfall and runoff. For that purpose, the monthly mean discharges are converted first to volumes per month and then to an equivalent depth per month $Q$ over the catchment area. Rainfall $P$ and runoff $Q$ being in the same units (e.g. in mm/month) may then be compared.

A typical monthly rainfall pattern is shown in Fig. 2.6 for the catchment of the Cunapo river in Trinidad. The monthly runoff has been plotted on the same graph. Fig. 2.7 shows the difference between $Q$ and $P$, which partly consists of evaporation $E$ (including interception, open water evaporation, bare soil evaporation and transpiration) and partly is caused by storage. On a monthly basis one can write:
\[ Q = P - E \cdot \Delta S / \Delta t \]  

(2.19)

The presence of the evaporation and the storage term makes it difficult to establish a straightforward relation between \( Q \) and \( P \). The problem is further complicated in those regions of the world that have distinctive rainy and dry seasons. In those regions the different situation of storage and evaporation in the wet and dry season make it difficult to establish a direct relation.

Figure 2.6 Monthly mean rainfall and runoff in the Cunapo catchment

Figure 2.7 Mean monthly losses and change in storage in the Cunapo catchment
Figure 2.8 Rainfall plotted versus runoff in the Cunapo river basin

Fig. 2.8 shows the plot of monthly rainfall $P$ against monthly runoff $Q$ for a period of four years in the Cunapo catchment in Trinidad. The plots are indicated by a number which signifies the number of the month. The following conclusions can be drawn from studying the graph.

- There appears to be a clear threshold rainfall below which no runoff takes place. This threshold value is the result of evaporation from intercepted rainfall (interception). It is the direct evaporation from wet leaves, the wet surface and the upper layer of the soil.

- It can be seen that the same amount of rainfall gives considerably more runoff at the end of the rainy season than at the start of the rainy season. The months with the numbers 10, 11 and 12 are at the end of the rainy season, whereas the rainy season begins (depending on the year) in the months of May to July. At the start of the rainy season the contribution of seepage to runoff is minimal, the groundwater storage is virtually empty and the amount to be replenished is considerable; the value of $\Delta S/\Delta t$ in Eq.(2.19) is thus positive, reducing the runoff $R$. At the end of the rainy season the reverse occurs.

After the interception $I$ has been subtracted from the rainfall the remainder: the effective rainfall can be thought to be split up between superficial runoff $Q_s$ and infiltration $F$. The infiltration replenishes the soil moisture, which feeds the transpiration $T$. If the water holding capacity of the soil is exceeded, the remainder of infiltration recharges the groundwater. This recharge $R$ joins the groundwater storage which through seepage $Q_g$ contributes to runoff.

The sum of $Q_s$ and $Q_g$ is the total runoff $Q$ of Eq. (2.19). The total evaporation $E$ consists of the sum of $I$ and $T$. At a monthly time scale, the storage $S$ is the sum of the water stored in the groundwater, in the soil and in reservoirs. Only in very large catchments (e.g. the Zambezi) is there a measurable storage in the watercourses. By taking into account a threshold $D$ for interception and the storage $S$, a relation can be obtained between $Q$ and $P$. 
2.5 The rainbow of water revisited

Of all water resources, "green water" is probably the most under-valued resource. Yet it is responsible for by far the largest part of the world's food and biomass production. The concept of "green water" was first introduced by Falkenmark (1995), to distinguish it from "blue water", which is the water that occurs in rivers, lakes and aquifers. The storage medium for green water is the unsaturated soil. The process through which green water is consumed is transpiration. Hence the total amount of green water resources available over a given period of time equals the accumulated amount of transpiration over that period. In this definition irrigation is not taken into account. Green water is transpiration resulting directly from rainfall, hence we are talking about rainfed agriculture, pasture, forestry, etc.

The average residence time of green water in the unsaturated zone is the ratio of the storage to the flux (the transpiration). At a global scale the soil moisture availability is 440 mm (see Tables 2.1 and 2.2: 65/149) In tropical areas the transpiration can amount to 100 mm/month. Hence the residence time of green water in tropical areas is approximately 4 months. This residence time, however, applies to deeply rooting vegetation. For shallow rooting vegetation the residence time in the root zone is much shorter. In temperate and polar areas where transpiration is significantly less the residence is much longer. At a local scales, depending on climate, soils and topography, these numbers can vary significantly.

Green water is a very important resource for global food production. About 60% of the world staple food production relies on rainfed irrigation, and hence green water. The entire meat production from grazing relies on green water, and so does the production of wood from forestry. In Sub-Saharan Africa almost the entire food production depends on green water (the relative importance of irrigation is minor) and most of the industrial products, such as cotton, tobacco, wood, etc.

There is no green water without blue water, as their processes of origin are closely related. Blue water is the sum of the water that recharges the groundwater and the water that runs-off over the surface. Blue water occurs as renewable groundwater in aquifers and as surface water in water bodies. These two resources can not simply be added, since the recharge of the renewable groundwater eventually ends up in the surface water system. Adding them up often implies double counting. Depending on the climate, topography and geology, the ratio of groundwater recharge to total blue water varies. In some parts the contribution of the groundwater to the blue water can be as high as 70-80%, in some parts (on solid rock surface), it can be negligible. Generally the groundwater contribution to the blue water is larger than one thinks intuitively. The reason that rivers run dry is more often related to groundwater withdrawals, than to surface water consumption.

Engineers always have had a preference for blue water. For food production, engineers have concentrated on irrigation and neglected rainfed agriculture, which does not require impressive engineering works. Irrigation is a way of turning blue water into green water. Drainage is a way of turning green water into blue water.

To complete the full picture of the water resources, besides green water and blue water, there is "white water". White water is the part of the rainfall that feeds back directly to the atmosphere through evaporation from interception and bare soil. Some people consider the white water as part of the green water, but that adds to confusion since green water is a productive use of water whereas the white water is non-productive. The white and green
water together form the vertical component of the water cycle, as opposed to the blue water, which is horizontal. In addition, the term white water can be used to describe the rainfall which is intercepted for human use, including rainwater harvesting.

### Table 2.4 Global Water Resources, fluxes, storage and average residence times

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>$T$</td>
<td>100 mm/month</td>
<td>$S_w$</td>
<td>440 mm</td>
<td>$S_w/T$ 4 months</td>
</tr>
<tr>
<td>White</td>
<td>$I$</td>
<td>5 mm/d *)</td>
<td>$S_i$</td>
<td>3 mm *)</td>
<td>$S_i/I$ 0.6 days</td>
</tr>
<tr>
<td>Blue</td>
<td>$Q$</td>
<td>$46 \times 10^{12}$ m$^3$/a</td>
<td>$S_w$</td>
<td>$124 \times 10^{12}$ m$^3$</td>
<td>$S_w/Q$ 2.7 years</td>
</tr>
<tr>
<td>Deep blue</td>
<td>$Q_g$</td>
<td>$5 \times 10^{12}$ m$^3$/a *)</td>
<td>$S_g$</td>
<td>$750 \times 10^{12}$ m$^3$ *)</td>
<td>$S_g/Q_g$ 150 years</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>$P$</td>
<td>$510 \times 10^{12}$ m$^3$/a</td>
<td>$S_a$</td>
<td>$12 \times 10^{12}$ m$^3$</td>
<td>$S_a/P$ 0.3 month</td>
</tr>
<tr>
<td>Oceans</td>
<td>$A$</td>
<td>$46 \times 10^{12}$ m$^3$/a</td>
<td>$S_o$</td>
<td>$1.3 \times 10^{18}$ m$^3$</td>
<td>$S_o/A$ 28000 yr</td>
</tr>
</tbody>
</table>

Note: transpiration and interception fluxes apply to tropical areas. Storage in the root zone can be significantly less than 440 mm.

*) indicate rough estimates

Table 2.4 presents the quantities of fluxes and stocks of these water resources, and the resulting average residence times, at a global scale. The stocks $S_w$, $S_i$, $S_w$, $S_g$, $S_a$ and $S_o$ represent the life storages of the unsaturated zone, the surface, the water bodies, the renewable groundwater, the atmosphere and the oceans, respectively. For catchments and sub-systems similar computations can be made. The relative size of the fluxes and stocks can vary considerably between catchments. Not much information on these resources exists at sub-catchment scale.

The study of the Mupfure catchment in Zimbabwe by Mare (1998) is an exception. Table 4.6 illustrates the importance of green water and renewable groundwater in a country where these resources have been mostly disregarded. Fig. 2.9, based on 20 years of records (1969-1989) in the Mupfure basin in Zimbabwe (1.2 Gm$^2$), shows the separation of rainfall into interception (White), Green and Blue water. The model used for this separation is described by Savenije (1997) (see equations 2.7, 2.10 and 2.11 above). It can be seen that there is considerably more green water than blue water available in the catchment. Moreover, the model showed that more than 60% of the blue water resulted from groundwater.
Figure 2.9 Partitioning of rainfall between "White", "Green" and "Blue" water in the Mupfure sub-catchment in Zimbabwe (records of 1969-1989)

Table 2.5 Water resources partitioning and variability in the Mupfure River Basin, Zimbabwe

<table>
<thead>
<tr>
<th>Mupfure river</th>
<th>Source</th>
<th>Vertical component</th>
<th>Horizontal Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station: C70</td>
<td>Rainfall (P)</td>
<td>&quot;White&quot; (W)</td>
<td>&quot;Green&quot; (G)</td>
</tr>
<tr>
<td>Catchment area: 1.2 Gm²</td>
<td>Mean annual flux (µ)</td>
<td>775 mm/a</td>
<td>446 mm/a</td>
</tr>
<tr>
<td>Record length: 1969-1989</td>
<td>Partitioning</td>
<td>100%</td>
<td>62%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation (σ)</td>
<td>265 mm/a</td>
<td>48 mm/a</td>
</tr>
<tr>
<td></td>
<td>Interannual variability (σ/µ)</td>
<td>34%</td>
<td>11%</td>
</tr>
</tbody>
</table>

It can be seen from Table 2.5 that the variability of the "white" water is much lower (11%) than the variability of the "green" (67%) and "blue" water (69%). This is a general phenomenon which can be understood from the fact that interception is the first process to occur and that this process has an upper boundary. The maximum amount of interception per day is limited by the amount of interception storage and the potential evaporation.

2.6 The water balance as a result of human interference

Attempts have been made to incorporate the interference of man in the hydrological cycle through the introduction of the water diversion cycle, which includes water withdrawal and water drainage. This diversion cycle is exerting significant influence on the terrestrial water cycle, especially in highly economically developed regions with a dense population (See Fig. 2.10)

The water diversion cycle including human interference results in the following annual
average water balance equation (neglecting storage variation):

\[ P + D = E + C + Q \]  
(2.20)

\[ C = U_s + U_g - R_s - R_g + H + D \]  
(2.21)

where:  
\( P \) = precipitation  
\( E = T + I + O \) = total evaporation from the land surface (transpiration + interception + open water evaporation)  
\( C \) = net water consumption due to water use  
\( Q \) = runoff from land to ocean  
\( U_s + U_g \) = intake from surface and groundwater  
\( R_s + R_g \) = return flows to surface and groundwater  
\( H \) = rainwater harvesting  
\( D \) = desalination

Figure 2.10 Scheme of the hydrological cycle with the diversion cycle (after Rodda and Matalas, 1987)
2.7 References


Savenije, H.H.G., 2000, Water resources management: concepts and tools. Lecture note. IHE, Delft and University of Zimbabwe, Harare
3. Water allocation principles

3.1 Introduction

An important purpose of water management is to match or balance the demand for water with its availability, through suitable water allocation arrangements. Water availability is dealt with in other courses (e.g. Hydrology). This lecture note of Water Using Activities aims to provide tools to estimate the demand for water for different types of use.

There are a large number of types of water use. Among these are:
- Hydropower
- Irrigation
- Domestic use in urban centres
- Domestic use in rural areas
- Livestock
- Industrial use
- Commercial use
- Institutions (e.g. schools, hospitals etc.)
- Cooling (e.g. for thermal power generation)
- Waste and wastewater disposal
- Navigation
- Recreation
- Fisheries
- The environment (wildlife, nature conservation etc.)

Demand for water is the amount of water required at a certain point. The use of water refers to the actual amount reached at that point.

We can distinguish withdrawal uses and non-withdrawal (such as navigation, recreation, waste water disposal by dilution) uses; as well as consumptive and non-consumptive uses. Consumptive use is the portion of the water withdrawn that is no longer available for further use because of evaporation, transpiration, incorporation in manufactured products and crops, use by human beings and livestock, or pollution.

The terms “consumption”, “use” and “demand” are often confused. The amount of water actually reaching the point where it is required will often differ from the amount required. Only a portion of the water used is actually consumed, i.e. lost from the water resource system.

3.2 Balancing demand and supply

There are various ways how to allocate water. The challenge is to find an optimal allocation that, firstly, adheres to laid-down legal and other regulations, and secondly, satisfies the water demand of all users as much as possible. Or,
"to balance properly between a whole set of obligations: to international conventions, to human basic rights for well-being of both upstream and downstream societies, for protection of land productivity, for delivery of ecological goods and services from both terrestrial and aquatic ecosystems, and for resilience of ecosystems to both natural and man-made disturbances."
(Falkenmark and Folke, 2001)

Water allocation is not an issue when water availability far surpasses the demand. In such situations all demands can be satisfied, and in fact there is no need for a regulated allocation of water. In many catchment areas and parts of river basins, however, water availability is frequently less than the demand for it. It is then necessary to find a suitable allocation of the scarce water.

Water allocation is not only concerned with the physical allocation of water. More broadly it is about satisfying conflicting interests depending on water. These may be functions derived from water such as navigation (navigability, minimum water levels), hydropower (head difference), environment (a water regime of water level fluctuation), recreation (availability of water but non-consumptive), etc. These functions are only to a certain extent consumptive, but can be conflictive in their timing and spatial distribution. Also flood protection is a function of the water resources system that related to the water resources. Flood protection through the construction of storage dams can have a positive impact on water availability for other functions (e.g. hydropower), but can have negative impacts on others (e.g. on the environment).

Finding a suitable allocation key for water can be quite complex, since a large number of parameters have to be considered, both on the supply- and the demand-side.

**Supply**
- The generation of water in a catchment area naturally fluctuates, both within years and between years.
- Water occurs in different forms, which often have different uses. Special reference is made to rainfall and its use as "green water" in agriculture. Green water cannot be allocated in the same way as "blue" water occurring in rivers and aquifers. Yet, dryland agriculture and other types of land use do influence the partitioning of rainfall into groundwater recharge, surface runoff and soil moisture (i.e. evaporation and transpiration), and hence their availability.

**Demand**
- The demand for water fluctuates, but normally much less than its generation. For many types of uses, water demand increases when water availability decreases, such as during the dry season.
- Many water uses are (partially) consumptive, meaning that the water abstracted will not return to the water system in the form of "blue water"; consumptive water use typically converts blue or green water into water vapour, which in this form cannot be allocated to other users.
- Water uses that are non-consumptive allow others to use the water afterwards. Recreational water uses are a typical example. However, some non-consumptive uses alter the time when this water becomes available for other users. A typical example is water used for the generation of hydropower: electricity is needed also during the wet season, and thus water has to be released from dams for this purpose, when demand for
it from other sectors may be low. As a result, this water used for electricity generation is unavailable to these potential uses when they need it. The environment is another (partially) non-consumptive user of water; its requirements are frequently out of sync with the needs of other users. (That is precisely why these environmental water requirements are now increasingly being recognised.)
- Many uses of water generate return flows, which, in principle, are available for other uses. However, return flows normally have a lower quality than the water originally abstracted. This may severely limit their re-use. Sometimes the quality of return flows is a hazard to public health and the environment.
- Different types of water use require different levels of assurance. For arable (non-perennial) irrigated crops, levels of assurance of 80% (i.e. a chance of failure in one out of five years) may be acceptable. For urban water supply assurance levels of 96% or higher are the norm (failing in one out of 25 years).

The legal framework

In many countries water is considered a public good. Here the water is owned by the citizens of a country, and the government manages this public good on their behalf. Laws and regulations will therefore provide the rules pertaining to the use of this public resource.

From a public to a private good

In countries where water is considered a public good, water allocation may be viewed as the process of converting a public good into a private one. An irrigator, for instance, will apply the water to his/her privately owned crop. The crop will consume a large part of the water, converting it into water vapour and increasing its yield. The irrigator derives direct and private benefit from using a public good, but in so doing s/he denies another person the opportunity to use that water and deriving similar private benefits.

Balancing supply and demand must be done within the established legal framework. A country's water law and subsidiary government regulations will prescribe many aspects of water allocation. Amongst these are:
- The law will prescribe the types of water use that are regulated and therefore require some kind of permit, concession, right etc.; and the types of water use that are not regulated and do not require permission. The use of water for primary purposes often does not require a permit or water right, just as the direct use of rainwater.
- A water permit or water right typically defines which water (groundwater, surface water) can be diverted, where (point of abstraction), and for which purpose (e.g. irrigation of x ha of land). A permit or right specifies certain conditions under which water use is permitted. A typical condition is that the permit or right is limited in that it does not permit the use of water that infringes on similar rights of others. Another condition frequently specified is that the water should be used beneficially and not be wasted, and that return flows should adhere to certain quality standards.
- The law often stipulates the hierarchy of different types of water use; distinguishing between, for instance, primary use, environmental use, industrial use, agricultural use, water for hydropower etc. In most countries water use for primary purposes has priority over any other type of water use. Some countries also specify a hierarchy of the remaining uses, whereby the most important economic use in that country normally receives a high priority of use. In other countries all uses of water other than for
primary (and sometimes environmental) purposes have equal standing. In times of water shortage the amount of water allocated to all non-primary uses will be decreased proportionally, so that all these user share the shortage equally.

The law may provide more detailed stipulations with a direct bearing on the allocation of water. The law may stipulate, for instance, that the allocation of water should be equitable. In some countries, in contrast, the law directs that junior rights may not affect senior rights.

In most cases, however, the legal framework does not provide a detailed "recipe" of how the water should be allocated. The water manager will therefore have to interpret the more general principles as laid down in the law, and translate these into operational rules for day-to-day allocation decisions. In many countries the water manager may not even do this without consulting all relevant stakeholders.

The value of water

The various uses of water in the different sectors of an economy add value to these sectors. Some sectors may use little water but contribute significantly to the gross national product (GNP) of an economy. Other sectors may use a lot of water but contribute relatively little to that economy. Table 1.1 (chapter 1) gives the contribution of the various sectors of the Namibian economy to its Gross National Product, and the amount of water each sector uses. Industry and commerce uses less than 3% of all water used in Namibia, but contribute 42% to the Namibian economy. In contrast, irrigated agriculture uses 43% of all water used, but contributes only 3% to the economy.

Care should be taken to interpret the above data. For instance, it is well known that the agricultural sector typically has a high multiplier effect in the economy, since many activities in other sectors of the economy depend on agricultural output, or provide important input services (Rogers, 1998). The "real" value added by water may thus be underestimated by the type of data given in the table. Box 3.1 provides some data on the added value of (irrigation) water for the production of maize in Zimbabwe.

The added value of some uses of water are very difficult, if not impossible, to measure. Consider for instance the domestic use of water: how to quantify the value of an adequate water supply to this sector? The damage to an economy by water shortage may be immense. It is well known, for instance, that a positive correlation exists between the Zimbabwe stock exchange index and rainfall in Zimbabwe. The drought of 1991/92 had a huge negative impact on the Zimbabwean economy (see box 1.1 in chapter 1).
Box 3.1: The value of water for maize in Zimbabwe (see also Figure 3.1)

For selected plots in Nyanyadzi irrigation scheme, Pazvakawambwa and van der Zaag (2000) found that one additional m³ of water (irrigation+rainfall) supplied to the maize crop (rainfed with supplementary irrigation) gave an added yield of 1.5 kg of maize m⁻³ ($r^2 = 0.81$). Assuming a maize price of 0.10 US$ kg⁻¹, it follows that the marginal value of water (rainfall+irrigation) is 0.15 US$ m⁻³.

Yields were also correlated with net total irrigation water ($Inet$ in mm). The following mathematical relationship was found:

\[ Y = 1,450 + 19 \times Inet \]  
(correlation coefficient $r^2 = 0.71$)

The constant of 1,450 kg ha⁻¹ indicates the yields obtainable for a rainfed crop without irrigation. The marginal productivity of net summer supplementary irrigation water was 19 kg ha⁻¹ mm⁻¹, or 1.9 kg m⁻³. This means that 1 m³ of supplementary irrigation water will produce an additional 1.9 kg of maize, which is valued at US$ 0.19. The marginal value of supplementary irrigation for maize in Nyanyadzi is therefore 0.19 US$ m⁻³.

Figure 3.1: Relationship between water use and yield for maize, Nyanyadzi, Zimbabwe

Scales and boundary conditions

Any allocation decision potentially has third party effects: it may affect those not immediately involved in the allocation process, either beneficially or detrimentally. A special case, and a very important one, is where downstream users are affected that are located outside the jurisdiction of a given water allocation institution.

Any allocation process that does not encompass the entire river basin runs the risk of being affected by upstream uses and in turn impacting on downstream uses. Since most river basins are simply too large in extent, and often shared by more than one country, the water allocation processes is normally fragmented into catchment areas which form part of the larger basin. In such cases the allocation process must include boundary conditions; i.e. a specification of water requirements at the inlet and at the outlet of the catchment area under consideration. Even a most downstream catchment area, with its downstream
boundary being an estuary, will have to set such boundary conditions so as to minimise salt intrusion, and/or ensure the health of the estuary for environmental, social and/or economic purposes (e.g. for mangrove forests and prawn fisheries).

Boundary conditions are especially important in river basins that are shared by more than one country. If an upstream water allocation institution does not consider the requirements of the downstream country, it may even affect the bilateral relations of the two neighbouring countries.

It would be advisable to formalise such boundary conditions in writing and to get them endorsed by all water allocation institutions involved; in a similar manner as how claims of individual water users are formalised in water permits or rights.

The water allocation process should ideally consider both the detailed allocation decisions between individual water users at the local level, as well as the "big picture" allocation decisions covering the entire river basin. Obviously, these different spatial scales require different levels of accuracy and specificity. But they are both required, since decisions at these different spatial scales affect each other.

Historically, the decision-making process has been iterative, with an initial focus on the smaller spatial scales, especially in heavily committed parts of a basin. With the steadily increasing pressures on our water resources, the interconnectedness between the various parts of the basin have become apparent in many river systems. This has inevitably led to widening the scope of the water allocation process also to the largest spatial scale.

3.3 Issues in water allocation

In this section some important issues directly related to water allocation are briefly discussed. These issues typically cannot be solved overnight. Any actor involved in water allocation, however, must be aware of them.

1. Defining key concepts

Key concepts used in a country's water allocation system must be very precisely and clearly defined, and be known and understood by the water users. Such key concepts may include: the ownership of water, water use, primary use, equity, efficiency, and the precise rights and obligations conferred with a water permit.

Water use
The South African Water Act (1998) defines water use as taking and storing water, activities which reduce stream flow, waste discharges and disposals, controlled activities (declared activities which impact detrimentally on a water resource), altering a watercourse, removing underground water for certain purposes, and recreation.
A particularly important issue is the definition of water use, since this basically defines the point where water converts from a public to a private good. Lack of clarity about where exactly this conversion occurs will create confusion, which will directly impact on the effectiveness of the water allocation process. For instance, if a permitholder has lawfully stored water in his/her dam, has this water already been used and hence is owned by the permitholder, or not yet?

2. Uncertainty

Generally speaking, if a user does not know how much water he or she is entitled to, and how much water is likely to be available at a future time, he or she tends to over-use or hoard water often at considerable losses.

The allocation of water over different uses should therefore aim to effectively deal with uncertainty and increase the predictability of water available to the various uses. Increased predictability is an important condition that will allow users to use water more efficiently. Even a better understanding of how unpredictable water availability is will improve a user's ability to deal with this.

Two types of uncertainty may be distinguished: physical uncertainty and institutional uncertainty.

*Physical uncertainty*

Physical uncertainty does not so much refer to the stochastic nature of hydrological processes (which is normally quite well understood), but more to the impact of human activities on the hydrological cycle. At the global level, human-induced climate change is a possibility and may have wide-ranging effects, but the specific effects are not yet well understood. At a smaller spatial scale, the effects of land use change on the availability of blue water are difficult to predict. Will a more efficient use of soil moisture for rainfed crop production indeed translate into decreased blue water flows? A bit more straightforward is the link between groundwater and surface water abstraction; but still it is difficult to predict the precise effect of groundwater abstraction in a given location on the surface water availability somewhere downstream.

The physical uncertainties mentioned here must be acknowledged. If a proper understanding of such processes is lacking, in the first instance conservative estimates should be made on possible impacts of certain interventions. The water management agency should then put in place a programme of data collection meant to gradually improve the understanding of these dynamic processes.

*Institutional uncertainty*

A different type of uncertainty is created by the institutions that are involved in water allocation. If the manner in which such institutions allocate water is unknown to the users or ill-understood by them, or seen as haphazard, then users may distrust the allocation process. They will receive the wrong (perverse) incentives to, for instance, overstate their water requirements, hoard water or even over-use it.
The institutional system of water allocation should therefore be predictable to users. All users should know the principles and procedures guiding the allocation of water. Moreover, the allocation process must treat all users in the same way. It must also be transparent, and information on permits granted or permits refused must be freely accessible, not only to all water users, but to the wider public as well. A fair and transparent allocation process will enhance the individual users' trust in the process, and will increase their confidence in the worth of their permits/rights to use water. Trust in the allocation process will enhance users willingness to invest in water related infrastructure, and desist from "free-rider behaviour" in times of water scarcity.

3. Efficiency and equity

It could be argued that Postel's three *Es* (Equity, Efficiency and Ecological integrity; see chapter 1) should form the pillars of any water management activity. Since water allocation is a major water management activity, following this line of argument the three *Es* should also inform water allocation decisions. Suppose now that the environmental/ecological water requirements are adequately taken care of, by assigning to the environment rights to sufficient water with an acceptable ecological regime. Then two *Es* remain, i.e. equity and efficiency.

Some people believe that there is a trade-off between the principles of equity and efficiency; i.e. a more efficient allocation system may ignore certain issues of equity, and vice versa, a more equitable allocation system may be less efficient. This is not necessarily true for all situations. Here some tentative definitions are given, and some implications for water allocation briefly explored.

*Equity*

Equity can be defined as affording everyone a fair and equal opportunity in the utilisation of the resource according to one's needs. Equitable access does not necessarily mean access to equal quantities but rather equal opportunity to access water (WRMS, 1999). Equity deals with the distribution of wealth or resources among sectors or individuals of society.

*Efficiency*

Different definitions of efficiency can be used, depending on one's objective. The reason why efficiency is important is that water is a finite and often scarce resource. Generally, efficiency measures how much one can do with one unit of water. Economic efficiency would then measure the benefits derived from a unit volume of water used. Water use efficiency measures the amount of water actually used for a given use.

At a more abstract level, efficiency can also indicate to what extent the ensemble of technical, legal, institutional, economic and other measures induce efficient use of the scarce water. For instance, certain legal and institutional arrangements may enhance people's willingness to privately invest in water infrastructure, or induce them to waste less water, or pollute less. This will eventually lead to increased water use efficiency as well as increased economic efficiency.
This wider definition of efficiency calls for pricing arrangements that ensure cost recovery of water services. This will not only give the correct signal to water users, namely that water is valuable and should not be wasted, but will also lead to the sustainability of infrastructure and institutions. The wider definition of efficiency also calls for suitable legal arrangements that provide users with sufficient security of water tenure, such that they are willing to invest in water-related infrastructure.

**Trade-offs**

The principle of economic efficiency is often translated into proper pricing of water services. This may obviously jeopardise the equity principle, in that poorer households may not be able to buy such a service. The fact that poorer households are thus denied access to a basic amount of water may however be extremely costly to society, in terms of disease, ill health etc. From a societal perspective it may therefore be highly efficient to provide all households with a very cheap (subsidised) lifeline quantity of water, and to make up the financial shortfall through cross-subsidies. In this manner win-win combinations of efficiency and equity in water allocation systems may be achieved.

4. Water losses

Reducing water losses often has a high priority in attempting to balance demand with supply. However, water losses should always be carefully and precisely defined. This is because it depends on the scale and the boundaries whether water is considered a loss or not. At the global scale no water is ever lost. At the scale of an irrigation scheme, a water distribution efficiency of 60% indeed means that slightly less than half of the water is lost. Part of this water, however, may return to the river and be available to a downstream user. At the scale of the catchment, therefore, it is the transpiration of crops (40% in this example) that can be considered a loss!

In many situations, and especially in irrigated agriculture, a reduction of water losses may not free up the "saved" water. Even "real" water losses, such as when water is released from a dam through the river bed for a downstream user, may provide an important service; namely recharge of aquifers, water for the environment etc. Once such services are recognised and formalised into permits (or in a "Reserve", as done in South Africa), the water manager may sometimes be able to find interesting win-win solutions. In other cases, of course, this may not be possible.

Analysing water losses should therefore always:
- clarify the scale and boundaries at which the analysis is done
- acknowledge both the consumptive and non-consumptive parts of the water use under consideration
- consider any other type of use (including the environment) that may benefit from the water "lost".
5. Water allocation between sectors (Savenije and Van der Zaag, 2001)

As we have noted earlier, some types of water use add more value than others. The classic case is the different values attained in the agricultural and urban sectors: the value attained in urban sectors is typically an order of magnitude higher than in agriculture (Briscoe, 1996). If water is currently used in the agricultural sector, the opportunity cost, i.e. the value of the best alternative use, may be 10 times higher, subject of course of "location and the hydraulic connections possible between users" (Briscoe, 1996). Thus a shift towards the higher value use is often promoted.

Whereas the opportunity cost of water for domestic water use may be highest, the moment availability is higher than demand, the opportunity cost of the water will fall to the next best type of use. It is just not possible to consume all the water at the highest value use. The proper opportunity cost for irrigation water may therefore be only half, or less, than the best alternative use (Rogers et al., 1997). Even then the reliability of supply acceptable to irrigated agriculture is much lower than that for urban water supply: a storage dam yielding $x \text{ m}^3$ of water supplied to irrigation at 80% reliability, may yield only $0.5x \text{ m}^3$ (or more or less, depending on hydrology) for urban water supplied at 95% reliability. The effective opportunity cost of water used for irrigation should therefore again at least be halved. The resulting opportunity cost is thus only a fraction of what some neo-classical economists claim it to be.

Figure 3.2 illustrates the variation of supply and demand in an imaginary case. It shows that, in general, primary (domestic) and industrial demands, with the highest ability and willingness to pay, require a high reliability of supply, which is normally achieved through relatively large storage provision. Also environmental demands are not the most demanding on the resource. Agricultural water requirements tend to be much higher, fluctuate strongly but also accept a lower reliability of supply.
The emerging picture, then, is fairly straightforward and common sense: the sectors with highest value water uses should have access to water. In many countries these sectors require only 20-50% of average water availability, and these demands can easily be satisfied in all but the driest years. In most years much more water will be available, and this water should be used beneficially, for instance for irrigation. There is therefore no need for permanent transfers from agriculture to other sectors, except in the most heavily committed catchment areas of the world. What is needed is a legal and institutional context that allows temporary transfers of water between agriculture and urban areas in extremely dry years. No market is required to cater for such exceptional situations. A simple legal provision would suffice, through which irrigators would be forced to surrender stored water for the benefit of urban centres against fair compensation of (all) benefits forgone.

In those heavily committed catchment areas where permanent transfers of water out of the agricultural sector are required, normally voluntarily negotiated solutions can be agreed, provided the laws allow this to happen.

6. Do higher value uses of water need to have priority over lower value uses?

No, not necessarily. Higher value uses (such as urban water use) often have the potential to mobilise sufficient financial resources to secure a reliable supply. Higher value uses often require higher levels of reliability, meaning larger dams, and hence much larger investments, compared with lower value uses (e.g. irrigation). Often, the higher value uses are able to mobilise even these higher investment requirements. In such cases, it is not necessary to give higher value uses priority over lower value uses. The obvious economic advantage to society of not giving priority to various non-primary uses, is, that sectors have to fend for themselves, and will not, in all but the most extreme droughts, damage each other. As observed earlier, in extreme cases of drought, transfers between sectors will have to be done against fair compensation.

3.4 Conclusion

An important purpose of water management is to match or balance the demand for water with its availability, through suitable water allocation arrangements.

There is not one best way to balance water demand with water availability. This balancing act is basin and catchment-specific. It is also clear that the balancing act will often involve a process of decision-making where difficult compromises have to be made. Another course module (water resources analysis and planning) provides tools to assist with these decision processes.

In all cases, the water allocation process requires a sound quantitative understanding of both water availability and water demand. Water availability will be thoroughly dealt with in other course modules (e.g. hydrology). Water demand of different sectors are dealt with in subsequent chapters of this lecture note.
3.5 Exercise

1. In a similar but more detailed manner as Pallett (see section 1), Lange (1997) calculated the contribution of water by sector to the economy of Namibia:

<table>
<thead>
<tr>
<th>Sector</th>
<th>Value added 10^6 N$/yr</th>
<th>Water use 10^6 m³/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial agriculture</td>
<td>405</td>
<td>111.4</td>
</tr>
<tr>
<td>Communal agriculture</td>
<td>176</td>
<td>34.8</td>
</tr>
<tr>
<td>Mining</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diamond mining</td>
<td>609</td>
<td>13.6</td>
</tr>
<tr>
<td>Other mining</td>
<td>253</td>
<td>8.1</td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish processing</td>
<td>316</td>
<td>0.7</td>
</tr>
<tr>
<td>Other manufacturing</td>
<td>340</td>
<td>4.3</td>
</tr>
<tr>
<td>Services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hotels/Restaurants (Tourism)</td>
<td>129</td>
<td>1.1</td>
</tr>
<tr>
<td>Transportation</td>
<td>245</td>
<td>0.8</td>
</tr>
<tr>
<td>Other services</td>
<td>2,433</td>
<td>3.3</td>
</tr>
<tr>
<td>Households</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>n.a.</td>
<td>10.0</td>
</tr>
<tr>
<td>Urban</td>
<td>n.a.</td>
<td>34.7</td>
</tr>
<tr>
<td>Government</td>
<td>n.a.</td>
<td>2.3</td>
</tr>
</tbody>
</table>

1a. On the basis of the data provided, define an appropriate indicator for the “value added” by water.

1b. Calculate for each sector this indicator.

1c. Compare the sectors. What do you observe?

1d. Should Namibia decrease water use in certain sectors and allocate it to other sectors?

1e. What would be required to effectuate such re-allocation?
3.6 References


Falkenmark, M., and C. Folke, 2001(??), The ethics of socio-ecohydrological catchment management


4. Urban water demand

Public water companies provide water for different use categories:
- domestic use by households
- municipal use by government agencies for public functions, e.g. watering public lawns
- commercial use by all kind of public and private offices, agencies and institutes
- industrial use by factories.

For the last category either raw (limited treatment) or fully treated water can be supplied. The demand of this category usually is subject of separate studies. The following deals with the demand of the other three categories; domestic, municipal and commercial water demand. These demands depend, among other things, on:

a. number of people within the considered area
b. connection rate for different types of supply; e.g. stand pipe, piped supply
c. per capita consumption, which depends on such factors as level of development, type of supply and price of water
d. losses in infrastructure for transport, treatment and distribution

4.1 Estimation of urban water demand

The bottom line of water consumption can be defined as the 'lifeline' per capita water consumption. This lifeline water requirement is nowadays often set at 50 litres of clean and safe fresh water per capita per day (Table 4.1): Note that this figure excludes water required for food consumption and for other economic activities.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Minimum Level (l/c/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking water</td>
<td>5</td>
</tr>
<tr>
<td>Sanitation Services</td>
<td>20</td>
</tr>
<tr>
<td>Bathing</td>
<td>15</td>
</tr>
<tr>
<td>Food Preparation</td>
<td>10</td>
</tr>
<tr>
<td>Sum</td>
<td>50</td>
</tr>
</tbody>
</table>

Notes: (a) This is a true minimum to sustain life in moderate climatic conditions and average activity levels.
(b) Excluding water required to grow food. A rough estimate of the water required to grow the daily food needs of an individual is 2,700 l/c/d.

Source: Gleick 1996

Water demand is generally estimated applying standards for the various categories of users. Table 4.2 below gives the unit water demand standards as used in Harare:
Table 3.2  Standards for water demand by consumer category, Harare

<table>
<thead>
<tr>
<th>Consumption category</th>
<th>Unit</th>
<th>Annual average daily water demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High density</td>
<td>l/stands/d</td>
<td>900</td>
</tr>
<tr>
<td>Medium density</td>
<td>l/stands/d</td>
<td>1,800</td>
</tr>
<tr>
<td>Low density</td>
<td>l/stands/d</td>
<td>2,500</td>
</tr>
<tr>
<td>Flats</td>
<td>l/unit/d</td>
<td>1,000</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hotels</td>
<td>l/bed/d</td>
<td>800</td>
</tr>
<tr>
<td>Offices</td>
<td>l/employee/d</td>
<td>30</td>
</tr>
<tr>
<td>Shops</td>
<td>l/employee/d</td>
<td>30</td>
</tr>
<tr>
<td>Industrial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry industries</td>
<td>l/ha/d</td>
<td>20,000</td>
</tr>
<tr>
<td>Wet industries</td>
<td></td>
<td>To be calculated individually</td>
</tr>
<tr>
<td>Institutional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hospitals</td>
<td>l/bed/d</td>
<td>500</td>
</tr>
<tr>
<td>Clinics</td>
<td>l/100 m²/d</td>
<td>1,000</td>
</tr>
<tr>
<td>Day schools</td>
<td>l/pupil/d</td>
<td>30</td>
</tr>
<tr>
<td>Boarding schools</td>
<td>l/pupil/d</td>
<td>90</td>
</tr>
</tbody>
</table>

Source: Eng. E. Mudzuri, City of Harare, 1999

Connection rates refer to the percentage of the population which has access to a certain kind of supply, e.g. house connections (piped supply) or stand pipes. Rough ‘coverage’ percentages are inadequate. The usual ranges for per capita consumption in developing countries are:

-20-45 litres per day for stand pipe supply
-70-120 litres per day for piped private supply.

In developed countries total consumption rates can be as high as 1,000 litres per day in dry regions where lawn watering is not limited. Normal figures, however, for developed countries range between 200 and 500 litres per day. In developing countries, consumption of safe water is often below 50 litres per day, which could be considered as a minimum for public health purposes. In such situations connection rates and per capita consumption become social and political target values. Cost-benefit considerations are not relevant under such conditions and generally are replaced by cost-effectiveness approaches: how to reach target levels at minimum costs.

Measured consumption

It may be worthwhile to study in detail the measured consumption. It appears that the ownership of water-based appliances, such as washing machines and dishwashers but also swimming pools, greatly influences water use. Accurate projections of water demand therefore need to make good predictions of the growth in the use of these appliances by households over time.
Since the use of water-based appliances is related to the relative wealth of households, which again is related to neighbourhood, for accurate projections it may be necessary to distinguish water demand in the various neighbourhoods, and make separate projections. This is clearly shown by Dube (2002), who found that average water consumption of affluent households in Masvingo was three times higher than that in poor neighbourhoods (60 vs. 20 m³/month/connection). Moreover, climate has an obvious impact on water consumption. These influences are illustrated by Tables 4.3 and 4.4.

**Table 4.3 Average Water Consumption (l/c/d) of households**

<table>
<thead>
<tr>
<th>Component</th>
<th>California</th>
<th>UK</th>
<th>RSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing machine</td>
<td>32</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>Toilet</td>
<td>95</td>
<td>37</td>
<td>48</td>
</tr>
<tr>
<td>Bath/Shower</td>
<td>73</td>
<td>22</td>
<td>65</td>
</tr>
<tr>
<td>Kitchen</td>
<td>27</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>227</strong></td>
<td><strong>107</strong></td>
<td><strong>160</strong></td>
</tr>
</tbody>
</table>

Source: Davies & Day 1998: 325

**Table 4.4 Components of domestic water consumption in England and Australia**

<table>
<thead>
<tr>
<th>Component</th>
<th>Domestic Water Consumption (l/cap/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking, cooking</td>
<td>5.0</td>
</tr>
<tr>
<td>Washing, cleaning</td>
<td>48.3</td>
</tr>
<tr>
<td>Toilets</td>
<td>32.5</td>
</tr>
<tr>
<td>Laundry</td>
<td>13.4</td>
</tr>
<tr>
<td>External usage</td>
<td>5.1</td>
</tr>
<tr>
<td>Other usage</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>110.0</strong></td>
</tr>
</tbody>
</table>

Source: Hall et al., 1988; Metropolitan Water Authority, 1985

**Unaccounted-for water**

An essential component of water demand for public water supply may be the losses in transport, treatment and distribution systems. These losses are normally dubbed ‘unaccounted-for water’ and may reach levels of 60% in old and deteriorated systems. Normal percentages are 15 to 25%, including a 5% “consumption” in treatment plants. In addition to quantitative considerations, leaking systems may present substantial threats to public health, because of possibilities for infiltration of contaminated groundwater under low pressure conditions in the distribution network.

Unaccounted-for water, which may exceed one quarter of the water put into supply, can represent a substantial financial loss to any water undertaking. In Harare, unaccounted-for water is around 37% (see box). In England, following the publication in 1980 of the guidelines on leakage policy and control, the water authorities and water supply companies made an effort to introduce active leakage control policies (Table 4.5).
### Table 4.5  Reduction in net night flow in England

<table>
<thead>
<tr>
<th>Water Authority</th>
<th>Reductions in net night flow (l/property/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thames Water Authority (Hounslow)</td>
<td>Before 18.2  After 7.5</td>
</tr>
<tr>
<td>Mid-Kent Water Company (Ashford, Canterbury)</td>
<td>Before 11.8  After 6.0</td>
</tr>
</tbody>
</table>

(Source: Borrows and Bloomfield, 1984; Setford, 1985)

In order to cope with the 1992 drought, the City of Kwekwe in Zimbabwe (150,000 inhabitants) introduced a water loss management programme using electronic leak detection. This resulted in a reduction of water losses from 30% in 1992 to 14% in 1996. Together with other water demand management measures, water consumption in 1997 (1.3 Mm³/month) was still less than during the pre-drought period (1.5 Mm³/month). As a result, the Z$ 40 million upgrading of the city's treatment works, planned for 1995, has been deferred indefinitely, saving the city a substantial capital burden. (Goldblatt et al., 2000).

**Box 4.1: Council losing $180m to water leakages**

Harare City Council is losing $180 million [US$ 10 million] worth of treated water every year because of leakages which can be controlled through a detection and control system. The mayor, Clr. Solomon Tawengwa, said about 37 per cent of the city's treated water was lost to the ground because of leaks. ... A $77.6 million tender for leakage detection and control and infrastructure management was finally awarded to Biwater International on Thursday night. ...

It costs the council more than $30 million a month [US$ 1.7 million] to purify its water. The water account relies heavily on sales and any loss of water results in the council failing to recoup all its expenses.

Harare pumps 150 million litres of water a day and loses about 60 million cubic metres [sic]. ... The director of works, Mr. Christopher Zvobgo, said yesterday that it would not help much if the multi-million-dollar Kunzwi Dam project was to start while there were a lot of leaks.

Source: The Herald, 20 December 1997

**Projections of water demand**

An important element in the demand assessment is the **projection of demographic developments** (for the life period of the new infrastructure). Population developments have two components: autonomous growth and migration. Care should be taken that a proposed water resources management strategy may itself have a substantial impact on migration.

Autonomous growth models vary from a simple trend analysis - which in its simplest form extrapolates the monitored growth over the past few years - to more complicated population projection models, taking into account the build up of age groups, and the differentiated birth \((b)\) and death rates \((d)\) for the different age groups. Only with such more elaborate models can the effect of family planning programmes be assessed.
As a result of the exponential character of population growth, the outcome of population forecasts is highly sensitive to the assumed value of the fertility rate. Population projections should be made for the short term (2-5 years) and for the medium term (5-10 years). Projections for the long term (more than 10 years) are unreliable, though they may serve as an indicative estimate. Long term forecasts have seldom been close to correct. All over the world surprise changes have occurred that caused growth rates to seriously deviate from projections. Some of these unexpected changes are: the outbreak of wars, migration by refugees, political changes, economic recession or economic revival, migration to urban areas etc.

On the short and medium term, an inaccurate forecast would generally mean that the schedule of implementation of a group of phased projects must be speeded up or slowed down. However sometimes serious problems arise: a project may be a financial (or economic) failure if inadequate revenues (or benefits) are realized due to over-optimistic projections.

**Model of population growth based on the population balance** (Savenije 2000)

Population growth can be modelled through the equation of the population balance:

$$\frac{dP}{dt} = B - D + I - O$$  \hspace{1cm} (4.1)

where  
- \(dP/dt\) = change in population during time step t, e.g. year (capita)  
- \(B\) = number of birth per unit of time, e.g. per year (capita/year)  
- \(D\) = number of death per unit of time (capita/year)  
- \(I\) = immigration (capita/year)  
- \(O\) = emigration (capita/year)

It can be seen at once that Eq.(4.1) has a large similarity with the water balance, in which the population represents the storage, the births the precipitation, the deaths the evaporation, the immigration the inflow and the emigration the outflow.

The number of births can be expressed as the product of the birth rate \(b\) and the population:

$$B = b \frac{P}{L}$$  \hspace{1cm} (4.2)

where \(L\) is the life expectancy in years. The birth rate is the amount of children born per person during his/her lifetime. Hence, the birth rate equals one if each woman, on average, gives birth to two children. In publications often mention is made of the fertility rate \(f\), which is the amount of children born per woman. It is obvious that \(f=2b\).

Similarly, the number of deaths can be computed from the death rate \(d\):

$$D = d \frac{P}{L}$$  \hspace{1cm} (4.3)
In a steady state situation, \( d=1 \) and \( D=P/L \). However, if a population is growing, meaning that there are, in relative terms, far more young people than old people, then \( d \) can be less than unity. Similarly, if \( b<1 \) (as is the case in China) a time will come when there are relatively far more elderly people than young people, resulting in a death rate higher than unity. If we neglect, for the sake of the argument, the emigration and immigration, combination of Eq.’s (4.1), (4.2) and (4.3) yields:

\[
\frac{dP}{dt} = \frac{(b - d)}{L} \cdot P
\]  

(4.4)

If \( b \) and \( d \) are constants, then the solution of Eq.(4.4) is an exponential equation of the type:

\[
P(t) = P(0) \cdot e^{\frac{(b - d)}{L} \cdot t} = P(0) \cdot e^{r \cdot t}
\]

(4.5)

with \( P(0) \) = population at time = 0, and at time = t (capita) \( r = (b - d)/L \) \( e \) = exponential function \( (e=2.718) \)

If \((b-d)>0\), meaning that per capita more children are born than that people die, then the population increases exponentially. If \( b=d \), the population is constant. In China, where \( b=0.5 \), this point has not yet been reached. The adjustment to a lowering of the birth rate takes time, because the death rate is not equally distributed over the age groups. If \( b=1 \), the birth rate is equal to the replacement rate, which eventually will lead to a constant population but the time scale for reaching a death rate \( d \) equal to \( b=1 \) is the life expectancy \( L \).

**Other factors influencing water demand**

Apart from population growth, there are other factors influencing water demand, including (Singh, 1999, DFID, 2001):
- Rainfall/Droughts
- Economic development
- Rationing
- Water pricing

The influence of pricing on water demand will be discussed in the next section. Here and example is given for the City of Masvingo, Zimbabwe, for which a multiple linear regression (MLR) analysis was carried out of the influence of population, rainfall, economic development and rationing, on water demand.

Annual data for population and rainfall were available for Masvingo. For economic development, national data for GDP growth were used as a proxy. For rationing, a dummy factor was used with a memory of 5 years, which decreases from 1 to 0 in steps of 0.2 per year.

For the MLR, the following formula was used:

\[
Q = a + b \cdot N + c \cdot P + d \cdot G + e \cdot R
\]

(4.6)
Where

- $Q =$ annual treated water pumped (1,000 m$^3$/a)
- $N =$ population of Masvingo (1,000)
- $P =$ annual precipitation (mm/a)
- $G =$ GDP growth (%)
- $R =$ factor for rationing, with a memory of 5 years (decreasing from 1 to 0 in 6 years)

$a, b, c, d$ and $e$ are constants

The MLR analysis yielded the following values for the constants $a, b, c, d$ and $e$:

$$Q = 1,496 + 90.2 \times N - 1.5 \times P + 26.8 \times G - 837 \times R \quad (4.7)$$

$$r^2 = 96.5$$

Formula (4.7) implies that:

- The gross average "base" per capita water consumption is 90 m$^3$/a or 247 l/cd; population alone explains some 88% of total water supply.
- If rainfall is 100 mm above the average of 600 mm/a, water consumption decreases with 150,000 m$^3$/a; if rainfall is 100 mm below average, consumption increases with the same amount; including rainfall improves the correlation with 5%.
- GDP has relatively little effect on water consumption: a 1% increase in GDP leads to an increase in water consumption of 27,000 m$^3$/a; including this factor increases correlation with only 0.4%.
- Rationing has a significant impact on water consumption: in a drought consumption drops by 837,000 m$^3$/a; including this factor improved correlation with 3% to a total correlation of 96.5%.

The multiple linear regression analysis gave a good fit (Figure 4.1). Future water use can be projected based on past water use and various scenarios can be considered which take into account variations of the factors that influence water use.

![Figure 4.1: Actual and modelled water use, Masvingo, 1977-2001](image-url)
4.2 Pricing of urban water

At the Dublin and Rio conferences, as reported in Agenda 21, it has been recognized that water should be managed as an economic good, provided water for drinking purposes and other basic needs are made available at prices that are widely affordable locally. Providing water free of charge, or heavily subsidized, in the past has led to serious mis-allocations of water resources, inefficient use and overexploitation.

A good illustration of this problem is the “free water dilemma” (see Fig. 4.2). If water is for free, water industries do not receive sufficient payment for their services. Consequently, they are not able to maintain their systems adequately and, hence, to maintain the quality of their services. Consequently the system collapses, people have to drink unsafe water or pay excessive amounts of money to water vendors, while wealthy people receive piped water directly into their houses, for free. So the water-for-free policy results in rich people getting water for free and poor people buying water at excessive rates or drinking unsafe water.

![Free Water Dilemma](image)

**Figure 4.2 The "Free Water" Dilemma** (Savenije, 2000)

Water pricing has a number of important consequences, which makes it a key instrument for the implementation of demand management:

- increased price reduces demand;
- increased price increases supply (firstly, because marginal projects may become affordable; and secondly, because it becomes attractive to reduce losses);
- increased prices facilitate reallocation among sectors;
- increased prices improve managerial efficiency.

Water pricing has now been taken up by a number of ESAs, particularly The World Bank (1993), as the most important tool for demand management. Indeed, water pricing is an important element of demand management, but it is not the only issue that requires attention. Other facets of demand management, dealing e.g. with various aspects of improved efficiency, merit attention as well. See box 4.2 for the benefits of retrofitting.


**Box 4.2: The benefits of retrofitting** (Martindale & Gleick, 2001)

In the early 1990s New York City faced an imminent water shortage. With an influx of new residents and an increase in the number of drought years, the city needed to find an extra 90 million gallons of water a day (0.34 Mm$^3$/day) -- about 7 percent of the city's total water use. Instead of spending nearly US$1 billion for a new pumping station along the Hudson River, city officials opted for a cheaper alternative: reduce the demand on the current water supply, which was piped in from the Catskill Mountains.

Officials knew that persuading New Yorkers to go green and conserve water would require some enticement--free toilets. The city's Department of Environmental Protection (DEP) stepped in with a three-year toilet rebate program, which began in 1994. With a budget of US$295 million for up to 1.5 million rebates, the ambitious scheme set out to replace one third of the city's inefficient toilets -- those using more than five gallons of water per flush -- with water-saving models that do the same job with only 1.6 gallons per flush. With the rebate program, the DEP hoped to meet the largest part of its water-savings goal.

New Yorkers embraced the plan. Some 20,000 applications arrived within three days of its start. By the time the program ended in 1997, low-flow toilets had replaced 1.33 million inefficient ones in 110,000 buildings. The result: a 29 percent reduction in water use per building per year. The DEP estimates that low-flow toilets save 70 million to 90 million gallons a day citywide (0.27-0.34 Mm$^3$/day).

In addition to this, other demand management measures were implemented. Whereas in former times many users paid for water based on the size of their property, by 1998 all connections were metered.

Homeowners who want to keep their water bills down can request a free water-efficiency survey from the company that oversees the city's audit program. Inspectors check for leaky plumbing, offer advice on retrofitting with water-efficient fixtures etc. The company has made several hundred thousand of these inspections, saving an estimated 11 million gallons of water a day (0.04 Mm$^3$/day) in eliminated leaks and increased efficiency.

In efforts to save even more water, New York City has installed magnetic locking caps on fire hydrants to keep people from turning them on in the summer. The city is also keeping an eye underground by using computerized sonar equipment to scan for leaks along all 10,000 km of its water mains.

Although the city's population continues to grow, per person water use in New York dropped from 195 gallons a day (738 l/day) to 169 gallons/day (640 l/day) between 1991 and 1999.

(note: an American gallon is 3.785 litres)

The water price is composed of many different elements that reflect production (financial) costs, economic costs, the economic value of the commodity, and the client’s willingness to pay, which is the economic value for the water user (see Fig. 4.3). The economic value to the user is generally not the same as the economic value to society. The former is primarily financial, whereas the latter involves the general interests of society. Water pricing should have two purposes: the first purpose is to recover costs, the second is to enhance water use efficiency. In cost recovery, a distinction should be made between internal financial costs and external (or social) costs. From a financial point of view, the water should be priced to cover the operational costs (see Fig. 4.3), made to supply the water related goods and services, and to cover the depreciation of the infrastructure (capital costs). According to most economists the capital costs should be determined on the basis of
the marginal costs. Hence the financial costs are the sum of the capital and the operational costs.

General Principles for Cost of Water

General Principles for Value-in-Use

Figure 4.3 General Principles for Costs and Values of Water (Rogers et al., 1997)

The economic costs include, in addition to the financial costs, also external costs (economic externalities), such as environmental damage, pollution, effect on downstream users and societal costs (health hazards, resettlement, etc.). Taking these costs into account in the financial costs is what is called internalising externalities. The money received by internalising this cost should be paid to the actors that have incurred the damage.

Until this point the price reflects the total costs incurred by society in the production of the commodity. In addition, the economic price should reflect the scarcity of the resource, which is generally expressed in the opportunity cost (the cost of not being able to use the resource for another social or economic activity). Paying the opportunity costs is what is also called: paying the scarcity rent. With this money you pay compensation to the actors that could make benefit of the water. This money is taken from the price levied to the water user.

In the economic value a distinction can be made between the economic value to an individual user, which is reflected in the willingness to pay, and the economic value attributed by society.
The willingness to pay of water users is a function of the quantity that users consume and their ability to pay. It can be represented in price elasticity curves (see below). Only if the economic value attributed by society to the water is larger than (or equal to) the economic costs, is water resources development feasible. In that case, there are two possibilities: the willingness to pay is larger than the economic cost, in which case the government could apply a surcharge or tax to enhance the efficiency of water use (i.e. for demand management); or the willingness (or ability) to pay is less than the economic costs, in which case the government can subsidize water consumption to the level of the economic cost (which is also a form of demand management).

The economic value and the willingness to pay are not easily determined. Some users are willing to pay a higher price than others. Since these are often financial rather than economic (societal) considerations, willingness to pay is not always the right argument to establish the economic price (to prevent that water always goes to the highest bidder). In addition, willingness to pay is dynamic, depending on many parameters which include affordability, scarcity of the resource, and appreciation for the resource. Since all these parameters are time dependent and can be influenced by external and internal factors, the willingness to pay is a volatile parameter.

Although Fig. 4.3 is useful as an illustration of how the price of water should be established to reflect societal costs, recently, water economists at the World Bank have come to the conclusion that the water price should not be based on opportunity costs or long-term marginal costs, but that it should be a reasonable price between zero and the cost of desalination (about 2 US$/m³) which should at least reflect the financial cost, and which should send out the message to users that we are dealing with a precious and finite resource.

Water pricing has a number of important consequences, which makes it a key instrument for the implementation of demand management:

• increased price reduces demand
• increased price increases supply (firstly, because marginal projects may become affordable; and secondly, because it becomes attractive to reduce losses)
• increased prices facilitate reallocation among sectors
• increased prices improve managerial efficiency.

The (extreme) example of Selebi-Phikwe town in Botswana shows the influence of water pricing on water consumption (see box 4.3). In cases where tariff differentials are small, the effect of water pricing is however much less pronounced or even absent.
Box 4.3: Residential water consumption in Selebi-Phikwe, Botswana (Arntzen et al., 2000)

Selebi-Phikwe has the highest per capita water consumption of the urban areas in Botswana. In 1995/96, its per capita potable water consumption was 273 l/c/d. The figures for Gaborone and Francistown were much lower at 236 and 146 l/c/d respectively. The high water consumption in Selebi-Phikwe has been attributed to, among others, subsidisation of water by the local BCL mine for its employees. BCL houses without water metres were fully subsidised. “Standard staff” did not pay for the first 150 m³ of water consumed per month, whereas “senior and executive staff” did not pay for the first 200 m³ water per month.

To determine the impact of the water subsidy on water consumption, 40 households were interviewed in the high-income area of Selebi-Phikwe, where employees of the BCL copper nickel mine, civil service, and other sections of the private sector stayed. A multiple regression analysis was used to determine the relations between water consumption and the independent variables of access to water subsidy, incomes of the head of households, type of households, and household size. A significant relationship was found between potable water consumption and independent variables of income and the dummy for water subsidy. The regression equation of this relation was as follows:

\[ W_e = 0.016 Y + 41.85 S - 25.94 \]
\[ R^2 = 0.54 \]

Where \( W_e \) is monthly potable water consumption in m³/month,
\( Y \) is income of the head of households in Pula/month, and
\( S \) is the dummy variable for water subsidy (0: no subsidy, 1: subsidy)

The income of the head of households and access to water subsidy are important determinants for water consumption, such that water consumption increases as income increases and access to water subsidy is attained. A household with an income of P3,000 per month and not receiving any water subsidy consumes 22 m³ per month. A household with the same income with subsidies consumes 63 m³ per month or almost three times as much.

The subsidies appear to lead to a culture of wasteful use of water and insensitivity to report any water leakage. The clearest example of waste was the common practice of cooling roofs with water in summer.

Relation between price and demand

With ordinary economic goods there is a relation between price and demand following a demand curve. The dimensionless slope of this demand curve is called the price elasticity of demand. It is defined as the percentage of increase in demand resulting from a percentage of increase in price. This elasticity is a negative number since demand is expected to decrease as price increases, and normally ranges between -1 and 0. The general equation for the demand-price relation (the demand curve) is:

\[ Q = cP^E \]  \( (4.8) \)

where \( Q \) is the quantity of demand for the good
\( P \) is the price of the good
\( c \) is a constant
\( E \) is the elasticity of demand.
Fig. 4.4 gives the typical form of a demand curve. The demand curve is constructed on the assumption of constant prices for other goods, constant incomes, and constant preferences. When any of these change, the demand for system outputs may shift.

![Demand Curve Diagram](image)

**Figure 4.4 Relation between price \( P \) and water consumption \( Q \) for domestic water**

However, equation 4.7 is difficult to apply for the water sector as a whole, but for certain sub-sectors (urban water use, industrial water use, irrigation) it may serve the purpose of analysing the effects of tariff changes. The problem with this equation is that \( E \) is not a constant. It depends on the price, it depends on the water use and it varies over time. So it is an equation with limited applicability.

![Elasticity Diagram](image)

**Figure 4.5 Schematic figure of different uses of domestic water and their elasticities of demand**

Primary uses of water have a special characteristic in that the elasticity becomes rigid (inelastic; \( E \) close to zero) when we approach the more essential needs of the user (Figure 4.5). People need water, whatever the price. And for the most essential use of water
(drinking) few alternative sources of water are available. For sectors such as industry and agriculture demand for water is generally more elastic ($E$ closer to -1) which is more in agreement with the general economic theory. This is because alternatives for water use exist in these sectors (e.g. introducing water saving production technologies, shifting to less water demanding products/crops). For basic needs, however, demand is relatively inelastic or rigid. In urban water supply, elasticities are therefore generally close to 0, unless additional (non-financial) measures are taken. Poor consumers often only can afford to use small amounts of water (the basics), and any increase in tariffs will have little effect because they cannot do with less water. For large consumers (the ones that irrigate their gardens, own cars that need to be washed etc.) the ability to pay is such that the need to save money on water is limited. In the latter case, awareness campaigns, regulation, policing, leak detection, renewal of appliances, etc. are often more effective than the price mechanism per se.

Figure 4.6 illustrates the different patterns of water use during the year for high-density (poor) and low-density (rich) consumers for a town in Zimbabwe. The figure shows that for high-density consumers seasonal fluctuation of water demand is low, indicating that most uses are confined to essential purposes. Water consumption of low-density consumers is much higher during the dry season than during the rainy season, probably related to non-vital uses of water, such as watering gardens and filling pools when it is dry. One could hypothesise that part of the additional water use during the dry season for these consumers is relatively elastic, and could be influenced by tariffs, whereas this may not be the case for the other types of water uses.

![Figure 4.6 Water use in high and low density areas of Ruwa town, Zimbabwe; 1996 - 2000](source: Ms S. Chibaya, MEPP, UZ, 2001)

One can argue that with respect to drinking water the demand-price relation is under normal conditions going to be more elastic than -1. If someone has $100 to spend on water ($QP=100$), then for $QP$ to remain constant, a price increase of 10% should be compensated by a consumption reduction of 10% ($E=-1$). This is assuming that there is no cheaper alternative for water (e.g. buying it from water vendors). However, there is no need to save more water than 10%, since that would imply spending less than $100 on water. Hence price-demand relations for drinking water are always inelastic (-1<$E$<0).
Only in extreme situations, when the water price increases such that people cannot afford it any longer, will demand respond elastically, and people will either look for alternative sources of water (for certain uses), such as digging a well, using untreated water, or move out of the area. Only then has the demand-price relation become elastic \((E<-1)\).

Price-demand relations that are based on a fixed amount of money that people can spend on water are all of the type:

\[
Q = \frac{c}{P} \quad \text{or:} \quad Q \cdot P = c \tag{4.9}
\]

where \(c = \text{amount of money people are will, or able, to spend on water [e.g. Z$/year]}\)

These functions have a constant elasticity \(E = -1\). More generally, the price elasticity \(E\) of demand may be defined as:

\[
E = \frac{dQ/Q}{dP/P} = \frac{PdQ}{QdP} \tag{4.10}
\]

with

- \(E\) = elasticity [-]
- \(Q\) = water use [in volume per time unit, e.g. \(\text{m}^3/\text{d}\)]
- \(dQ\) = change in water use [volume per time unit, e.g. \(\text{m}^3/\text{d}\)]
- \(P\) = water price [e.g. \(Z$/\text{m}^3\)]
- \(dP\) = price change [e.g. \(Z$/\text{m}^3\)]

Economists classify elasticity either as elastic or inelastic as follows:

- If \(E<-1\), the response to a price increase is said to be elastic or reactive.
- If \(-1<E<0\), the response to a price increase is said to be inelastic or rigid.

If, for example, the price is increased by 100\% \((P_1=2*P_0)\), and this results in a 20\% decrease in water use \((Q_1=0.8Q_0)\), then

\[
dP/P = (P_1-P_0)/P_0 = (2P_0-P_0)/P_0 = 1
\]

\[
dQ/Q = (Q_1-Q_0)/Q_0 = (0.8Q_0-Q_0)/Q_0 = -0.20
\]

thus \(E = -0.20/1 = -0.20\).

The rigidity is normally higher for necessities for which there is no substitute (such as water for domestic use) than for luxury goods, or goods that have a cheaper alternative (e.g. butter and margarine). Since water is no luxury, water demands reduce relatively little with an increase in price.

Residential and industrial demand for water (except for cooling water) are inelastic while agricultural demands are more elastic. This has to do with the availability of alternative options for water use. For domestic use there is no alternative for water, and people are willing to pay a lot more for the same quantity (rigid). People must have minimum amounts of water in some form to survive, and households often pay extraordinary high prices to water vendors for small amounts of water.

In industry and agriculture the elasticity, although still low, is somewhat higher. In arid
areas there is no substitute for irrigation or industrial water leading to low elasticity, but farmers and industrialists can invest in water saving technology and farmers can change cropping patterns (leading to higher elasticity).

Concluding:
- the elasticity of water consumption is generally low.
- the price elasticity is greater when the price is higher.
- in the household sector, the price elasticity varies between -0.15 and -0.70.
- with respect to drinking water the demand-price relation will never be elastic (E < -1)
- in the industrial sector, the majority of estimates are in the range of -0.45 to -1.37.

**Table 4.6: Price elasticity ranges for urban public water supply (OECD, 1987)**

<table>
<thead>
<tr>
<th>Country</th>
<th>Price elasticity (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>-0.04 - -0.75</td>
</tr>
<tr>
<td>Canada</td>
<td>-0.25 - -1.07</td>
</tr>
<tr>
<td>England and Wales</td>
<td>-0.3</td>
</tr>
<tr>
<td>Finland</td>
<td>-0.11</td>
</tr>
<tr>
<td>Sweden</td>
<td>-0.15</td>
</tr>
<tr>
<td>United States</td>
<td>-0.06 - -0.61</td>
</tr>
</tbody>
</table>

When the demand for water is relatively inelastic, as is the case for urban water, the water provider may be tempted to raise tariffs, since this will always result in higher revenues, while water consumption drops only slightly (see box below). The provider may not be interested in curbing water demand through other means (e.g. through awareness campaigns or through subsidising the retrofitting of houses with water saving devices). It is therefore that water utilities should preferably remain publicly owned. If privatised they should operate within a stringent and effective regulatory environment.

**Increase in revenue due to price increase**

Since the elasticity of water demand is generally between -1 and 0 (-1<E<0), a price increase of water always results in an increase of income by the water supplier. This can be easily demonstrated by combining eq. 3.6 with the equation for the relative change in revenue ($\Delta QP$):

$$\frac{dQ}{QP} = \frac{QdP}{QP} + \frac{PdQ}{QP} = (1 + E)\frac{dP}{P}$$

(4.11)

Since (1-E)>0, an increase of the price results in an increase of revenue. If E= -1, the revenue does not increase, which is in agreement with eq. 4.11.
Increasing block tariff system

It should further be noted that any pricing policy aimed at influencing demand should consider the basic right of people to access of safe drinking water. Thus demand management through economic means should consider financial (full cost recovery) and equity criteria. The increasing block tariff pricing structure implies a cross-subsidy from rich to poor users. It is a good example of a satisfactory compromise between both criteria and is becoming increasingly adopted, especially in water scarce regions.

Below examples are given of block tariff systems of Windhoek (Namibia), Gaborone (Botswana), and Hermanus (South Africa) (Figure 3.8). The block tariff structures of Bulawayo and Harare (Zimbabwe) incorporate a fixed monthly charge (Figure 3.9).

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>consumption</strong></td>
<td><strong>tariff</strong></td>
</tr>
<tr>
<td>(m³/month/connection)</td>
<td>(US$/m³)</td>
</tr>
<tr>
<td>0-8</td>
<td>0.44</td>
</tr>
<tr>
<td>8-15</td>
<td>0.62</td>
</tr>
<tr>
<td>15-36</td>
<td>0.76</td>
</tr>
<tr>
<td>36-45</td>
<td>1.00</td>
</tr>
<tr>
<td>45+</td>
<td>1.30</td>
</tr>
<tr>
<td>25-30</td>
<td>0.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Gaborone</strong> (Macy 1999: 22-23)</th>
<th><strong>Hermanus</strong> (Macy 1999: xxi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>consumption</strong></td>
<td><strong>tariff</strong></td>
</tr>
<tr>
<td>(m³/month/connection)</td>
<td>(US$/m³)</td>
</tr>
<tr>
<td>0-10</td>
<td>0.30</td>
</tr>
<tr>
<td>10-15</td>
<td>0.88</td>
</tr>
<tr>
<td>15-25</td>
<td>1.12</td>
</tr>
<tr>
<td>25+</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Figure 4.7 Block tariffs of Windhoek (Namibia), Gaborone (Botswana), and Hermanus (South Africa) (after Macy 1999)
### Block Tariffs in Harare (Zimbabwe) with Fixed Charge of US$ 0.70 per Month

<table>
<thead>
<tr>
<th>Consumption (m$^3$/month/connection)</th>
<th>Tariff (US$/m$^3$)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-14</td>
<td>0.11</td>
<td>US$/m$^3$</td>
</tr>
<tr>
<td>14-40</td>
<td>0.20</td>
<td>US$/m$^3$</td>
</tr>
<tr>
<td>40-70</td>
<td>0.28</td>
<td>US$/m$^3$</td>
</tr>
<tr>
<td>70-300</td>
<td>0.42</td>
<td>US$/m$^3$</td>
</tr>
<tr>
<td>300+</td>
<td>0.50</td>
<td>US$/m$^3$</td>
</tr>
</tbody>
</table>

### Figure 4.8 Block Tariffs of Harare (Zimbabwe) and Average Water Price

#### The Increasing Block Tariff Systems: Defining the Functions for Each Block

In order to find a satisfying compromise between full cost recovery and equity, each block should have a clearly defined purpose, from which block size and tariff can be derived. Below is an example of how the functions of four blocks could be defined:

1. the poorest households have access to a life line amount of water and do not spend more than a certain percentage of their income on water;

2. the ‘ideal’ per capita water consumption level is defined, which will ensure “well-being”; this “well-being” amount is e.g. twice the lifeline amount; all water consumed over and above the lifeline amount, but less than the well-being amount, is charged at the Full Cost of Water Supply (FCWS expressed in e.g. US$/m^3$); meaning that the average price of water is still less than FCWS, so these households still receive subsidy;

3. those households that use water over and above the well-being amount, but less than a certain upper limit (e.g. 4 times the lifeline amount) will pay the full cost of water over their entire use; this means that the tariff of the third block should off-set the implicit subsidy that these users receive in the first block;

4. water use over and above the amount specified in the third block will be charged at a
rate that will off-set the subsidy received by households falling within blocks 1 and 2.

The above functions of the tariff blocks would ensure full cost recovery and equity.

**Reduction of water demand in Windhoek (Macy, 1999)**

In Windhoek, water demand was 242 litre per day per person in 1995, with unaccounted for water being only 11%. Windhoek adopted an integrated policy on water demand management in 1994, which is financed by a 0.5 percent levy. Efforts that started in the 1950s have primarily focused on re-use of water. Nowadays, Windhoek can re-use all its waste water for the watering of parks, sport fields and cemeteries through a two-pipe system and the reclamation of waste water to a potable standard. Of all domestic water use, 13% is treated for reuse. About 60% of all water used in up-market households is for gardens. Its infiltration into lawns and gardens makes it unavailable for reuse. Water for gardening still represents a large sector for water savings.

An important part of the water demand management programme involves appropriate tariffs. When tariffs are sufficiently high, they tend to keep exterior irrigation demands reasonable. Water tariffs were recently raised by 30% and any water demand exceeding 45 m³/month per household or enterprise was billed at US$ 1.30 per m³.

Other water demand measures include:

- Public awareness and education
- No irrigation of gardens between 10:00-16:00 hrs (mandatory)
- Use of swimming pool covers (mandatory)
- Use of low-flush toilets (mandatory for all new buildings since 1997)
- Metering of all connections
- Reuse of purified effluent for irrigation and reclamation to potable standard
- Water conservation guidelines for wet industries

The combined effect of all these measures is that per capita water consumption decreases: in 1996 per capita water use decreased from 242 litre per day per person to 196 litres per day. Whereas the residential population grew 5%, total residential water consumption decreased from 10 to 7.8 10⁶ m³ yr⁻¹.

The benefits from water conservation are mostly obvious:

- up to 30% of long-term savings can be achieved; short-term savings may be double
- less waste water has to be treated, and less energy is used
- the environment will benefit from reduced alteration of flow patterns and from less or reduced dams and other infrastructure
- financial savings from reduced capital as well as operating costs; Figure 4.9 illustrates savings due to delay in construction of “the next dam”.

WaterNet / CCR / ISRI / Catalic / UNESCO-IHE Delft / UZ for UNESCO
4.3 Exercises

4.1 Population growth

Assuming that the rate of growth of a certain city (as a proportion of its current population) is 5 per cent per annum;

4.1a How many years will it take for the city to grow by 30 per cent from its present level?
4.1b Compare this growth with that during the same period of time of a city that grows by a constant 5 per cent of its base population per year

4.2 Population growth

Over the last 5 years, the population level of a certain area has gone from 120,000 to 150,000, and seems to follow an exponential pattern.

4.2a If the same pattern of growth continues, what will be the population after another 5 years?
4.2b How long will it take under the same conditions to reach a population level of 200,000?
4.3 Population growth

Assume the city’s population to have doubled over the last 20 years.

4.3a What was the average annual growth rate of that city?

Assume further that in the next 5 years city population increases with the same growth rate, while average per capita water consumption increases 2% annually.

4.3b What will be the city’s gross water use 5 years from now?

4.4 Given are the following block tariff systems of Windhoek and Harare urban water supplies.

2.4a Calculate the total water bill (US$/month) and the average cost of water (in US$/m³) for households in both cities that consume 1, 10, 50 and 100 m³/month.

<table>
<thead>
<tr>
<th>Windhoek 1997</th>
<th>Harare 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption</td>
<td>Consumption</td>
</tr>
<tr>
<td>(m³/month/connection)</td>
<td>(m³/month/connection)</td>
</tr>
<tr>
<td>tariff (US$/m³)</td>
<td>Tariff unit</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0-8</td>
<td>0.44</td>
</tr>
<tr>
<td>8-15</td>
<td>0.62</td>
</tr>
<tr>
<td>15-36</td>
<td>0.76</td>
</tr>
<tr>
<td>36-45</td>
<td>1.00</td>
</tr>
<tr>
<td>45+</td>
<td>1.30</td>
</tr>
<tr>
<td>0-14</td>
<td>0.68</td>
</tr>
<tr>
<td>14-40</td>
<td>0.20</td>
</tr>
<tr>
<td>40-70</td>
<td>0.28</td>
</tr>
<tr>
<td>70-300</td>
<td>0.42</td>
</tr>
<tr>
<td>300+</td>
<td>0.50</td>
</tr>
</tbody>
</table>

4.5 Price elasticity of domestic water

Azania’s capital city has 50,000 people connected with piped water supplied to their houses. (The balance of the population is served by un-metered communal standpipes.) Water consumption for the connected households is metered. The connected households pay for the water consumed on a volumetric basis. City council increased water rates; see table, with corresponding measured water consumption levels: (Please note: Azania does not experience any inflation.)

<table>
<thead>
<tr>
<th>year</th>
<th>water rate (A$/m³) as at 1 January</th>
<th>consumption (l/capita/d) at 1 July</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>1990</td>
<td>1.50</td>
<td>97</td>
</tr>
<tr>
<td>1992</td>
<td>2.00</td>
<td>90</td>
</tr>
<tr>
<td>1994</td>
<td>2.50</td>
<td>80</td>
</tr>
<tr>
<td>1996</td>
<td>3.00</td>
<td>67</td>
</tr>
</tbody>
</table>

4.5a What is the price elasticity of domestic water use in Azania? How much did an average person spend on water through these years?

4.5b Explain the different elasticities found.

4.5c On 1 January 1998, city council further increased the rate to A$4.00/m³; consumption was measured in July 1998 to be 65 l/c/d. What do you observe?
4.6 Population growth and demand management

A city had the following population in 1990 and 1995:

<table>
<thead>
<tr>
<th>year</th>
<th>city population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>10,000</td>
</tr>
<tr>
<td>1995</td>
<td>12,000</td>
</tr>
</tbody>
</table>

It has been established that the population grew exponentially during this period.

4.6a What is the average annual growth rate of the population of this city during the period under consideration?

4.6b Make a projection of the city population in the year 2000.

The city has a source of water supply of $600 \times 10^3$ m$^3$/annum. Total net water use in the city was measured in 1990 and in 1995, and, expressed in per capita terms, was 100 l/cap/day for both years. Unaccounted-for-water was estimated to be 20% of total water use in both years. The water price remained constant between 1990 and 1995.

4.6c What is the projected water use of the city in the year 2000?

4.6d Given the answer in c), mention four water resource strategies which the city could consider?

A consultant established the price elasticity of water in the city to be

$$E = \frac{dQ}{Q}/\frac{dP}{P} = -0.50.$$

4.6e Consider the situation that the only feasible water resources strategy for the city is water pricing. What should the city do?

4.6f What will be the income into the city’s water account from water users in the year 2000, expressed in terms of the 1995 income?
4.4 References


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Martindale, D., and P. H. Gleick, 2001, How We Can Do It. Scientific American February

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5. Agricultural water demand

Rainfed agriculture remains the bulk producer of our food and fibre. Since there is little scope of policy-makers influencing rainfall, at this level there is little to plan and forecast. We can safely leave this task to our rainfed farmers. In this section we rather concentrate on irrigation water demand. One remark however: there is still a lot of scope to improve the productivity of rainfed farming, and the water utilisation efficiency, for instance through:

- alternative tillage techniques best suited for the local climatic and soil conditions, which conserve soil and water;
- appropriate fertilization; as water is not the only constraint in crop production, improved fertilization will result in higher production per mm of rain water;
- the best possible choice of crops and crop varieties given local conditions; this includes the option of e.g. intercropping.

Such measures may translate into higher production, offsetting the need to create new irrigation schemes, and thus freeing water and monetary resources.

Irrigation is in many river system the main water user. Often water use for irrigation accounts for at least 80% of total water use in a water resources system. For the proper planning and management of such a system it is therefore important to have adequate tools to reliably estimate the demand for irrigation water, the possible yield reductions due to water shortages, and the economic benefits of irrigation water.

The present subject belongs to the working area of specialists such as agriculturalists and irrigation engineers. However, it is important that water resources managers have a basic understanding of the subject matter, such that they can weigh the water demand from the agricultural sector vis-a-vis the demands for water from other sectors.

5.1 Yield response to water

Plant growth occurs through the process of photosynthesis (also known as CO₂ assimilation). Photosynthesis is the manufacture, in green plant leaves, of organic materials (carbohydrates, (CH₂O)n), through reduction of carbon dioxide (CO₂) from the air by means of solar energy (sunlight = short-wave radiation) in the presence of H₂O:

\[ \text{CO}_2 + \text{H}_2\text{O} + \text{solar energy} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \]

Photosynthesis itself uses a negligible amount of water. However, through transpiration of water through the stomata of plant leaves, nutrients flow from the plant roots through the stem to the leaves. Transpiration of water, thus, should not be considered a ‘water loss’; it is essential to plant production.

Crops utilise a lot of water. The water utilization efficiency for harvested produce (Ey) range, for grain crops such as wheat, sorghum, maize and rice, between 0.6 and 1.6 kg harvested grain per m³ of water used. For tuber and root crops, such as potatoes, the water utilization efficiency is around 4-7 kg/m³. For fresh vegetables and fruits, such as fresh
beans, tomatoes, water melon, this efficiency ranges from 1.5-12 kg/m$^3$ (Table 5.1).

In a situation where nutrients are not in short supply, crop yield ($Y_c$) is a function of incoming shortwave radiation ($R_s$) and maximum evapotranspiration ($ET_{m}$), and inversely related to the moisture in the air (expressed as the difference between the saturation vapour pressure $e_a$ and actual vapour pressure $e_d$: $e_a-e_d$):

$$Y = f(R_s, ET_{m}, 1/(e_a-e_d))$$

In this relationship, evapotranspiration is of greatest interest since this is the term which can be influenced by irrigation: more water available to the crop translates to more evapotranspiration and to higher yields, provided nutrients are not in short supply.

Relations between crop yield and evapotranspiration may be established from field experiments. The relationship found will always be site specific. Field experiments with maize in California and Israel found a linear relation between dry matter production (a specific measure of yield) and the evapotranspiration (Figure 5.1).

![Figure 5.1 Relation between dry matter yield ($Y$) and evapotranspiration ($ET$) for maize grown in California (open symbols) and Israel (black symbols) (Source: Feddes, 1984, cited in De Laat 1996)](image)

A more generalized relationship has been established: the relative reduction of crop yield is proportional to the relative reduction of evapotranspiration by a yield response factor $K_y$. This will be further elaborated in section 5.3.
### Table 5.1 Good yields ($Y_m$) and water utilization efficiency ($E_y$) of selected crops (tropics and subtropics) (source: FAO, 1977: 6-7, table 2 and 88, table 39)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield ($Y_m$)</th>
<th>Water utilization efficiency for harvested yield ($E_y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ton/ha</td>
<td>kg/m³ (%) moisture</td>
</tr>
<tr>
<td>Banana</td>
<td>fruit</td>
<td>30-60, 2.5-6, (70)</td>
</tr>
<tr>
<td>Bean:</td>
<td>fresh (pod)</td>
<td>6-8, 1.5-2.0, (80-90)</td>
</tr>
<tr>
<td></td>
<td>dry (grain)</td>
<td>1.5-2.5, 0.3-0.6, (10)</td>
</tr>
<tr>
<td>Cabbage</td>
<td>head</td>
<td>40-60, 12-20, (90-95)</td>
</tr>
<tr>
<td>Citrus</td>
<td>fruit</td>
<td>20-60, 2-5, (70-85)</td>
</tr>
<tr>
<td>Cotton</td>
<td>seed cotton</td>
<td>3-4.5, 0.4-0.6, (10)</td>
</tr>
<tr>
<td>Groundnut</td>
<td>nut</td>
<td>3-4.5, 0.6-0.8, (15)</td>
</tr>
<tr>
<td>Maize</td>
<td>grain</td>
<td>6-10, 0.8-1.6, (10-13)</td>
</tr>
<tr>
<td>Onion</td>
<td>bulb</td>
<td>35-45, 8-10, (85-90)</td>
</tr>
<tr>
<td>Pea</td>
<td>fresh (pod)</td>
<td>2-3, 0.5-0.7, (70-80)</td>
</tr>
<tr>
<td></td>
<td>dry (grain)</td>
<td>0.6-0.8, 0.15-0.2, (12)</td>
</tr>
<tr>
<td>Pineapple</td>
<td>fruit</td>
<td>65-90, 5-12, (85)</td>
</tr>
<tr>
<td>Potato</td>
<td>tuber</td>
<td>15-35, 4-7, (70-75)</td>
</tr>
<tr>
<td>Rice</td>
<td>paddy</td>
<td>5-8, 0.7-1.1, (15-20)</td>
</tr>
<tr>
<td>Sorghum</td>
<td>grain</td>
<td>3-5, 0.6-1.0, (12-15)</td>
</tr>
<tr>
<td>Soybean</td>
<td>grain</td>
<td>2.5-3.5, 0.4-0.7, (6-10)</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>cane</td>
<td>100-150, 5-8, (80)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6-1.0, (0) (sugar)</td>
</tr>
<tr>
<td>Sunflower</td>
<td>seed</td>
<td>2.5-3.5, 0.3-0.5, (6-10)</td>
</tr>
<tr>
<td>Tobacco</td>
<td>leaf</td>
<td>2-2.5, 0.4-0.6, (5-10)</td>
</tr>
<tr>
<td>Tomato</td>
<td>fruit</td>
<td>45-75, 10-12, (80-90)</td>
</tr>
<tr>
<td>Water melon</td>
<td>fruit</td>
<td>25-35, 5-8, (90)</td>
</tr>
<tr>
<td>Wheat</td>
<td>grain</td>
<td>4-6, 0.8-1.0, (12-15)</td>
</tr>
</tbody>
</table>

#### 5.2 Crop water requirements

**The water balance**

A water balance for an irrigated crop may read (Figure 5.2):

\[ P + I = ET - (C-R) + \frac{\Delta S}{\Delta t} \]  

where  
- $P$: precipitation (mm)  
- $I$: irrigation (mm)  
- $ET$: evapotranspiration (mm)  
- $C$: capillary rise (mm)  
- $R$: deep percolation, which may include the Leaching Requirement $LR$ (mm)  
- $\Delta S/\Delta t$: change of soil moisture over the considered period (mm)
Often, capillary rise and deep percolation are assumed small, resulting in the following simple equation:

\[ P + I = ET + \Delta S/\Delta t \]  

(5.2)

In the following sections the terms \( ET \) (evapotranspiration), \( P \) (precipitation) and \( I \) (irrigation) will be briefly elaborated.

**Figure 5.2 Simplified water balance for an irrigated crop**

**Evapotranspiration \( ET \)**

The amount of water consumed by a crop equals the amount the crop transpires through the leaves and the amount of water the soil evaporates. Transpiration and evaporation are normally lumped together, as there is little practical use (and very difficult) in attempting to keep both terms separate. The combined water use of both crop and soil is known as evapotranspiration (\( ET \)). Evapotranspiration is a function of, among others, crop characteristics, the growth stage of the crop, climatological conditions (length of day, temperature, wind, sunshine, cloudiness), and the available moisture in the soil.

The maximum crop evapotranspiration (\( ET_m \)) occurs when water supply is not limited (and provided all other conditions for crop growth are optimal, such as available nutrients, no diseases etc.). \( ET_m \) is the amount of water that the plant requires for growth; it is the starting point of all calculations for the determination of agricultural water demands. \( ET_m \) can be expressed in terms of a so-called reference evapotranspiration (\( ET_0 \)).

\[ ET_m = K_c \times ET_0 \text{ [mm/d]} \]  

(5.3)

where \( K_c \): crop coefficient (crop dependent on crop and crop stage)

\( ET_0 \) is defined as the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (FAO, 1977).
The evapotranspiration of water can be measured, but is normally estimated on the basis of climatological data. The preferred estimation method was developed by Penman in 1948, and contains an energy (radiation) and an aerodynamic (wind) term. See FAO (1977) for a detailed 'recipe' how to compute $ET_0$ according to Penman. Tables 5.2 and 5.3 give indicative figures for $ET_0$ for different climatic regions and for Zimbabwe.

**Table 5.2 $ET_0$ [mm/d] for different agro-climatic regions (FAO 1979: 16, table 8)**

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean daily temperature °C</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cool</td>
<td>moderate</td>
<td>warm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt;15)</td>
<td>(15-25)</td>
<td>(&gt;25)</td>
</tr>
<tr>
<td>TROPICS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>humid</td>
<td>3-4</td>
<td>4-5</td>
<td>5-6</td>
<td></td>
</tr>
<tr>
<td>subhumid</td>
<td>3-5</td>
<td>5-6</td>
<td>7-8</td>
<td></td>
</tr>
<tr>
<td>semi-arid</td>
<td>4-5</td>
<td>6-7</td>
<td>8-9</td>
<td></td>
</tr>
<tr>
<td>arid</td>
<td>4-5</td>
<td>7-8</td>
<td>9-10</td>
<td></td>
</tr>
<tr>
<td>SUBTROPICS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>humid</td>
<td>3-4</td>
<td>4-5</td>
<td>5-6</td>
<td></td>
</tr>
<tr>
<td>subhumid</td>
<td>3-5</td>
<td>5-6</td>
<td>6-7</td>
<td></td>
</tr>
<tr>
<td>semi-arid</td>
<td>4-5</td>
<td>6-6</td>
<td>7-8</td>
<td></td>
</tr>
<tr>
<td>arid</td>
<td>4-5</td>
<td>7-8</td>
<td>10-11</td>
<td></td>
</tr>
<tr>
<td>Winter rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>humid - subhumid</td>
<td>2-3</td>
<td>4-5</td>
<td>5-6</td>
<td></td>
</tr>
<tr>
<td>semi-arid</td>
<td>3-4</td>
<td>5-6</td>
<td>7-8</td>
<td></td>
</tr>
<tr>
<td>arid</td>
<td>3-4</td>
<td>6-7</td>
<td>10-11</td>
<td></td>
</tr>
<tr>
<td>TEMPERATE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>humid - subhumid</td>
<td>2-3</td>
<td>3-4</td>
<td>5-7</td>
<td></td>
</tr>
<tr>
<td>semi-arid - arid</td>
<td>3-4</td>
<td>5-6</td>
<td>8-9</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.3 Reference evapotranspiration ($ET_0$) for selected stations of Zimbabwe**

(calculated from CROPWAT on the basis of reference files)

<table>
<thead>
<tr>
<th>Year (mm/yr)</th>
<th>Daily max. (mm/day)</th>
<th>Year (mm/yr)</th>
<th>Daily max. (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nyanga</td>
<td>1268</td>
<td>4.8</td>
<td>Gweru</td>
</tr>
<tr>
<td>Marondera</td>
<td>1399</td>
<td>5.2</td>
<td>Kwekwe</td>
</tr>
<tr>
<td>Mutare</td>
<td>1414</td>
<td>5.4</td>
<td>Bulawayo</td>
</tr>
<tr>
<td>Chipinge</td>
<td>1496</td>
<td>5.3</td>
<td>Hwange</td>
</tr>
<tr>
<td>Makoholi</td>
<td>1547</td>
<td>5.6</td>
<td>Tsjolotsjo</td>
</tr>
<tr>
<td>Harare</td>
<td>1562</td>
<td>6.3</td>
<td>Kariba</td>
</tr>
<tr>
<td>Chivero</td>
<td>1587</td>
<td>6.0</td>
<td>Binga</td>
</tr>
<tr>
<td>Karoi</td>
<td>1610</td>
<td>6.5</td>
<td></td>
</tr>
</tbody>
</table>

FAO developed a simple computer programme (CROPWAT) which calculates evapotranspiration according to Penman (Figure 5.3 and Table 5.3). CROPWAT is a computer program to calculate reference evapotranspiration, crop water requirements, irrigation requirements, and to evaluate rainfed production and drought effects. CROPWAT uses an extensive climatic database, CLIMWAT, which includes data from a
Both programmes can be downloaded from

Figure 5.3: CROPWAT output screen with monthly ETo data for Chivero, Zimbabwe

Estimating $ET_0$ through pan evaporation

Another way of estimating $ET_0$ is through pan-evaporation measurements, which are routinely collected at meteorological stations. The most common type of pan is the so-called Class A pan (figure 5.4). Evaporation pans provide a method by which the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface can be measured. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient:

$$ET_0 = k_{pan} * E_{pan} \text{ [mm/d]}$$

$k_{pan}$ values may vary from 0.35 - when the pan is placed in a dry fallow area and wind speed during the measurements is very strong - to 0.85, when the pan is placed in a short green cropped area and winds are light. For practical purposes 0.60 is recommended as a first estimate for $k_{pan}$ if no additional information is available.
Figure 5.4: Diagram of a Class A evaporation pan (source: Allen et al., 1998)

NB 1: $ET_0$ and $E_{pan}$ data are known to vary greatly in Zimbabwe and Southern Africa, and no simple relationship between them has been established.

NB 2. $ET_0$ calculated with the modified Penman method is reported to overestimate evapotranspiration by as much as 20%.

The amount of water actually consumed by the crop, subject to constraints, is the Actual Evapotranspiration ($ET_a$). The factor $ET_a / ET_m$ is a measure for the degree of water shortages experienced by the crop (section 5.3).

Crop coefficient $K_C$

$K_C$ coefficients have been established for different crops. Once $K_C$ values are known as well as $ET_0$, the evapotranspiration demand of a crop ($ET_m$) can be estimated:

$$ET_m = K_C \times ET_0 \text{ [mm/d]}$$  \hspace{1cm} (5.5)

Table 5.4 gives figures of $K_C$ for selected crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>$K_C$</th>
<th>Crop</th>
<th>$K_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-green</td>
<td>0.90</td>
<td>Potato</td>
<td>0.85</td>
</tr>
<tr>
<td>-dry</td>
<td>0.80</td>
<td>Rice</td>
<td>1.10</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.85</td>
<td>Sorghum</td>
<td>0.80</td>
</tr>
<tr>
<td>Groundnut</td>
<td>0.80</td>
<td>Sugar cane</td>
<td>0.95</td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td>Sunflower</td>
<td>0.80</td>
</tr>
<tr>
<td>-green</td>
<td>0.90</td>
<td>Tobacco</td>
<td>0.90</td>
</tr>
<tr>
<td>-grain</td>
<td>0.85</td>
<td>Tomato</td>
<td>0.85</td>
</tr>
<tr>
<td>Onion</td>
<td>0.80</td>
<td>Watermelon</td>
<td>0.80</td>
</tr>
<tr>
<td>Pea (fresh)</td>
<td>0.90</td>
<td>Wheat</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Precipitation ($P$)

The aim of irrigation is to have always sufficient water in the rootzone to meet crop and soil water requirements. Too much water in the rootzone may lead to water percolating to the subsoil which is then lost to the crop. Too little water causes water stress and reduces yields. So ideally one will have to give water to the rootzone when the soil moisture is not yet depleted up to wilting point and one should not provide more water than to fill the soil profile up to field capacity. (The story on water supply for basin irrigation of rice is somewhat different. For this type of rice it is important to maintain a layer of water on the field.)

Two sources of water are available to meet the field water requirements: direct rainfall on the field and irrigation. Irrigation can be influenced in quantity and time, rainfall not. In practice, rain will fall also on moments that the soil has just received water by irrigation and the rain will be drained off. Sometimes rainfall will be too high, will saturate the soil profile and rainwater will be "lost" to percolation and surface runoff.

In order to determine how much of the rainfall may be used to reduce irrigation requirements, the notion of effective rainfall is introduced. Effective Rainfall ($P_{eff}$) is that portion of the rainfall, which is not lost through unnecessary percolation and surface runoff. The most "rough-and-ready" method to estimate the effective rainfall is as follows:

\[
P_{eff} = 0.8 \times P - 25 \quad \text{for } P > 75 \text{ mm/month}
\]

\[
P_{eff} = 0.6 \times P - 10 \quad \text{for } P < 75 \text{ mm/month}
\]

Another method often used was developed by the US Department of Agriculture Soil Conservation Service. The table below allows the mean monthly effective rainfall to be estimated provided the crop evapotranspiration and mean monthly rainfall are known.

Table 5.5: Mean monthly effective rainfall related to mean monthly ETcrop and mean monthly rainfall (FAO, 1977)

<table>
<thead>
<tr>
<th>Rainfall (mm/month)</th>
<th>12.5</th>
<th>25</th>
<th>37.5</th>
<th>50</th>
<th>62.5</th>
<th>75</th>
<th>87.5</th>
<th>100</th>
<th>112.5</th>
<th>125</th>
<th>137.5</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETcrop (mm/month)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>8</td>
<td>16</td>
<td>24</td>
<td>50</td>
<td>8</td>
<td>17</td>
<td>25</td>
<td>32</td>
<td>39</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>9</td>
<td>18</td>
<td>27</td>
<td>34</td>
<td>34</td>
<td>41</td>
<td>48</td>
<td>56</td>
<td>62</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>9</td>
<td>19</td>
<td>28</td>
<td>35</td>
<td>35</td>
<td>43</td>
<td>52</td>
<td>59</td>
<td>66</td>
<td>73</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>37</td>
<td>37</td>
<td>46</td>
<td>54</td>
<td>62</td>
<td>70</td>
<td>76</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>10</td>
<td>21</td>
<td>31</td>
<td>39</td>
<td>39</td>
<td>49</td>
<td>57</td>
<td>66</td>
<td>74</td>
<td>81</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>11</td>
<td>23</td>
<td>32</td>
<td>42</td>
<td>42</td>
<td>52</td>
<td>61</td>
<td>69</td>
<td>78</td>
<td>86</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>11</td>
<td>24</td>
<td>33</td>
<td>44</td>
<td>44</td>
<td>54</td>
<td>64</td>
<td>73</td>
<td>82</td>
<td>91</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>12</td>
<td>25</td>
<td>35</td>
<td>47</td>
<td>47</td>
<td>57</td>
<td>68</td>
<td>78</td>
<td>87</td>
<td>96</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>13</td>
<td>25</td>
<td>38</td>
<td>50</td>
<td>50</td>
<td>61</td>
<td>72</td>
<td>84</td>
<td>92</td>
<td>102</td>
<td>112</td>
</tr>
</tbody>
</table>

WaterNet / CCR / ISRI / Catalic / UNESCO-IHE Delft / UZ for UNESCO
Irrigation Requirement \((I)\)

Net irrigation requirement \((I_{\text{net}})\) is the amount of irrigation water to be supplied to the crop to satisfy its consumptive use:

\[
I_{\text{net}} = (K_C \times ET_0) - P_{\text{eff}} \quad \text{(mm/d)}
\]  

(5.6)

Gross irrigation requirement \((I_{\text{gross}})\) is the amount of irrigation water to be supplied to the field. A simplified formula:

\[
I_{\text{gross}} = \frac{K_C \times ET_0 - P_{\text{eff}}}{e_f}
\]  

(5.7)

where:
- \(K_C\) = crop coefficient
- \(ET_0\) = reference evapotranspiration [mm/d]
- \(P_{\text{eff}}\) = effective rainfall [mm/d]
- \(e_f\) = field application efficiency

The gross water requirement of an entire irrigation project \(Q_{\text{project}}\) is then calculated by multiplying the gross irrigation requirements of the various crops by their respective areas \(A\), and by incorporating two more efficiency figures:

- \(e_d\) which is the efficiency of water distribution between the intake of the tertiary or lateral section and the field edge; and
- \(e_c\) which is the conveyance efficiency from project intake (river diversion, storage dam etc.) to tertiary or lateral inlet.

Efficiencies determine to a large degree the gross amount of water required. Efficiencies tend to be relatively low in some, if not most, irrigation schemes. Some indicative figures are given in table 5.6.

Table 5.6 Order of magnitude of irrigation efficiencies (after FAO, 1979)

<table>
<thead>
<tr>
<th>Field Application Efficiency ((e_f))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface methods:</td>
</tr>
<tr>
<td>basin and level border</td>
</tr>
<tr>
<td>furrow</td>
</tr>
<tr>
<td>Sprinkler:</td>
</tr>
<tr>
<td>hot dry climate</td>
</tr>
<tr>
<td>moderate climate</td>
</tr>
<tr>
<td>humid and cool</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distribution Efficiency (within tertiary unit) ((e_d))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units &gt; 20 ha</td>
</tr>
<tr>
<td>unlined</td>
</tr>
<tr>
<td>lined or piped</td>
</tr>
<tr>
<td>Units &lt; 20 ha</td>
</tr>
<tr>
<td>unlined</td>
</tr>
<tr>
<td>lined or piped</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conveyance Efficiency (main system) ((e_c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous supply with no substantial change in flow</td>
</tr>
<tr>
<td>Rotational supply with effective management</td>
</tr>
<tr>
<td>Rotational supply, less effective management</td>
</tr>
</tbody>
</table>
5.3 Yield reduction due to water shortage

In principle, maximum yield will be obtained when the crop receives sufficient water, thus when $ET_a = ET_m$.

For planning purposes, it is useful to know what the relation is between the quantity of water supplied and the yield obtained: what the reductions in yield will be when less than the optimal amount of water is supplied. The plant will experience a shortage of water, when the soil moisture is reduced to a level for which it can not satisfy its potential evapotranspiration.

A number of issues arises when this question has to be answered:

- water, the available soil moisture, is only one of the factors that determine the potential maximum yield; other factors are climate, soil, water quality level, nutrients, control of diseases, farm management, etc.
- yield reductions because of water shortages often relate to the potential (maximum) yield, but it is questionable whether these maximum yields would be obtained anyhow.
- water shortages often refer to shortages of supply at the intake of the irrigation system; these are not representative for soil moisture deficits.
- in case of (predicted) water shortages, farmers will take corrective action such as improving management, improving irrigation efficiencies or selecting other crops; this will reduce the impact of water shortages.

Here the role of water is considered on its own merits, assuming all other factors indifferent or independent. The analysis of the effect of water shortages on yield is based on the following reasoning:

- there is a maximum obtainable yield ($Y_m$) for a given environment (soil, climate etc.), all other things (inputs etc.) being fair to optimal.
- reduction of $Y_m$, leading to the actual yield $Y_a$, is caused by water stress.
- water stress is expressed as:
  a relative reduction in plant evapotranspiration: $1 - ET_a / ET_m$, where $ET_a$ and $ET_m$ are the actual and maximum evapotranspiration
- this translates in a formula, which indicates that the relative reduction of the yield is proportional to the relative reduction of evapotranspiration by a yield response factor $K_y$:

$$
  \left( 1 - \frac{Y_a}{Y_m} \right) = K_y \left( 1 - \frac{ET_a}{ET_m} \right)
$$

(5.8)

The Yield Response Factor ($K_y$) depends upon the crop and the growing stage of the crop. $K_y$ can be taken for the total growing period of the crop, assuming that the water deficit (ratio $ET_a / ET_m$) occurs continuously over the total growing period, or it may be taken over any one of the individual growth periods (establishment, vegetative, flowering, yield formation, ripening). Table 5.7 gives figures of $K_y$. 
Table 5.7 Yield response factors $K_y$ of selected crops (FAO 1979).

<table>
<thead>
<tr>
<th>Crop</th>
<th>$K_y$</th>
<th>Crop</th>
<th>$K_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beans</td>
<td>1.15</td>
<td>Sorghum</td>
<td>0.9</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.85</td>
<td>Sugar cane</td>
<td>1.2</td>
</tr>
<tr>
<td>Groundnut</td>
<td>0.7</td>
<td>Sunflower</td>
<td>0.95</td>
</tr>
<tr>
<td>Maize</td>
<td>1.25</td>
<td>Tobacco</td>
<td>0.9</td>
</tr>
<tr>
<td>Onion</td>
<td>1.1</td>
<td>Tomato</td>
<td>1.05</td>
</tr>
<tr>
<td>Pea</td>
<td>1.15</td>
<td>Watermelon</td>
<td>1.1</td>
</tr>
<tr>
<td>Potato</td>
<td>1.1</td>
<td>Wheat (winter)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The "Maximum" (Good) Yield ($Y_m$) depends upon climatic conditions, soils and management. It is defined as the harvested yield of a high-producing variety, well-adapted to the given environment, where water, nutrients, pests and diseases do not limit yield. Table 5.1 gives values for a number of crops.

With the above figures, as well as with actual figures of gross water use and yields obtained in specific situation, it is possible to estimate, and critically analyse, current water demand for irrigation.

Projections of current water use into the future in this sector are difficult to make with any certainty. Three major factors influencing water demand include:

1. Future investments in irrigation infrastructure by the public and private sector, increasing the area under irrigation;
2. Future developments in maintenance, modernising and rehabilitating existing irrigation schemes, changing the efficiency of these schemes;
3. Future developments in cropping patterns.

Of course, prices of crops and water heavily influence all three factors mentioned. Especially development of crop prices, dependent on the world market, are difficult to forecast.

Water use can be substantially reduced in existing schemes through investing in maintenance, rehabilitation and modernising existing irrigation infrastructure, as current efficiencies obtained in some sectors are low. The water saved can then put to new developed areas.

Planning irrigation demand under water scarcity

It is important to note that water shortage for crops with $K_y < 1$ (e.g. sorghum) leads to less than proportional yield reductions. If the aim is to maximise crop production, for these crops it makes sense to "spread" the shortage over the entire irrigated area. Here, crop production per unit of land is sub-optimal, but crop production per unit of water optimal.

Water shortage for crops with $K_y > 1$ (e.g. maize) leads to larger than proportional yield reductions. If the aim is to maximise crop production, for these crops it makes sense to "concentrate" all irrigation water to a limited area which can be supplied with optimal water. Here, crop production per unit of land and crop production per unit of water are both optimal.
Another indicator in considering what crop to grow when water is limited, is the water utilization efficiency in crop production, with $E_y$ (see section 4.1 above) for the harvested yield, as a measure of production per unit of water supplied (kg/m³). [This figure can also be calculated if gross water use $I_{gross}$ or $Q_{project}$ and total yield $Y$ of crops under irrigation are known for specific cases.]

One can get the monetary productivity of water $M_e$ (Z$/m³) by multiplying $E_y$ by the market price of that crop $P_c$ (Z$/kg). When water is limited, one would select crops with a high $M_e$, and a low $K_y$.

### 5.4 Exercises

#### 5.1 Water utilisation efficiency

**Given:** Consider a rainfed maize crop. Precipitation is 700 mm, of which 100 mm is intercepted and evaporates, 100 mm runs off into stream. Of the remaining 500 mm that infiltrates into the soil, 100 mm percolates to the subsoil and recharges aquifers. The maize crop yields 4000 kg/ha.

**5.1a** What is the water utilisation efficiency of this rainfed crop?

#### 5.2 Calculation of Irrigation water requirement

**Given** Irrigated maize, length of growing season: 120 days no effective rainfall;
- $E_{to}$=5 mm/d;
- $K_c$=0.9
- $e_r$=0.7;
- farm size: 1 ha

**5.2a** Calculate water requirement for the farm

#### 5.3 Yield reduction

**Given**
- crop: Maize
- Water required: 840 mm / full growing season
- Effective rainfall: 20 mm / full growing period
- Available water at intake: 13,750 m³/ha
- Irrigation efficiency: 0.4
- Yield response factor: 1.25

**5.3a** What is the total amount of irrigation water required at the intake? Is available water sufficient?

**5.3b** Estimate the reduction in yield as a result of the deficit.
3.5 Priorities

Given In an irrigation scheme, three crops are normally grown, namely maize, beans and sorghum. However, regular water shortages are being experienced.

Yield response factors $K_y$ for Maize, Beans and Sorghum

<table>
<thead>
<tr>
<th>Crop</th>
<th>$K_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>1.25</td>
</tr>
<tr>
<td>Beans</td>
<td>1.15</td>
</tr>
<tr>
<td>Sorghum</td>
<td>0.9</td>
</tr>
</tbody>
</table>

3.5a Find the crop for which there is the least yield reduction.

3.6 Priorities

A water shortage is forecast: only 70% of $ET_o$ will be available for the next irrigation season. The dilemma of the planner is to decide which crops to choose.

Crop coefficients, yield response factors, maximum yields and farm gate prices for Maize, Cotton, Sunflower are given:

<table>
<thead>
<tr>
<th>Crop</th>
<th>$K_c$</th>
<th>$K_y$</th>
<th>$Y_{max}$ (kg/ha)</th>
<th>Value crop (US$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>0.85</td>
<td>1.25</td>
<td>4000</td>
<td>0.9</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.85</td>
<td>0.85</td>
<td>3000</td>
<td>1.2</td>
</tr>
<tr>
<td>Sunflower</td>
<td>0.80</td>
<td>0.95</td>
<td>2000</td>
<td>1.6</td>
</tr>
</tbody>
</table>

3.6a Find the crop that gives the highest return (value).

3.7 The following graph indicating the relationship between evapotranspiration and yield for maize is given.

3.7a Find $K_y$. 

![Evapotranspiration - Yield relationship for Maize](image-url)
5.5 References

*Agricultural compendium for rural development in the tropics and subtropics*. Elsevier, Amsterdam, 1981


6. Environmental Water Use

6.1 Introduction (Bullock, 1998)

The river environment include flora and fauna found in-stream, as well as the riverine area, including floodplains, wetlands etc.

The environment needs water for the following purposes:
- to live (physical habitat)
- to function (e.g. transpiration in trees)
- to move (e.g. migration)
- to feed
- to breed

The environment requires:
- flow of water (seasonality)
- depth of water
- velocity
- quality of water (levels of oxygen, pH, tolerable levels of pollution, sediment)
- temperature

It has now been generally accepted that the environment is a ‘legitimate water user’. This is not merely a nice gesture to animal and plant-life, a luxury. It is also simply a survival strategy for us, human beings, and for our children. Because water is the basis of life.

Considering the environment a legitimate water user, however, poses a challenge: how much water must be reserved for the environment? The answer to this question must be very complex, as water for the environment should be specified spatially, temporally, and in terms of quality. Ecosystems thrive on fluctuations in discharge through the year: floods and low flows. Floods and low flows are, however, considered by many humans as problems. Therefore, many infrastructural measures have been taken to attenuate the hydrograph, without considering the environmental impact (as well as the economic and social impact on rural societies who live off recession agriculture and fisheries). As to quality, seemingly minute and insignificant changes in water characteristics, such as changes in temperature and silt load downstream of a man-made lake, may have large environmental consequences.

The man-made infrastructure makes it impossible to entirely restore a pristine environment. But given the rapidly growing environmental knowledge we should avert new projects which severely harm the environmental, while making the best of the existing infrastructure. The case of flood management is an example.
Flood management (Savenije and van der Zaag, 1998)

River development in the past was often equivalent to ‘taming the floods’ while harnessing the water for hydropower, navigation and irrigation. The outcome was nearly always the construction of dams and dikes. During the last 15 years, research findings point to a re-assessment of the ‘taming the floods’ paradigm, not only in Africa, but also in Asia (Bangladesh for instance) and Europe (Savenije 1996). In the river Rhine, for instance, the complete control of the river course by dikes has resulted in higher flood levels along the lower reaches of the river. Land use change has had an impact on the rainfall-runoff relations, resulting in more rapid runoff, higher flood peaks and reduced low flows in summer. In the lower part of the river, the complete harnessing of the river cannot continue indefinitely, mainly because of sedimentation, land subsidence and sea level rise. In certain parts of the Rhine delta, the riparians will eventually have to get used to ‘living with the floods’ again rather than continuing to try to shut floods out completely. The hydrology of the Rhine thus forces us to fundamentally change our thinking. As much as we want to, humans are not the masters of the river. We are partners sharing the same space, and we cannot confine the river into an increasingly narrow straight-jacket. The recent floods in the Netherlands of 1993, 1995 and 1998 are slowly teaching us this lesson.

The reality of African rivers is not fundamentally different. Also here, the value of river floods is being re-assessed:

The construction of large dams has been a major feature of water management in Africa over the past 50 years. .. The resulting reduction in flooding downstream was seen as a benefit and thus constructing a dam which was capable of making flood releases was never contemplated. More recently the great value of natural flooding to fisheries, recession agriculture and groundwater recharge has been realised. So much so that many authorities are now examining the possibility of creating artificial floods.

(Scudder and Acreman 1996: 101)

The experiences of the Senegal basin (shared by Mali, Senegal and Mauritania), the Yobe (shared by Niger, Nigeria and Chad), the Kafue river (in the Zambezi basin shared by Angola, Zambia, Namibia, Botswana, Zimbabwe, Tanzania, Malawi and Mozambique), and the Phongolo river (in the Phongolo-Maputo basin shared by South Africa and Mozambique) show that it is environmentally beneficial, and economically feasible to simulate artificial floods by manipulating releases from existing dams. There is however an important technical prerequisite. Apart from the obvious fact that the design of dams should enable sufficiently large releases, artificial floods require that all operational decisions across the entire basin should be coordinated. Moreover, artificial floods require sophisticated real-time monitoring of hydrological and climatological phenomena (Hollis 1996: 184). This is because artificial flooding is only feasible if properly timed such that it ‘surfs’ on top of the limited natural flood streams that still occur.
New criteria and operational rules

The example of flood management shows that it is possible to minimise the damage to our environment, and better anticipate possible negative impacts of new infrastructural projects. What is required are certain volumes of water which are set aside, or ‘reserved’ for the environment; this is now done under the new water act of South Africa.

Bullock et al. (1998) estimated that the water requirements of the environment in the Mazowe catchment (Zimbabwe) may range between 5 to 15% of total generated runoff.

What is also required are criteria that will assist policy-makers in making balanced decisions in which the immediate economic interests are weighed against the interest of the environment. These criteria would generate practical operational rules, related to, for instance:

- reservoir releases which accommodate the environment
- water rights or permits, which contain conditionalities only allowing abstractions when a certain specified flow is let through
- water quality objectives and discharge permits
- dam designs to allow for artificial floods and fish passes.

6.2 Quantifying environmental water requirements
(HR Wallingford, 2001, chapter 2)

There are several assessment procedures for determining environmental flows. The decision on which procedure to use is dependent on the sensitivity of the aquatic environment, the complexity of the decision to be made and the increased cost and difficulty of collecting large amounts of information. Procedures for determining environmental flow requirements fall into one of four basic categories:

1. Historical discharge method: the Tennant method;
2. Hydraulic method: the wetted perimeter method
3. Holistic method: the building block method
4. Habitat rating method: Instream Flow Incremental Methodology

Each method differs in its data requirements, procedures for selecting flow requirements, ecological assumptions and effects on river hydraulics. The most commonly used methods for each of the categories are discussed below.

Historical discharge method: the Tennant method

Discharge methods are based on historical flow records and are the simplest and least data intense methods for estimating instream flows. The most commonly used method is known as the Tennant (or Montana) method. This method is based on discharge statistics and historical flows. The minimum flow requirement for a watercourse is expressed as a percentage of the mean annual flow at a specified site. The Tennant method was developed in the USA and designed to be applicable to all stream sizes and to warm or cold climates (Tennant 1976). The minimum flow required to sustain the aquatic environment is...
expressed as a percentage of the mean annual flow, with different percentages used for wet and dry seasons (Table 6.1).

### Table 6.1: Instream flow recommendations using the Tennant method

<table>
<thead>
<tr>
<th>Health of the habitat</th>
<th>Recommended minimum flow as a percentage of the mean annual flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wet season</td>
</tr>
<tr>
<td>Optimum</td>
<td>60% to 100%</td>
</tr>
<tr>
<td>Outstanding</td>
<td>40%</td>
</tr>
<tr>
<td>Excellent</td>
<td>30%</td>
</tr>
<tr>
<td>Good</td>
<td>20%</td>
</tr>
<tr>
<td>Fair or degrading</td>
<td>10%</td>
</tr>
<tr>
<td>Poor or degrading</td>
<td>10%</td>
</tr>
<tr>
<td>Severe degradation</td>
<td>0% to 10%</td>
</tr>
</tbody>
</table>

Source: Orth and Leonard 1990

The Tennant method can be extended to incorporate seasonal variations by specifying monthly minimum flows as a percentage of the monthly mean flow.

**Advantages of the Tennant method**

- It is simple to use;
- It requires relatively little data;
- It does not require costly fieldwork to be carried out.

**Disadvantages of the Tennant method**

- It does not preserve the natural variability of the watercourse by taking account of daily and yearly variation of flows i.e. the method only prescribes a minimum environmental base flow;
- The method never produces a zero flow recommendation. However, in semi-arid regions where watercourses are naturally dry for some months of some years a zero flow may be appropriate;
- The method is based on fieldwork carried out in the USA and may not be applicable to semi-arid regions of the world;
- The relationship between flow and the state of the aquatic ecosystem is poorly established.

**Hydraulic method: the wetted perimeter method**

Hydraulic methods relate various parameters of the hydraulic geometry of a watercourse channel to discharge. The most commonly used hydraulic method is the wetted perimeter technique. This method is the simplest of the field survey-based, site-specific techniques that allows the minimum instream flow of a watercourse to be calculated (Gippel and Stewardson 1998). It should be noted that the wetted perimeter technique includes no explicit representation of the aquatic habitat. To establish the minimum environmental flow a wetted perimeter-discharge relationship is generated. The wetted perimeter of a watercourse is defined as the length of the line of intersection of the channel wetted surface with a cross-sectional plane normal to the direction of the flow.
The wetted perimeter-discharge relationship should be generated for watercourse cross-sections that are at riffle sites or at sites where fish passage is likely to be limited. A riffle is an area of shallow rapids in an open stream where a turbulent water surface is induced by obstructions that are wholly or partly submerged.

The method assumes that preserving the wetted perimeter in critical habitat areas such as riffles, adequate flow will be available to maintain aquatic life. The wetted perimeter method is illustrated in Figure 6.1 and applied as follows:

- The relationship between the wetted perimeter and the discharge of the watercourse at a riffle, or where the passage of fish is limited, is established;
- A non-dimensional graph of wetted perimeter versus discharge is plotted. The values of wetted perimeter and discharge are expressed as a proportion of their maximum value;
- The breakpoint of the curve is established. The breakpoint indicates where small decreases in the flow result in increasingly greater decreases in the wetted perimeter; i.e. where the slope of the curve \( \frac{dy}{dx} = 1 \);
- Compound cross-sections with multiple benches may produce an irregular relationship between wetted perimeter and discharge, and there may be more than one breakpoint. In these cases the lowest breakpoint is usually the most relevant to minimum flow determination;
- Once the breakpoint has been established the minimum instream flow requirement can be estimated.

**Figure 6.1 Use of the wetted perimeter method to estimate instream flows** (HR Wallingford, 2001)
An important consideration in site selection is the ease with which the flow through the site can be measured or calculated. Discharge through a riffle is relatively difficult to measure directly with any confidence by manual flow gauging. It is often better to measure the discharge at a nearby site suitable for manual gauging or use readings from a nearby gauging station. These surrogate discharge measurements should be sufficiently close to the site of interest that any losses or inflows between the two sites could be ignored.

Advantages of the wetted perimeter method
- It is relatively simple to use;
- It requires relatively little data.

Disadvantages of wetted perimeter method
- It recommends only a minimum environmental base flow

Holistic method: the building block methodology

The most widely used holistic method in southern Africa is the building block methodology. This methodology was developed in South Africa by the Department of Water Affairs and Forestry and various academic institutions (Hughes et al., 1999). The building block methodology requires the following:
- The total flow volume for the four building blocks components which are:
  - Maintenance of low flows;
  - Maintenance of high flows;
  - Drought low flows;
  - Drought high flows;
- Monthly distribution of the four building block components;
- Establishment of the present ecological state (A to F) and future management category (A to D). These are given in Table 6.2.

Table 6.2: Ecological states used in the building block methodology

<table>
<thead>
<tr>
<th>Class</th>
<th>Description of ecological state</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Unmodified</td>
</tr>
<tr>
<td>B</td>
<td>Largely natural with few modifications</td>
</tr>
<tr>
<td>C</td>
<td>Moderately modified</td>
</tr>
<tr>
<td>D</td>
<td>Largely modified</td>
</tr>
<tr>
<td>E</td>
<td>Natural habitat loss extensive</td>
</tr>
<tr>
<td>F</td>
<td>Modifications at a critical level</td>
</tr>
</tbody>
</table>

Source: Hughes et al., 1999

The major objective of the method is to estimate the values of the four building block components as a percentage of the mean annual runoff of the natural flow regime. A building block instream flow study would be carried out as follows:

(i) The monthly naturalised flow series for the site of interest must be established.

(ii) The ecological management class of the site is established with A being an unmodified site and F representing a site that had been modified to a critical level. There are methods for estimating the ecological management status of the site based
upon various habitat integrity indices developed in South Africa.

(iii) The flow variability has to be established to summarise the variability within the wet and dry seasons. This is based on the average coefficient of variation (i.e. standard deviation/mean) for the three main wet season months and the three main dry season months (excluding those that have zero mean monthly flows). The actual coefficient of variation (CV) is the sum of these two means. The assumption is that rivers with a high degree of variability in their flow regime will require a lower proportion of their natural mean annual runoff because they are used to experiencing such conditions. Rivers with more reliable flows and less flow variation are assumed to be ecological less well adjusted to frequent extremes in the flow regime.

(iv) The base flow is calculated. The base flow index (BFI) is the proportion of the total flow occurring as the base flow. There are various hydrological methods to assess the base flow.

(v) A combined variability index is calculated by dividing the coefficient of variation by the base flow index.

(vi) For particular sub-catchments, curves can be constructed for maintenance low flow estimation and maintenance high flows versus the variability index (CV/BFI) for the future ecological management classes. A typical set of curves is shown in Figure 6.2.

(vii) The drought low and drought high flow are established.

(viii) The monthly distribution of flows is then produced. It should be noted that one of the basic principles of the approach is that a higher proportion of the natural monthly flow is required during the dry months than during the wet months.

![Figure 6.2: Typical curves to establish maintenance low flows](HR Walingford, 2001)
The hypothetical instream flow requirement created using the Building Block Methodology is shown in Figure 6.3.

![Figure 6.3: Hypothetical instream flow requirement using the building block methodology](image)

**Advantages of the building block methodology**
- It takes into account the monthly flow variability for both high and low flows;
- It has been developed specifically for use in southern Africa;
- The low flow building block can be used to assess preliminary instream flow requirements.

**Disadvantages of the building block methodology**
- It requires an estimation of base flow, the natural mean annual runoff and naturalised flows.

**Habitat method: Instream Flow Incremental Methodology**

Habitat rating methods provide the most complex and the most flexible approach to environmental flow assessments. They provide information on how habitats change with flow for instream uses, either biological or recreational. No prior assumptions are made about the state of the natural ecosystem. Changes of physical habitats with stream flow are accounted for and combined with the habitat preferences of a given species to determine the amount of habitat available over a range of stream flow conditions. The result is a curve relating available habitat area and stream discharge. Optimum stream flows for a certain number of species can be ascertained from these curves, and the results can be used as a guide for recommending environmental flows. The most commonly used habitat method is the Instream Flow Incremental Methodology (IFIM).
The Instream Flow Incremental Methodology (IFIM) is a conceptual framework for assessing the effect of water resources development or management activities on aquatic and riverside ecosystems, and for solving water resources management problems and conflicts that involve the definition of an ecological flow to minimise impacts on ecosystems. The goal of this method is to relate fish and wildlife parameters to stream discharge in equivalent terms to those used to estimate other beneficial uses of water.

IFIM is based on the assumption that living organisms in running water have their distribution (longitudinally and laterally) controlled by the hydraulic conditions. The decision variable generated by IFIM is the total habitat area with suitable conditions for a species at a particular life stage or for a particular activity (e.g. spawning), computed as a function of discharge. The environmental flow is usually the highest value of a range of minimum flows computed for several species, assuming that this value will be adequate for the preservation of the ecosystem. The target species, one or more, are usually game, commercial, endangered or indicator fish species.

IFIM relates changes in the extent of habitats that are available to aquatic species to changes in discharge. This allows instream flow demands to be expressed in the same terms as other water resource demands. The IFIM methodology is usually coupled with the Physical Habitat Simulation System (PHABSIM) model to generate a habitat-discharge relationship. IFIM coupled with PHABSIM can be used to predict changes in environmental parameters that can be quantified in the form of a flow dependent relationship.

PHABSIM is a collection of computer programs that combine aquatic organisms preferences for velocity, depth and channel conditions to predict habitat availability at various discharge levels. PHABSIM simulates suitable habitats for aquatic species by using depth, velocity and stream channel characteristics to describe local physical niches that are occupied by aquatic species. PHABSIM allows changes in habitat resulting from changes in instream flow to be quantified and thus provides answers to “what if” water management questions.

Hydraulic modelling techniques such as PHABSIM require detailed hydraulic and morphological surveys and knowledge of habitat preferences of the species of interest.

**Advantages**
- If employed correctly IFIM allows the values of every legitimate stakeholder to be taken into account;
- The method takes into account the flow requirements of the indicator species over its entire life cycle;
- An assessment of the natural flow requirement can be made independently of the naturalised flow data.

**Disadvantages**
- It is time consuming and costly to carry out an IFIM study;
- The IFIM techniques have been mainly applied at micro- and meso-habitat levels focusing on one or a few river reaches. There is little experience of using IFIM techniques to assess environmental water demands at a catchment or even a sub-catchment level;
- To implement IFIM requires a multi-disciplinary team with expertise in hydrology,
river morphology, water quality, aquatic and terrestrial ecology, carrying out biological field surveys and hydraulic engineering.

**Comparison of the instream flow methods**

Historical and hydraulic techniques such as the Tennant Method and wetted perimeter technique are applicable for establishing minimum environmental demands for high level water resources management. These techniques provide an initial “low confidence” estimate, and can be applied rapidly at a large number of sites to provide a first estimate of the likely quantities of water required to maintain the ecology in a given condition. The building block methodology can also be used for rapid assessments. However, in order to use this method for rapid environmental flow appraisals, monthly naturalised flow series are required and a country specific piece of software (possibly based on the one produced by Rhodes University in South Africa) needs to written. The IFIM method utilising PHABSIM is a commonly used method for more complex decisions e.g. the construction of a hydropower plant or the setting abstractions limits from an ecologically sensitive watercourse.

In conclusion there is no one methodology that should be used for establishing the instream flow demand. The choice of the method used is a function of the complexity of the decision to be made and the complexity of the system.
6.3 References


Savenije, H.H.G., 1996, Recent extreme floods in Europe and the USA; Challenges for the future. Physics and Chemistry of the Earth 20(5-6): 433-437


Constitution of UNESCO (excerpt)
London, 16 November 1945

The Governments of the States Parties to this Constitution on behalf of their peoples declare:

That since wars begin in the minds of men, it is in the minds of men that the defences of peace must be constructed;

That ignorance of each other’s ways and lives has been a common cause, throughout the history of mankind, of that suspicion and mistrust between the peoples of the world through which their differences have all too often broken into war;

That the great and terrible war which has now ended was a war made possible by the denial of the democratic principles of the dignity, equality and mutual respect of men, and by the propagation, in their place, through ignorance and prejudice, of the doctrine of the inequality of men and races;

That the wide diffusion of culture, and the education of humanity for justice and liberty and peace are indispensable to the dignity of man and constitute a sacred duty which all the nations must fulfil in a spirit of mutual assistance and concern;

That a peace based exclusively upon the political and economic arrangements of governments would not be a peace which could secure the unanimous, lasting and sincere support of the peoples of the world, and that the peace must therefore be founded, if it is not to fail, upon the intellectual and moral solidarity of mankind…