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Chapter 28

Environmental flows

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Introduction

The rivers, lakes and wetlands of Africa have been vibrant and biologically diverse ecosystems from before the time, more than 100 million years ago, when Africa split from South America to become a continent. Over the geological ages, freshwater ecosystems and the organisms inhabiting them evolved and shifted in response to biotic interactions and a physical landscape continually reshaped by tectonic and climatic processes (Stewart, 2001; Otero et al., 2009, 2017; Roberts et al., 2017; Masese and Dalu, 2024, Chapter 1; Dube et al., 2024, Chapter 2; O'Brien et al., 2024, Chapter 3; Mwaijengo et al., 2024, Chapter 4; Muvundja et al., 2024, Chapter 5; Dalu et al., 2024b,c, Chapters 6 and 7). *Homo sapiens* appeared on the continent approximately 0.2 million years ago, likely in an area of palaeo-wetlands in southern Africa (Chan et al., 2019). The wetlands, with their abundance of water and food sources, formed the homeland for these early communities for tens of thousands of years before humans began to migrate northward along green corridors formed during wetter periods of orbital-scale climate shifts (Timmermann and Friedrich, 2016; Tierney et al., 2017). The continent's earliest civilizations appeared around 0.005 million years ago along the Nile River in North Africa. These civilizations, notably the Egyptians, were the first to build structures that significantly altered water flows and levels (Dalton et al., 2023; Matanzima, 2024, Chapter 22). But the impacts were largely confined to North Africa for thousands of years, and it is only in the past few hundred years that water flows and levels in sub-Saharan freshwater ecosystems have been significantly altered by human interventions. The degree of alteration increased in many basins after 1950 due to rapid population growth, expansion of irrigated agriculture and a sharp increase in the rate of dam construction (Frankema, 2014; Manning, 2014; FAO, 2024).

Today, freshwater ecosystems across Africa are under pressure from multiple stressors (Fouchy et al., 2019; Mpopetsi et al., 2024, Chapter 25), and more than 20% of the continent's freshwater species are classified as threatened (Darwall et al., 2011). The degree of hydrological alteration varies spatially. Of the more than 3500 documented large- and medium-sized dams currently regulating the continent's rivers, most are concentrated in southern, western and northern Africa (Mulligan et al., 2020). But many new large dams are planned or under construction in eastern and central regions (Zarfl et al., 2015). Statistics for small dams are not available, but the total number is likely to be orders of magnitude higher. The area of wetlands on the continent has also been steadily decreasing. Current estimates are that as much as 450,000 km^2 of wetlands have been lost, amounting to 16% of the total (Hu et al., 2017). The cause is the conversion of wetlands to other land uses, mainly agriculture, to feed a growing human population (Hu et al., 2017; Fluet-Chouinard et al., 2023). The United Nations (2022) projects that the continent's population will grow by another 1 billion people by 2050, which is an 82% increase. Meeting the water needs of this growing population is certain to place additional pressure on freshwater ecosystems.

Water laws and policies across most countries in Africa recognize the need to manage water resources in a manner that also protects freshwater ecosystems (Raburu et al., 2024; Chapter 21). In many countries of eastern and southern Africa, this includes reserving water for freshwater ecosystems during allocation planning. In western Africa, the National Water Policy of Nigeria calls for all dams to be operated in a manner that "ensures provisions for downstream releases for the environment and other uses" (GoN, 2004), while the National Water Policy of Ghana states that water resources planning

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is to be made "with due recognition of environmental flow requirements" (GoG - Government of Ghana, 2007). The term "environmental flows" has become the standard international term for water managed to protect aquatic ecosystems, and the most widely recognized definition is "*environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being*" (Arthington et al., 2018).

This chapter explores some of the key aspects of environmental flow science and practice in Africa, beginning with a review of natural river flow variability across the continent and the relationships between these variations and the ecology of aquatic ecosystems. The degree and impact of flow alterations are highlighted, as well as the nature and extent of environmental flow assessment and implementation to avoid and mitigate negative impacts. The chapter concludes with a reflection on future actions.

River flow regime and its influence on freshwater ecosystems

The flow regimes of rivers across Africa significantly influence the structure and function of the continent's freshwater ecosystems. This is not surprising given that the quantity of water and its variability over time determine the three-dimensional extent of the freshwater world and its array of habitats, including riparian habitats along river margins. Ecologically-relevant aspects of a river's flow regime include the magnitude of flow (e.g., monthly means in m^3s^{-1}), the frequency with which a given flow magnitude is met or exceeded (% of time), the duration of time (e.g., number of days) that a given high or low flow magnitude persists, the timing of high or low flows during the year (e.g., Julian day of maximum or minimum flow), and the rate of change in flow levels (e.g., Δm^3s^{-1} per hour) (Richter et al., 1997).

The average magnitude of river flow depends mainly on the size and mean annual rainfall of the river's upstream catchment (Fig. 28.1). Scatter in the data reflects the influences of catchment configuration, underlying geology and human influences (Tramblay et al., 2021). The African continent is divided into 13 different Köppen–Geiger climate zones (Fig. 28.2), ranging from tropical zones near the Equator, where annual rainfall may exceed 2000 mm, to desert zones in

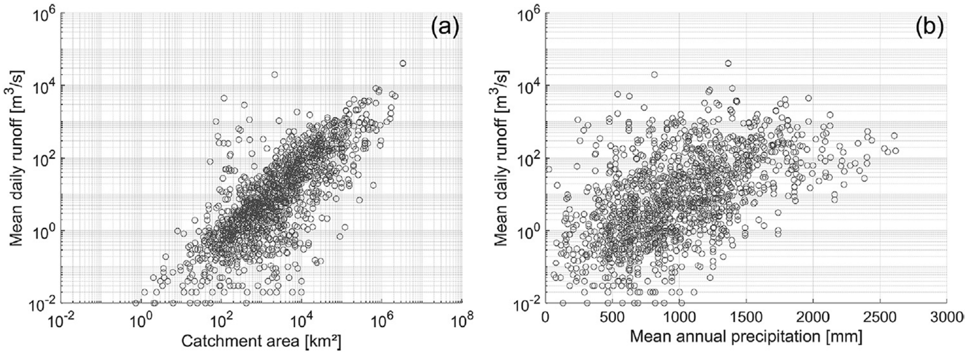

FIGURE 28.1 Relationship between mean daily river discharge and catchment area (a) and mean annual precipitation (b) for 1466 African discharge gauging stations with records extending at least 10 years. *African Database of Hydrometric Indices (Tramblay et al., 2021).*

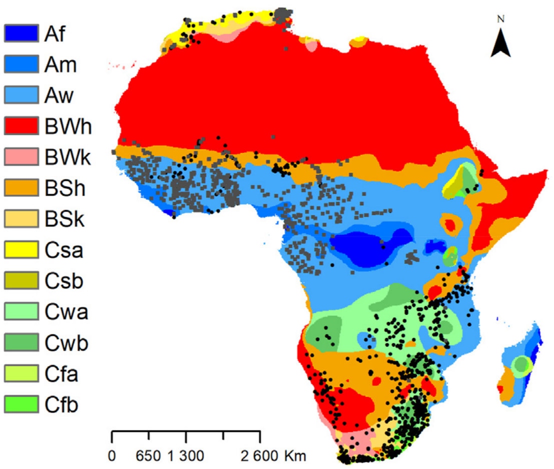

FIGURE 28.2 Map of Köppen–Geiger climate zones showing the locations of discharge stations represented in the African database of hydrometric indices. *Slightly modified from Tramblay et al. (2021).*

the north and south where annual rainfall rarely exceeds 100 mm. Between these extremes there are steppe zones of intermediate rainfall levels, as well as cooler, and usually wetter, temperate zones at higher elevations. Of the continent's 10 largest river basins, 8 have their headwaters in wetter equatorial or higher elevation zones. For many rivers, rainfall in headwaters sustains downstream flows that pass through semiarid and even arid zones, such as the middle and lower reaches of the Nile River. Generally, there is an increase in the biodiversity of rivers as they grow in size due to a greater diversity of habitats, including adjacent floodplains (Hugueny, 1990; Kouamé et al., 2008).

The seasonal variability of river flow is similarly dependent on the seasonal variability of rainfall (Sidibe et al., 2019; Ekolu et al., 2022). Excluding arid zones, where river flow occurs mainly as flash flows in response to infrequent rain events, more than 90% of semiarid to humid zones of the continent experience seasonal rainfall regimes (Fig. 28.3) (Herrmann and Mohr, 2011). Most experience a single wet season, but large areas of East Africa, and smaller areas of the south, experience two wet seasons. Additional variability within wet seasons is also possible, as some areas experience a bimodal (or even trimodal) distribution of rain during the wet season (Herrmann and Mohr, 2011). In general, as the amount of annual rainfall decreases, the degree of variation between wet and dry season flows increases (Fig. 28.4),

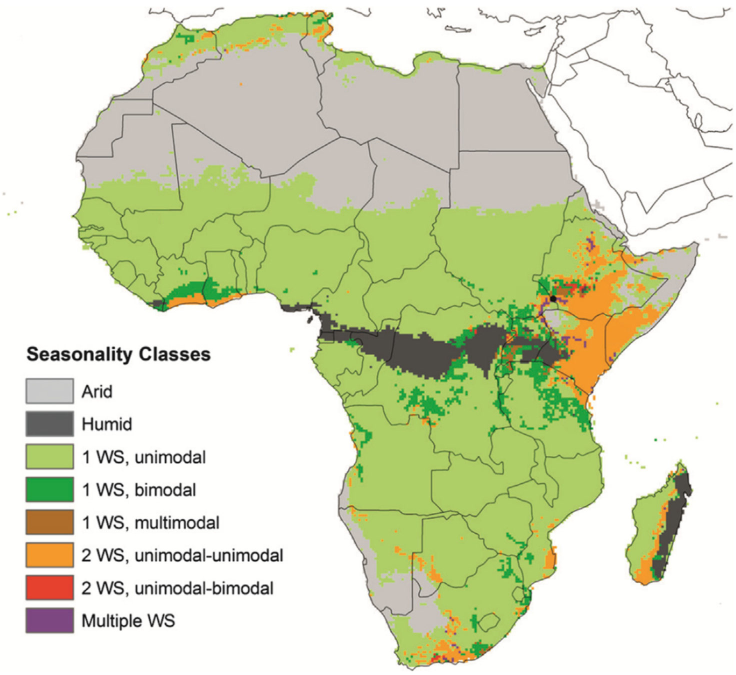

FIGURE 28.3 Map of rainfall seasonality based on the tropical rainfall measuring mission multisatellite precipitation analysis at 0.25 degrees spatial resolution. Number of wet seasons (WSs) is indicated, along with the modality of wet seasons (uni- or bi-modal). The humid class is nonseasonal. *Slightly modified from Herrmann and Mohr (2011).*

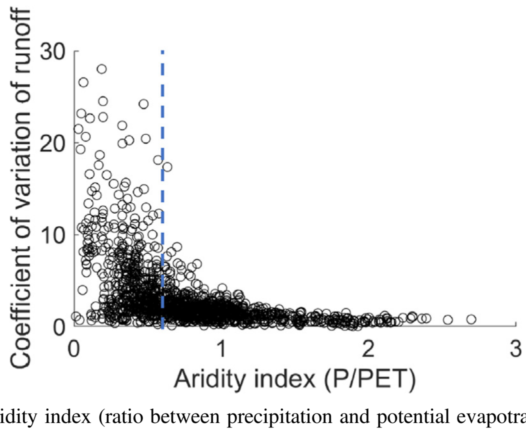

FIGURE 28.4 Relationship between the aridity index (ratio between precipitation and potential evapotranspiration) and the coefficient of variation of runoff for discharge stations represented in the African database of hydrometric indices (Tramblay et al., 2021). The dashed line marks the aridity index of 0.60, below which is indicative of arid to semiarid conditions.

resulting in more extended dry season low flows. In smaller catchments of semiarid and arid zones, many rivers cease to flow for periods, sometimes only days but potentially extending to several months of the year.

Both baseflows and flood flows are important to the ecology of river systems. Baseflows sustain the flow of perennial rivers between rainfall events and especially during dry seasons, when rivers are most vulnerable to over abstractions by water users. Floods maintain channel form, connect rivers to floodplains and cue different phases of species' life-cycles, such as migration and reproduction (Bunn and Arthington, 2002). Baseflows may be fed by either groundwater or surface runoff, but groundwater is generally the more important source for dry season baseflows. Baseflow levels vary with rainfall from month to month, with lag times ranging from approximately 1 month in western Africa to 2 months in the south (Ayers et al., 2023). Annual high flood events also vary regionally, especially with respect to the mechanisms generating them. Annual flood peaks in semiarid and arid zones are mostly generated by longer rainfall events (rainfall above the 90th percentile of rainfall summed over 7 days), while peak annual floods in humid zones are mostly generated by above average rainfall events falling on saturated soils (Tramblay et al., 2022). Floods of longer duration, and inundating larger floodplains, occur in the middle to lower reaches of the larger river basins.

The organisms inhabiting Africa's freshwater systems are adapted to these natural hydrological variations, as well as a number of other aspects of the annual and interannual hydrograph that have not yet been analyzed. For example, during flood flows, many fish species migrate onto floodplains to access seasonal habitats for spawning and feeding. The importance of this access is such that annual fish yields rise and fall in relation to the extent of flooding (Welcomme, 1979). During dry season baseflows, fish species will spatially segregate themselves into different refuge areas based on flow depths and velocities (Pouilly, 1993). Dry season refuges are important for fish survival because available habitats and food resources are significantly reduced. Some species are also adapted to survive natural periods of dryness. The West African lungfish (*Protopterus annectens*) and the Marbled lungfish (*Protopterus aethiopicus*) are obligate airbreathers able to survive periods of total desiccation by burrowing into soft mud and secreting mucus that encases their bodies in a cocoon until flow returns to the river (Beadle, 1981). Similarly, the air-breathing Catfish (*Clarias* spp., Clarriidae) can survive in sand or mud for periods of no-flow in rivers as long as the substrate remains moist (Bruton, 1979a). Many species take advantage of population booms of prey species during flooding periods to build the body reserves of energy to enable them to survive the dry season when food resources are limited. For example, *Clarias gariepinus* and *Clarias anguillaris* are large-bodied, enabling them to survive prolonged droughts (Bruton, 1979a,b). Notably, as river flows subside and a series of pools remain along savanna rivers, large numbers of Clariid catfishes are often the last and only aquatic survivors (Fig. 28.5). Some species of African cyprinids and cichlids can also survive in remnant pools for long periods of time despite high temperatures and low dissolved oxygen levels, and this has enabled them to be widespread and abundant in severe environments. The annual killifish *Nothobranchius* is considered to be one of the extremophiles in African temporary systems, where it employs embryonic diapause as one of its survival mechanisms (Watters, 2009). Killifishes also utilize r-selected strategies (Colinvaux, 1986) to survive extreme desiccation, including small adult size, rapid growth and maturity, and daily spawning with frequent egg fertilization and deposition into the substrate throughout the rainy season when water is available (Watters, 2009).

FIGURE 28.5 Large-bodied catfish *Clarias gariepinus* captured in a remnant pool along the seasonal Talek river, Mara river basin, Kenya. Many individuals of the species remain in pools during prolonged dry periods. *Picture by Evans Ole Keshe—with permission.*

Macroinvertebrates in seasonal streams and rivers have also evolved several strategies to cope with hydrologically variable flows (Masese et al., 2024a, Chapter 17). These range from changes in the timing of emergence and egg hatching to more extreme differences involving the production of additional generations within a year, given differing environmental conditions (Dallas, 2008, 2012; Chakona et al., 2008). Many large-bodied macroinvertebrate taxa such as the predatory bugs (Hemiptera), beetles (Coleoptera), and damselflies and dragonflies (Odonata) are able to survive the drying of pools by flying away to colonize permanent ones. Hence, these groups numerically dominate and persist in temporary streams and rivers in African savanna landscapes (Stewart and Samways, 1998; Masese et al., 2021). Other macroinvertebrate taxa, such as *Afrobaetodes* (Ephemeroptera), employ r-selected strategies such as high abundances (a proxy for fecundity), smaller body size and short life cycles that are completed while flow persists (Chakona et al., 2008).

The examples above demonstrate some of the extraordinary strategies African freshwater species employ to survive the natural periods of low flow or even no-flow in seasonal river flow regimes, but these strategies are adapted for natural dry conditions and do not necessarily enable species to survive under unnatural and usually harsher low flow and dry conditions created by overabstraction of river water. There is still much to be learned about the full complexity of flow-ecology relationships across African freshwater ecoregions, which number 90 in total (Thieme et al., 2005). Each freshwater ecoregion is composed of distinct assemblages of freshwater communities and species. They differ in biological distinctiveness, which depends on richness of freshwater species, level of endemism, as well as the rarity of species and habitats, but all hold special values for the human communities bordering them. And all are now facing some level of threat from the pressures imposed by human development.

Alteration of African river flow regimes and ecological responses

African freshwater systems are under pressure from water quality contamination, resource overexploitation, direct destruction of habitats, fragmentation, introductions of alien species, and alteration of natural water flows and levels (Fouchy et al., 2019; Tickner et al., 2020; Mpopetsi et al., 2024, Chapter 25). River flow regimes are directly altered by river water withdrawals, regulation of flows by dams and reservoirs, and training works disconnecting river channels from floodplains (e.g., dikes and levees). In most cases, these interventions affect only the river system where they occur, but adjacent river systems may also be impacted when there are interbasin transfers of water (Snaddon et al., 1998). Flow regimes may also be indirectly altered by changes to land use and land cover, overabstraction of groundwater, and anthropogenic climate change.

It is safe to say that some amount of water is abstracted from nearly every African river for human use. This abstraction becomes ecologically significant when it substantially alters the physicochemical environment and reduces the abundance, diversity and specific characteristics of habitats used by aquatic and riparian species (Table 28.1). Because water quantity and quality are closely linked, reductions in flow levels can affect concentrations of substances, water temperature and water states (Nilsson and Renöfält, 2008). Supra-reduced flow is susceptible to thermal pollution, increased concentrations of solutes, salinization and a reduction in dissolved oxygen concentrations (Strauch, 2011, 2013). The shrinkage of habitats increases inter- and intraspecific competition. Connections to terrestrial systems may also be changed in ways that alter terrestrial inputs of organic matter, which affects riverine food webs (Masese et al., 2024b; Chapter 20). Ecological responses to these alterations include changes in the abundance and diversity of riverine and riparian organisms (Bunn and Arthington, 2002; Poff and Zimmerman, 2010).

Impacts may occur in any river system and at any time of year, but they are especially prevalent during the dry season in rivers flowing through areas of water stress, where human demands are large relative to the availability of water (Falkenmark, 1992). Well documented examples include the Naro Moru and Great Ruaha rivers in eastern Africa and the Limpopo River in southern Africa. Water abstracted in 2002 from the Naro Moru River in Kenya amounted to approximately 30% of the annual discharge, and during the dry season abstractions amounted to 80−100% of low flows (Aeschbacher et al., 2005). Low flows in the Great Ruaha River of Tanzania have steadily declined over past decades as water abstractions for irrigation grew, eventually consuming all river water during periods of the dry season (Kashaigili, 2008). The average number of no-flow days during the dry season increased from zero prior to 1973, to 10 by 1985, and to 60 by 2004. Drying of the river caused serious ecological consequences to riverine species as well as dependent terrestrial species (Kashaigili et al., 2005). In the northern Limpopo Basin of Zimbabwe, increasing withdrawals exacerbate an already declining trend in river flows due to reduced rainfall (Love et al., 2010). More broadly, reductions in river and lake levels have been reported in 60 case studies across eastern and southern Africa, with water withdrawals cited as having the strongest influence (Schäfer et al., 2016). Similar cases no doubt exist in water stressed areas of central, western and northern Africa.

TABLE 28.1 Examples of documented impacts of flow alteration on ecological conditions in African streams and rivers.

Flow variable	Ecosystem property affected	Physical and ecological effects	References
Increased flow (flood magnitude and duration)	Physicochemical parameters	- Increased erosion and turbidity (sediments) - Increased organic matter input - Increased blackwater backflow into the river from the floodplain	Guzha et al. (2018)
	Physical habitat	- Increased flood-plain connectivity and duration of flooding - Instream habitat loss/restructuring - Alteration of river geomorphology - Increased importance of allochthonous energy sources for communities	Pettit et al. (2005) and Mumba and Thompson (2005)
	Assemblage characteristics	- Life cycle disruption - Reduced species richness - Altered assemblages and relative abundance of taxa - Loss of sensitive fish species - Reduced primary production - Reduction of elements by downstream transport, retention or emission - Prolonged anoxia in riparian soils caused by flooding leads to plant deaths - Invasion by exotic species of fish and plants	Pettit et al. (2005) and Mumba and Thompson (2005)
Reduced flow	Physicochemical parameters	- Increase temperature- thermal pollution - Decrease in dissolved oxygen (DO) concentration - Increase in biological oxygen demand (BOD) - Increased concentration of solutes/ salinization of water - Increased concentration of chemicals and pathogens - Increased concentration of nutrients - Acidification and mobilization of toxic metals	Shivoga (2001) and Strauch (2011, 2013)
	Physical habitat	- Loss of longitudinal connectivity - Reduced floodplain connectivity and flooding extent - Reduction in habitat availability and loss of refugia - Hydraulic biotope isolation and dominance by low-velocity shallow biotopes - Armouring of the river bed in gravel-bed rivers when flows lose competence for transporting sediment - Planform adjustments, which alter sinuosity and bed stabilization, - Formation of islands, benches and bars	Chakona et al. (2008), Tharme (2010), and Mulatu et al. (2022)

TABLE 28.1 Examples of documented impacts of flow alteration on ecological conditions in African streams and rivers.—cont'd

Flow variable	Ecosystem property affected	Physical and ecological effects	References
		- Riparian vegetation encroachment into the channel - Changes in species composition through terrestrialization of the riparian community - Increase in herbaceous cover in the riparian understory - Increased reliance on autochthonous energy sources by communities	
	Assemblage characteristics	- Creates favorable conditions for phytoplankton growth - cyanobacterial in particular and microbial contamination - Dampened biofilm production in lowland rivers - Altered biofilm composition - Dominance of macroinvertebrate taxa with r-selected strategies - Decreases in richness of invertebrate taxa - Reduced fish production - Low diversity of fish fauna - Low breeding success for native fish species - Low abundance ratios of native to alien species	Chakona et al. (2008), Yillia et al. (2008), Shivoga (2001), and Mulatu et al. (2022)

The construction of dams and reservoirs enables a wide range of potential river flow alteration, which generally increases as the proportion of reservoir storage to annual river discharge increases (Grill et al., 2019). The FAO AQUASTAT database contains information on approximately 2000 African dams across 45 countries (FAO, 2024). The largest number of dams are in the South (e.g., 552 in South Africa and 196 in Zimbabwe), West (146 in Burkina Faso and 110 in Nigeria), and North (110 in Morocco). The largest proportion (61%) are for the purposes of consumptive water use for irrigation (37%) and water supply (24%). Just over 20% of dams are for the purpose of hydropower generation, and smaller numbers are for flood control (4%) and livestock watering (7%). The GOODD database of dams reports an even larger number of dams, in excess of 3500, including medium-sized dams (Fig. 28.6) (Mulligan et al., 2020). The fragmentation of rivers caused by dams, and the degree of regulation they can potentially exert, are the two largest pressures influencing the free-flowing nature of African rivers. Of the continent's 58 rivers longer than 1000 km in length, less than half (47%) are still classified as free flowing (Grill et al., 2019).

Dams with large reservoirs can cause significant alteration of flow regimes in even the largest rivers. The Aswan High Dam and its reservoir have the potential to store 150% of the mean annual discharge of the Nile River. This enables water managers to completely control the flow regime of the Nile. Operation of the dam has altered the natural flood pulse and reallocated flood flows for irrigated agriculture throughout the year. This has led to a 60% reduction of average annual flow of the river through Egypt, and much more than this during dry and drought periods (Sharaf El Din, 1977). The new Grand Ethiopian Renaissance Dam on the Blue Nile River also has the capacity to store approximately 150% of the river's annual flow, empowering water managers to completely control the Blue Nile's flow regime (Wheeler et al., 2020). Further upstream in the Lake Tana Basin, at the source of the Blue Nile, smaller dams such as the Ribb Dam impose similar but more localized impacts. The Ribb dam will divert river water flowing to Lake Tana and instead supply local irrigation schemes. Diversion of river flows will reduce flooding of the Fogera Plain, which is an important fish breeding area for lake fish migrating through the lower reaches of the river to access the plain (Mulatu et al., 2022).

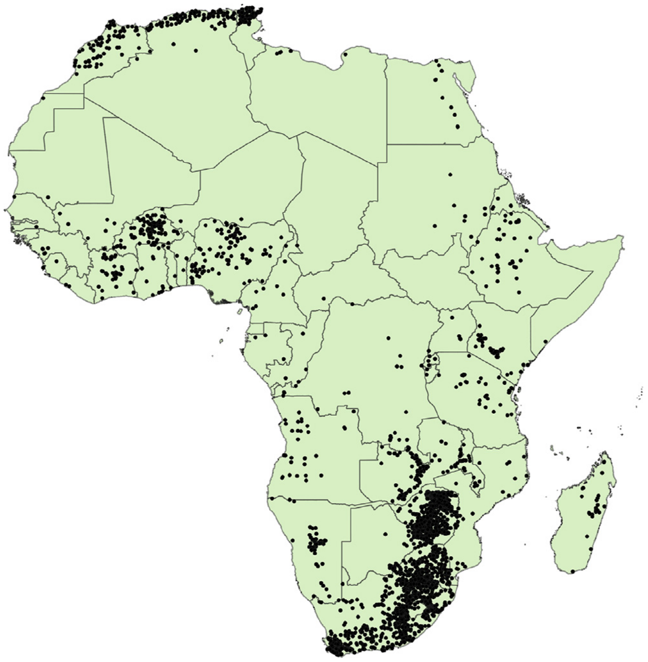

FIGURE 28.6 Map of 3558 large and medium sized African dams contained in the global georeferenced database of dams (Mulligan et al., 2020).

Direct alteration of flow regimes caused by dam operations is occurring across the continent, and the effect is not only to reduce river flows and the inundation of floodplains. If reservoirs are large enough, water stored during high flows can be released during the natural period of low flows, causing unnaturally high low-flows. A case in point is the Kafue River in southern Zambia, which has been significantly impacted by flow alteration caused by Itezhi-tezhi and Kafue Gorge dams, which are 270 km apart. The dams are operated jointly to maximize electricity generation at the downstream Kafue Gorge dam. Wet season flows of the Kafue River are stored in the upstream Itezhi-tezhi dam and released downstream to the Kafue Gorge hydropower plant during the dry season. Between the dams lies Kafue Flats, a 6500 km^2 floodplain system of high ecological value (Ellenbroek, 2012). For the past 50 years, the maximum extent of flooding on the plain has been reduced by the storage of flood flows in Itezhi-tezhi reservoir, but the duration of flooding on the remaining floodplain has been extended by 3 months due to the higher dry season flow releases. In some parts of the plain the flooding has become permanent, leading to the invasion of alien woody plants that are displacing native grasses fed upon by floodplain wildlife (Mumba and Thompson, 2005).

Unnaturally high low-flows and other changes to the physicochemical environment and natural flow regime may also occur in rivers receiving water from interbasin transfers. The Orange River Project in South Africa began transferring water from the Orange River to the Great Fish River in 1976 to supply users in the Eastern Cape Province. In so doing, the mean annual runoff of the Great Fish River increased between 500% and 800% and the river's regime changed from seasonal to perennial (O'Keeffe and De Moor, 1988). This resulted in substantial changes in the macroinvertebrate community, including an increase in the dominance of the blackfly *Simulium chutteri*, which has become a serious pest spreading disease among livestock in the region (O'Keeffe and De Moor, 1988; Rivers-Moore et al., 2007). The unnatural connection created between the river systems also transferred new species of fish to the Great Fish River (Cambray and Jubb, 1977).

Indirect alterations of river flow regimes may be caused by abstraction of groundwater from aquifers contributing to river baseflows and changes in land use and land cover (LULC) that alter rates of evapotranspiration and soil properties influencing the partitioning of rainfall between recharge to aquifers and runoff to streams and rivers (Kiersch, 2000). Overpumping of groundwater is estimated to have already caused ecologically unsustainable reductions in the baseflows of rivers in arid and semiarid zones across the continent, and the extent of this impact is projected to grow (de Graaf et al., 2019). Studies investigating the effects of agricultural expansion, deforestation and urbanization in southern and eastern Africa overwhelmingly report decreases in dry season flows and increased floods (Schäfer et al., 2016). Such changes occur when the infiltration capacity of soils is reduced, leading to less groundwater recharge and increased surface runoff. Significant increases in river flow and floods due to LULC change have also been reported in the Sahel region and other parts of western Africa, but these increases appear to occur across all seasons and to be sufficiently high to also increase recharge of connected aquifers (Descroix et al., 2018). Flow levels in Sahelian rivers increased even during a 20-year period of drought from 1970 to 1990. This seemingly illogical response is known as the "Sahelian hydrological paradox" (Descroix et al., 2013). In the absence of other pressures, the singular impact of LULC on river flow regimes is generally modest in comparison with those of dams and significant water withdrawals (Schäfer et al., 2016).

Finally, climate change is a source of anthropogenic alteration of African river flow regimes, although the impacts are not so clear in comparison with other sources. No clear or consistent signals of anthropogenic climate change appear in rainfall and runoff records of Sub-Saharan Africa during the 20th Century. West Africa and North Africa experienced declines in decadal rainfall, especially after the 1970s, while other regions experienced high variability but no obvious trends (Conway et al., 2009; Mahe et al., 2013; Dube et al., 2024, Chapter 2). Future projections of river flows in a changing climate are uncertain but have been simulated using a hydrological model driven by the outputs of five different earth system models (Aich et al., 2014). The results are most consistent for East Africa, projecting increasing annual mean discharge, high flows and low flows for the Upper Blue Nile River. Projections for western and southern Africa are more variable, with some models showing increasing trends while others show decreasing trends. Strong responses from individual models suggest that the regions' river will be sensitive to changing climate, whichever direction it goes. Humid areas of central Africa, by comparison, appear to be less sensitive to climate change and unlikely to experience large impacts (Aich et al., 2014).

Whatever the eventual impacts of climate change, direct alteration of river flow regimes by water withdrawals and operation of dams will continue to exert the greatest impact on flow and freshwater ecosystems. This means the ability to manage flows to sustain freshwater ecosystems will remain in the hands of African nations and water and environmental authorities charged with the task of implementing environmental flows.

Implementation of environmental flows

The implementation of environmental flows should be viewed as a measure (or instrument) to achieve specific objectives in water resources management. The main objective is generally to protect aquatic ecosystems, but social objectives may also be included, such as instream flows for recreational or spiritual purposes. Environmental flow implementation should be part of an adaptive management cycle enabled by multiple factors (Arthington et al., 2023). Important factors include proper legal recognition, embedding in water resource management planning, assessment of environmental flow requirements using appropriate methods, implementation of measures ensuring that environmental flows are maintained in the river, and follow-up monitoring to verify both compliance and that environmental objectives are met. Ensuring that these factors are in place also requires that there be sufficient technical capacity, stakeholder engagement, and financial and human resources.

Legal recognition of environmental flows and embedding in water resources management

The environmental consequences of water resource development became a global issue following the 1992 International Conference on Water and the Environment held in Dublin, Ireland. The conference produced a statement of principles that was submitted later that same year to the United Nations Conference on Environment and Development (the Earth Summit) held in Rio de Janeiro, Brazil. The first principle stated that "Fresh water is a finite and vulnerable resource, essential to sustain life, development, and the environment" (ICWE, 1992). The Dublin Principles were later incorporated in the framework of Integrated Water Resources Management (IWRM), which is defined as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000). Today, IWRM features in Target 6.5 of the United Nations Sustainable Development Goals (SDGs), calling on all countries to "by 2030 implement integrated water resources management at all levels, including through transboundary cooperation as appropriate" (United Nations, 2024). Environmental flows are recognized as one of the ecosystem management instruments of IWRM. The implementation of IWRM across Africa is monitored by the African Ministers' Council on Water, which reported in 2018 that the capacity for the effective implementation of IWRM is still inadequate for most (71%) African countries, and capacity is even lower with respect to the cover of ecosystem management instruments, with 87% of countries reporting inadequate coverage (AMCOW, 2018).

Environmental water needs are therefore not yet universally protected in laws and regulations across Africa. They are, however, explicitly recognized in some countries of southern, eastern and western Africa. South Africa is most notable for including environmental water as part of the Reserve in its 1998 Water Act, defining the ecological component of the Reserve as the quantity and quality of water "*to protect aquatic ecosystems in order to secure ecologically sustainable*

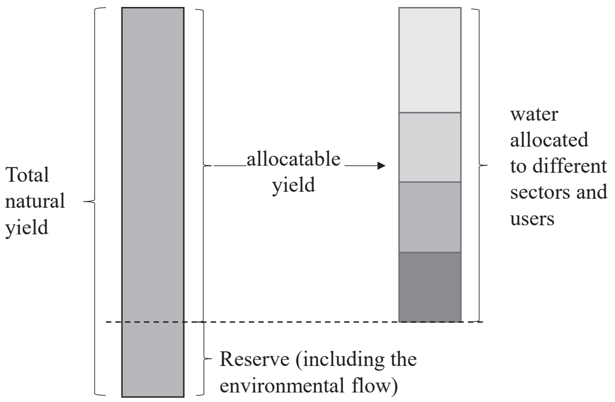

FIGURE 28.7 Illustration of how environmental flows in the form of a reserve are removed from the total natural yield of a river prior to allocating water to other users. *Modeled after a similar figure in Speed et al. (2013).*

development and use of the relevant water resource" (RSA, 1998). Other countries followed with similar legislation, often adopting the same definition as South Africa. Zimbabwe and Kenya were the first in 2002, followed by Lesotho in 2008, Tanzania in 2009, Zambia in 2011, and Malawi and Namibia in 2013 (Brown et al., 2020).

Water reserved for aquatic ecosystems, together with water reserved to meet basic human needs, are given highest priority in water allocation. In fact, freshwater ecosystems have a right to water under the law, just as humans have a right to water to meet their basic needs. All other water uses must be authorized. When developing water allocation plans, water authorities first quantify the total natural yield of the water body and then subtract the Reserve from the total. The remaining water is the allocatable yield that may be authorized for use by other water users (Fig. 28.7).

The amount of water reserved for freshwater ecosystems depends on the management class ascribed to the water body, with more water reserved for higher classes. South Africa recognizes four management classes (Table 28.2), three of which may be used as objectives in water resource planning. Class I water bodies are to be maintained in near natural conditions, with minimal human impacts on the natural flow regime. Classes II and III may be increasingly impacted, but still require that ecological sustainability is maintained. Class IV refers to water bodies that have been unacceptably degraded. This class may be designated as the present condition of the water body, but higher classes must be targeted in water resources planning, with the goal of ecologically rehabilitating the water body (Department of Water Affairs, 2011). For each water body, specific resource quality objectives are set and should be measured to verify that the desired level of aquatic ecosystem protection is being achieved. Differing levels of ecological objectives are expressed in Ecological Classes ranging from A to F (Table 28.3) (Kleynhans and Louw, 2007), with Class A designating rivers that are unmodified and thus natural, and subsequent classes designating increasing levels of modification and ecological impairment. Classes E and F may be used to designate the present ecological class of a water body, but they are not considered sustainable and may not be set as targets for management. Few countries protecting environmental flows in the form of a reserve have

TABLE 28.2 Management classes for water resources within the South Africa Water Resource Classification System.

Management class	Description
Class I	Natural—minimal impact of humans, natural water quality and safe for most uses, of high significance. Other classes are defined in terms of degree of deviation from the natural class.
Class II	Moderately used/impacted—slightly altered from natural due to human activity.
Class III	Heavily used/impacted—significantly changed from natural due to human activity but nevertheless ecologically sustainable.
Class IV	Unacceptably degraded resource—due to overexploitation. Management class is set higher in order to rehabilitate.

Department of Water Affairs (2011).

TABLE 28.3 Generic Ecological Class used to indicate the present ecological status of a water resource. Classes A–D may also be set as targets for management objectives.

Ecological class	Description
A	Unmodified, natural.
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.
C	Moderately modified. Loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	Critically/Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

Kleynhans and Louw (2007).

developed classification systems and resource quality objectives to the extent of South Africa, but most follow this model to some degree (Brown et al., 2020).

The requirement to protect water for environmental purposes is also mentioned in the water policies of Nigeria (GoN, 2004) and Ghana (GoG - Government of Ghana, 2007), and there may be other countries with policies and laws explicitly protecting water for the environment, but these are unknown to the authors. It is almost certain, however, that most African countries include reference to environmental protections in their national laws, even if environmental water and flows are not mentioned explicitly. These policies and laws provide the basic enabling conditions for the protection of environmental flows in water resources development and management. Requirements for protecting environmental flows may also come from authorities other than governments. For example, the World Bank may require environmental flows to be protected as a condition of receiving financing for water development projects. These protections are embedded in the bank's Environmental and Social Safeguard Policies—Policy (World Bank, 2024).

Assessment of environmental flows requirements

Progress in the assessment of environmental flow requirements across Africa is aligned with the progress in ascribing legal protections. South Africa has made by far the greatest progress. Since the 1990s, South Africa has assessed environmental flow requirements at more than 300 sites along the country's rivers (Eriyagama et al., 2024). This was accomplished with strong government support and financing by the county's Water Research Commission (Brown et al., 2020). In the process, South African scientists developed holistic approaches to environmental flow assessment that are well suited for African conditions and have also been applied in rivers beyond Africa (Acreman and Ferguson, 2010). These include the prescriptive Building Block Methodology (BBM) (King et al., 2000a), which results in specific water requirements for different components (building blocks) of the environmental flow regime, and the scenario-based DRIFT method (Brown et al., 2013), which enables the user to evaluate the consequences of different flow scenarios on the condition of the river ecosystem and the impacts on human users. Detailed studies at holistic study sites were also used to develop and calibrate a Desktop Model (Hughes and Hannart, 2003) that is routinely used by water authorities in the review of water use permit requests. A smaller number of assessments have been completed in other countries with legal protections for environmental flows, including Kenya, Lesotho, Malawi, Namibia, Tanzania and Zimbabwe. In these countries, however, a significant proportion of the funding and motivation came from international donors, hydropower developers and development banks (Brown et al., 2020). A number of assessments have also been reported from countries without strong legal support for environmental flows, including Angola, Benin, Botswana, Eswatini, Mozambique, Senegal, South Sudan, Sudan and Tunisia (Brown et al., 2020; Eriyagama et al., 2024).

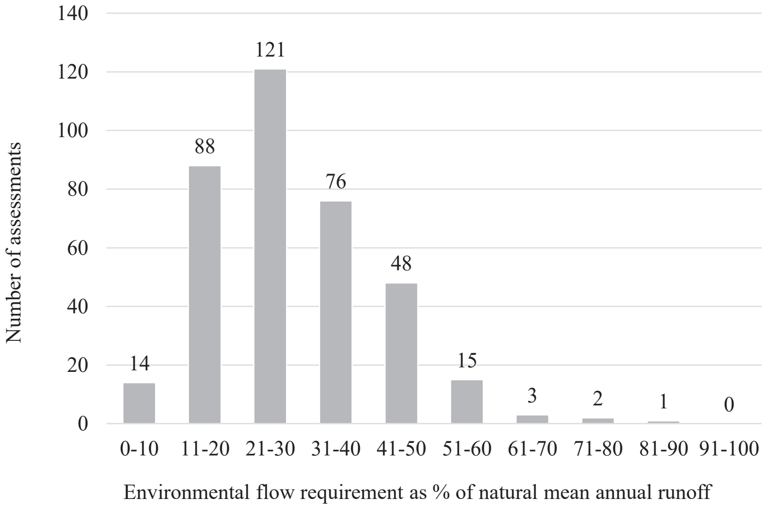

FIGURE 28.8 Distribution of environmental flow requirements reported as a proportion of the natural mean annual flow at the assessment site from 368 assessments. *Source of data is Eriyagama et al. (2024).*

As part of a comparison of locally determined environmental flow requirements to the results of a global environmental flows information system, the results of 368 different environmental flow assessments in Africa were compiled (Eriyagama et al., 2024). Environmental flow requirements were reported as a proportion of the natural mean annual flow at the assessment site. The average environmental flow requirement for all 368 sites was 29% of the natural mean annual flow. The minimum value was 1% and the maximum value was 86% (Eriyagama et al., 2024). The distribution of values is shown in Fig. 28.8. The vast majority (94%) of assessments used in the comparison came from South Africa, but limited data were also available for Lesotho, Senegal, South Sudan, Sudan, Tanzania, Tunisia, and Zambia.

The results of environmental flow assessments should be expressed in units appropriate for their application in water resource planning and operation. Water allocation planning is routinely done on an annual time scale, using volumetric units of millions of cubic meters (MCM). Operational decisions, however, are made on seasonal, monthly or even weekly time scales. Assessments applying best practice methodologies such as BBM and DRIFT will generally recommend both low (base) flows as well as high flows on a monthly basis. Separate environmental flow recommendations may also be made for years with normal rainfall and drought years. Finally, recommendations may include scenarios for different levels of ecological condition to be supported. For example, Table 28.4 presents annual environmental flow (or ecological reserve) recommendations for a site assessed along the upper Sabie River in South Africa (DWAF, 2010). Recommendations are presented for two types of low flows, as well as high flows. Low flows (in MCM) are presented for both "maintenance" years, when sufficient water is available to meet most environmental objectives, and "drought" years, when insufficient water is available and environmental flow objectives are to ensure the short-term survival of riverine species.

TABLE 28.4 Example of results of an environmental flow assessment establishing annual volume requirements (million m^3—MCM) for low and high flows designed to achieve different ecological class. Results are for the upper Sabie River, South Africa. Natural mean annual runoff (nMAR) and present mean annual runoff (pMAR) included for reference. Ecological categories correspond to those in Table ×.2 for present (PES), recommended (REC) and alternative (AEC) ecological category.

nMAR	pMAR	% pMAR of nMAR	Ecological class	Maintenance low flows		Drought low flows		High flows	
MCM	MCM	MCM		MCM	%nMAR	MCM	%nMAR	MCM	%nMAR
140.18	109	78%	B/C PES	46.54	33.2	16.96	12.1	7.43	5.3
			B REC	61.82	44.1	16.96	12.1	8.55	6.1
			C/D AEC	29.02	20.7	16.96	12.1	6.31	4.5

DWAF (2010).

Recommendations for high flows may also differ between maintenance and drought years. For each flow type, recommendations are made for three ecological classes (Table 28.4): (1) the present ecological state of the river (Class B/C), (2) a recommended state (Class B), which in this case is slightly higher than the present state, and (3) an alternative state (Class C/D), which in this case is lower than the present state but still legally acceptable. To maintain the present ecological class (B/C) at the site during maintenance years, an ecological reserve of 46.54 MCM of water is recommended, which is equivalent to 33.2% of the natural mean annual runoff. During drought years, however, an ecological reserve of just 16.96 MCM, or 12.1% of the natural mean annual runoff is recommended. The recommended ecological reserve volumes increase to achieve the recommended ecological class (B) and decrease if the alterative ecological class (C/D) becomes the objective of managers (DWAF, 2010).

Another, more detailed, example of environmental flow (or ecological reserve) recommendations comes from the Kilombero River of Tanzania (CDM Smith, 2016). Table 28.5 presents the recommendations for maintenance and drought years at the Ifwema site. The present and recommended ecological class at this site is A/B, based on ecological classes equivalent to those in South Africa (Table 28.3). This indicates the river's ecological condition is largely natural, and the recommended ecological reserve is therefore 82.3% of the natural mean annual flow, and between 77% and 94% of the mean monthly flows. The percentage of mean annual flow is reduced in the drought year recommendation, but the monthly recommendations are a higher proportion (from 77% to 98%) of the natural monthly flows during a drought year. This example also provides more detail about the recommended high flows, indicating the month in which each should occur, the magnitude, the duration in days, and the recurrence interval, which may be annually or only once in 2 years as indicated for the high flow for April in a maintenance year (Table 28.5). This monthly, and even daily in the case of high flows, level of detail in environmental flow recommendations is needed to properly protect freshwater ecosystems. The next implementation step is to incorporate these values into measures designed to enact them.

Management measures to maintain environmental flows in rivers

Management measures to ensure that environmental flows are maintained in rivers may be broadly grouped into those restricting abstractions of river water by users and those requiring the release of water downstream of dams. Restrictions are made possible by establishing thresholds related to river flow levels. This approach is taken by Kenya and Tanzania and can be applied at basin scales. In addition to the reserve flow, Kenya's Water Resource Regulations (GoK, 2021) define "flood flow" as the flow met or exceeded 80% of the time in a river and "normal flow" as a flow less than flood flow. Water users in Kenya must request a water use permit, and rules applying to permits vary depending on the intended water use. For example, users holding permits to abstract water for irrigation purposes are allowed to abstract water only when river flows are greater than the flood flow threshold. When river flow levels drop below this threshold, irrigators must stop abstracting river water and turn to water previously stored on their farms for irrigation. Irrigators are expected to make provision for storing a volume of water equivalent to 90 days of irrigation (GoK, 2021). Similarly, when river flows drop below the reserve threshold, all abstractions must stop, except for those necessary to meet the basic needs of domestic users. This approach has been applied in the water allocation plan for the Naivasha Basin, with added restrictions related to thresholds in groundwater and lake levels (WRMA, 2010).

The Water Supply Regulations of Tanzania do not specify restrictions at the same level of detail as those in Kenya, but the government is empowered to restrict the nondomestic uses of water when conditions warrant (GoT, 2019), and the Water Allocation Planning Guidelines for Tanzania (GoT, 2020) establish similar flood and normal flow thresholds to those in Kenya. No evidence was found of specific actions enforcing these measures in Kenya or Tanzania, but the measures exist. The extent to which this measure protecting environmental flows is explicitly provided in other African countries is unknown to the authors, but most countries require that water users apply for permits, and most permits will include terms for governmental restrictions on abstractions. When recognizing the importance of water use permit systems in protecting environmental flows, it is also important to recognize other inherent difficulties with the system, including inequities persisting from colonial times and challenges in the logistics of their implementation (van Koppen and Schreiner, 2018).

Where river flows are regulated by dams, releases of environmental flows must be incorporated into the operational rules of the dam, which determine the amount of water released downstream at any time. Reservoirs are constructed for single or multiple objectives (purposes), and they are designed and operated in ways that maximize the achievement of single objectives or optimize the achievement of multiple objectives. Ideally, maintaining the health of downstream ecosystems will be included as one of the dam's objectives from the beginning and thus built into its design and operation. The assessment of environmental flow requirements is generally done as part of the environmental impact assessment prior to dam construction. For example, the Sector Guidelines for Environmental Impact Assessment for Hydro-Power Development Projects in Rwanda specify the assessment and release of environmental flows as a measure to mitigate

TABLE 28.5 Example of results of comprehensive environmental flow requirements for each month of a normal (maintenance) and dry (drought) year. Results are for the Kilombero River at Ifwema, Tanzania.

Year	Index	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Maintenance	Average	94.9	94.7	148.1	223.4	264.7	321.0	406.2	326.9	199.8	166.7	144.6	110.0	208.4
	Monthly low flows													
	Magnitude (m3/s)	73.0	89.4	129.7	186.5	217.8	260.2	308.0	264.7	168.7	143.7	127.1	101.0	172.5
	% mean annual flow	3.0%	3.5%	5.3%	7.6%	8.0%	10.6%	12.1%	10.7%	6.6%	5.8%	5.2%	4.0%	82.4%
	Flood pulses													
	Magnitude (m3/s)		150.0	109.5			525.0	861.0						
	Duration (days)		3.0	3.0			7.0	7.0						
	% mean annual flow		0.6%	0.4%			4.8%	7.9%						13.7%
	Return period (years)		<year	<year				2.0						
	Total % mean annual flow													96.1%
Drought	Average	79.3	76.7	120.3	178.5	210.9	276.9	327.2	245.7	160.7	134.2	106.9	91.1	167.4
	Monthly low flows													
	Magnitude (m3/s)	62.0	75.5	115.6	169.1	198.9	259.6	290.0	230.9	152.8	128.4	103.3	88.8	156.2
	% mean annual flow	2.5%	3.0%	4.7%	6.9%	7.3%	10.5%	11.4%	9.4%	6.0%	5.2%	4.2%	3.5%	74.6%
	Flood pulses													
	Magnitude (m3/s)				80.0			400.0						
	Duration (days)				3.0			7.0						
	% mean annual flow				0.3%			3.7%						4.0%
	Return period (years)				<year			1.5						
	Total % mean annual flow													78.6%

CDM Smith (2016).

the impacts of flow alteration by dams. In the assessment of environmental flows, the guidelines indicate the need to assess not only the downstream flow requirements of freshwater ecosystems, but also the downstream water needs of terrestrial fauna and the livelihoods of people (GoR, 2008).

Unfortunately, requirements for the assessment and release of environmental flows were not in place at the time many of Africa's dams were constructed, so re-operation of many of those dams is required to begin to provide sufficient downstream flows to protect riverine ecosystems. Re-operation is a challenging task worldwide, as requiring environmental flow releases from dams already operated to maximize other objectives will inevitably result in some reduction in the achievement of those other objectives (e.g., hydropower generation). Such trade-offs foment resistance among stakeholders, which impedes the re-operation process. Additional factors impeding re-operation include a lack of enabling policy and legislation and physical constraints related to the design of the dam and associated infrastructure (Owusu et al., 2022).

Despite the challenges, there have been successful cases of dam re-operation to improve environmental flow releases. Early examples are the re-operation of Diama Dam, near the mouth of the Senegal River (Duvail and Hamerlynck, 2003) and re-operation of the Wolwedans Dam near the mouth of the Great Brak River in South Africa (Slinger et al., 2005). Diama dam was constructed in 1986 for the purposes of providing irrigation water and facilitating navigation on the river. The operation of the dam and associated infrastructure significantly reduced the annual downstream flood, which previously inundated a broad floodplain in the estuary. This led to desiccation of the floodplain, loss of native grasses and sedges grazed by wildlife and livestock, declines in estuary fish productivity, and decreasing numbers of water birds. Local communities dependent on these resources experienced an economic collapse as a result (Hamerlynck et al., 1999). In response, a restoration effort began in 1994 that included re-operating Diama Dam so as to release a managed flood re-inundating 40,000 ha floodplain. The magnitude and timing of the flood was negotiated with all stakeholders and could be accomplished with little impact on the other objectives of the dam. Monitoring in the years since has documented significant improvement of the floodplain ecosystem, including the return of native grasses and sedges and increasing numbers of wildlife and livestock feeding on them. Fish productivity increased, along with numbers of water birds (Duvail and Hamerlynck, 2006). Re-operation of Wolwedans Dam on the Great Brak River in South Africa also involved the release of managed floods to maintain brackish salinities in the estuary and flush accumulated sediments from the mouth of the river. A decade of monitoring data following the re-operation confirmed that ecological objectives were being met and that the system had recovered to near natural conditions (Slinger et al., 2005).

Other examples of dam re-operation have had more mixed outcomes. Katse Dam, on the Malibamatso River in the Lesotho Highlands, began operations in 1995 with the dual purpose of generating hydropower for Lesotho and supplying water to South Africa. During its initial years of operation, the dam's downstream flow release was held at 0.5 m^3/s year-round, which was less than 3% of the mean annual runoff of the river (Brown and King, 2012). Between 1998 and 2001 a proper environmental flow assessment was conducted, and a more ecologically relevant set of variable low flows and flood releases was recommended (King et al., 2000b). The full set of recommended flows could not be released, however, because the dam lacked the necessary outlets to release mid- or large-range floods. Thus, releases were restricted to low flows and low-range floods (Brown and King, 2012). After re-operation of the dam, the new and feasible environmental flow requirements have been mostly met, but the results of monitoring conducted in 2015−16 indicate that the status of riparian vegetation and fish have worsened in the downstream river reaches (LHDA, 2016).

In another case of the Kogelberg Dam on the Palmiet River of South Africa, a full set of environmental flow requirements was negotiated in 2000 and the dam was re-operated to release all but the highest recommended flood levels (Brown and King, 2012). The downstream effects were limited, however, because another dam, Arieskraal Dam, impounds the Palmiet River just 5 km downstream. Unlike the Kogelberg Dam, the Arieskraal Dam is not able to release flood flows, and it is able to release low flows only from a bottom valve that produces turbid downstream flows of low temperature year-round (Brown and King, 2012).

These few cases suggest a very limited implementation of measures to limit water abstractions from rivers and re-operate dams to release environmental flows in Africa. Other examples undoubtedly exist on the continent but have either not been documented or are reported in grey literature that has not appeared in searches conducted for this chapter.

Accelerating the implementation of environmental flows

The biodiversity of Africa's freshwater ecosystems is the product of millions of years of evolution, but its future lies in the hands of a single species that is increasingly consuming and altering river flows. While there has been progress in the implementation of environmental flows across Africa in recent decades, the pace of progress must increase if the continent's riverine ecosystems are to remain vibrant living systems. Africa is not facing this challenge alone. Implementation of environmental flows is a global challenge, as highlighted in the 2018 Global Action Agenda, which was formulated through an open international consultation process and agreed at the 20th International Riversymposium and Environmental Flows Conference, held in Brisbane, Australia, in 2017 (Box 28.1) (Arthington et al., 2018). The Action Agenda

BOX 28.1 The Global Action Agenda on environmental flows (Arthington et al., 2018)

The delegates to the 10th International Riversymposium and Environmental Flows Conference call upon all governments, development banks, donors, river basin organizations, water and energy associations, multilateral, and bilateral institutions, community-based organizations, research institutions, and the private sector across the globe to commit to the following actions for restoring and maintaining environmental flows.

Estimate Environmental Flow Needs Everywhere Immediately
Environmental flow needs are currently unknown for the vast majority of freshwater and estuarine ecosystems. Scientifically credible methodologies quantify the variable—not just minimum—flows needed for each water body by explicitly linking environmental flows to specific ecological functions and social values. Recent advances enable rapid, region-wide, scientifically credible environmental flow assessments.

Integrate Environmental Flow Management into Every Aspect of Land and Water Management
Environmental flow assessment and management should be a basic requirement of Integrated Water Resource Management (IWRM); environmental impact assessment (EIA); strategic environmental assessment (SEA); infrastructure and industrial development and certification; and land-use, water-use, and energy-production strategies.

Establish Institutional Frameworks
Consistent integration of environmental flows into land and water management requires laws, regulations, policies and programs that: (1) recognize environmental flows as integral to sustainable water management, (2) establish precautionary limits on allowable depletions and alterations of natural flow, (3) treat ground water and surface water as a single hydrologic resource, and (4) maintain environmental flows across political boundaries.

Integrate Water Quality Management
Minimizing and treating wastewater reduces the need to maintain un-naturally high streamflow for dilution purposes. Properly-treated wastewater discharges can be an important source of water for meeting environmental flow needs.

Actively Engage All Stakeholders
Effective environmental flow management involves all potentially affected parties and relevant stakeholders and considers the full range of human needs and values tied to freshwater ecosystems. Stakeholders suffering losses of ecosystem service benefits should be identified and properly compensated in development schemes.

Implement and Enforce Environmental Flow Standards
Expressly limit the depletion and alteration of natural water flows according to physical and legal availability, and accounting for environmental flow needs. Where these needs are uncertain, apply the precautionary principle and base flow standards on best available knowledge. Where flows are already highly altered, utilize management strategies, including water trading, conservation, floodplain restoration, and dam re-operation, to restore environmental flows to appropriate levels.

Identify and Conserve a Global Network of Free-Flowing Rivers
Dams and dry reaches of rivers prevent fish migration and sediment transport, physically limiting the benefits of environmental flows. Protecting high-value river systems from development ensures that environmental flows and hydrological connectivity are maintained from river headwaters to mouths. It is far less costly and more effective to protect ecosystems from degradation than to restore them.

Build Capacity
Train experts to scientifically assess environmental flow needs. Empower local communities to participate effectively in water management and policy-making. Improve engineering expertise to incorporate environmental flow management in sustainable water supply, flood management, and hydropower generation.

Learn by Doing
Routinely monitor relationships between flow alteration and ecological response before and during environmental flow management, and refine flow provisions accordingly. Present results to all stakeholders and to the global community of environmental flow practitioners.

calls on all governments and stakeholders engaged in water resources management to estimate environmental flow needs everywhere immediately, to integrate these needs into land and water management, and to act to ensure that environmental water needs are met. Achieving these actions will in many cases, including much of Africa, require establishing or revising institutional frameworks, actively engaging all stakeholders, building technical capacity and empowering local communities.

There is growing global momentum to increase environmental flow assessment and implementation over the coming decade, and all African countries have committed to do their part. Assessing and implementing environmental flows are necessary to meet targets 6.4 on (increasing water use efficiency), 6.5 (implementing integrated water resources management), and 6.6 (protecting and restoring water-related ecosystems) of the Sustainable Development Goals. In fact, monitoring indicator 6.4.2 requires countries to assess environmental flow requirements at a national scale to quantify their level of water stress (FAO, 2019), which is calculated as:

$$Water\ Stress\ (\%) = \frac{Total\ Freshwater\ Withdrawal}{Total\ Renewable\ Freshwater\ Resources - Environmental\ Flow\ Requirements} * 100$$

All African countries are also parties to the Convention on Biological Diversity (CBD), which adopted a new Global Biodiversity Framework in 2022. The framework set targets for signatory countries to achieve by 2030, including integrating ecological objectives into river basin management plans covering the full national territory, restoring 30% of degraded inland water areas and conserving 30% of inland waters in protected areas or through other effective conservation measures. The 2030 target of managing rivers within the context of integrated management plans is also consistent with target 6.5 of the Sustainable Development Goals (United Nations, 2024).

At the scale of transboundary basins, the Nile Basin Initiative has taken ambitious steps to advance the assessment and implementation of environmental flows in its 10 member states (NBI, 2024). In 2015, it published its Nile Basin Environmental Flows Framework, establishing general standards for environmental flows in the basin and providing technical manuals, a database and training to support member states in the implementation of the standards. Basin organizations such as the Okavango River Basin Water Commission, the Lake Victoria Basin Commission, the Niger Basin Authority, the Orange-Senqu River Commission and others have also committed to environmental flow assessment and implementation to differing degrees.

It will ultimately be up to the individual countries to act within their own and shared river basins to ensure that environmental flows are properly assessed and protected for the benefit of aquatic ecosystems and the people who depend on them for a range of ecosystem services. Ideally actions will be led by the government. Despite its challenges with implementation, the South Africa government has demonstrated what can be accomplished when environmental flows are legally recognized and the country's scientific community is supported to develop suitable methodologies and conduct quality assessments. In the absence of such government leadership, progress can be initiated by other actors, including international development banks and agencies, and nongovernmental organizations (NGOs) working with a wide array of stakeholders (including government). Development agencies such as the United States Agency for International Development, the United Kingdom's Department for International Development, and the German Development Ministry have supported high quality environmental flow assessments as part of their water development support in several countries with the involvement of water authorities and including capacity development. The World Bank and other development banks have required that environmental flows be assessed and protected as part of their environmental safeguards in development projects. And international NGOs such as the Worldwide Fund for Nature (WWF) and The Nature Conservancy (TNC) have driven environmental flow programs in river systems of high conservation value, also involving and strengthening national and local authorities and civil society organizations.

Conclusion

Progress in environmental flow implementation will certainly benefit from continued research, but sufficient knowledge and tools are available today to act. While there is still much to learn about the ecological effects of flow alterations and how much flow regimes can be altered without causing unacceptable ecological harm, new knowledge most useful to improving environmental flow management will be created in the act of implementation itself through monitoring, evaluation and adaptation (Dalu et al., 2024a, Chapter 29). The vast body of existing knowledge on African rivers contained in this book and the literature cited in its chapters provides the foundation to act now in all rivers across Africa.

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