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Ali Torabi Haghighi

ANALYSIS OF LAKE AND RIVER FLOW REGIME ALTERATION TO ASSESS IMPACTS OF HYDRAULIC STRUCTURES

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FACULTY OF TECHNOLOGY

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ANALYSIS OF LAKE AND RIVER FLOW REGIME ALTERATION TO ASSESS IMPACTS OF HYDRAULIC STRUCTURES

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Abstract

A key challenge in Integrated Water Resources Management (IWRM) is determination of environmental flow (EF). This is relevant in all water use scenarios and river regulation work. Water use and management alter water availability for ecosystems and the timing and distribution of runoff. Increased water consumption and allocation of water to different types of consumption impose pressures on aquatic ecosystems, affecting their status and ability to deliver important services, well–known examples being the Aral Sea in Asia and Lake Chad in Africa. This thesis presents new methods to determine the impacts of hydraulic structures on the flow regime of lakes and rivers. Methods to quantify different characteristics of flow in a non–dimensionless way are also presented. These tools allow more environment–based regulation of flow regimes.

By using three main flow characteristics of river regime (magnitude, timing and intra–annual), three impact factors, MIF (magnitude impact factor), TIF (timing impact factor) and VIF (variation impact factor), were developed. Combining these impact factors produced a new river impact (RI) index to assess the impacts of hydraulic structure using monthly flow data. Based on RI variations, a classification was developed rating impacts along a scale from ‘Low’ to ‘Drastic’.

The importance of climate patterns and river flow regime in controlling lake levels was examined. The lake simulation results were compared using a new index, Degree of Lake Wetness (DLW) and lake response time to changes in hydrology or climate was evaluated.

Environmental flow allocation and optimisation of annual EF distribution are critical for ecosystem health. Flow release from reservoirs can be partly supplemented or compensated for by natural runoff from downstream (residual) catchment areas. In a new hydrological approach, optimal intra–annual flow regime for EF can be estimated while considering water inflow from the downstream residual sub-catchment.

This thesis provides methods and indices to help quantify river and lake regimes, better understand the possible impacts of changes and manage these impacts optimally. This knowledge is crucial for decision making about EF regimes and achieving water release patterns from dams and hydropower that minimise the hydrological, morphological and biological impacts.

Keywords: dams, environmental flow, hydrological impact assessment, regulation, water construction

Torabi Haghighi, Ali, Järvien ja jokien virtaamamuutosten analysointi vesirakennushankkeiden vaikutusten arvioinnissa.
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Tiivistelmä

Integroidun vesivarojen suunnittelun ja hallinnan (IWRM) yhtenä haasteena on ympäristövirtaaman määrittäminen valuma-alue-tasolla. Tämä on tärkeää arvioitaessa säännöstelyn ja vesirakentamisen ympäristövaikutuksia. Vedenkäyttö ja hallinta muuttavat veden saatavuutta jokiekosysteemissä ja virtaaman vuosittaista ajoittumista sekä jakautumista eri kuukausien välillä. Vesivarojen lisääntyvä käyttö eri tarkoituksiin voi vaikuttaa vesiekosysteemeihin ja niiden tuottamiin ekosysteemipalveluihin. Aral-järvi Aasiassa ja Chad-järvi Afrikassa ovat hyviä esimerkkejä veden liiallisesta käytöstä ja ympäristönäkökulman huomiotta jättämisestä. Väitöstyön keskeisin tavoite oli kehittää menetelmiä, joilla voidaan arvioida miten vesirakentaminen vaikuttaa jokien virtaamiin ja järvien vedenpintoihin. Jotta vesistövaikutuksia voidaan yleistää, menetelmät kehitettiin dimensiottomiksi. Nämä menetelmät luovat perustan ympäristöystävällisemmällä vesistöjen virtaamien säännöstelylle.

Käyttäen kuukausittaista keskivirtaamaa ja kolmea tyypillisintä virtaamaluokkaa (suuruus, ajoittuminen ja vuodenaikainen vaihtelu), määritettiin uusi yhdistetty jokivaikutusindeksi (RI). Tämän indeksin avulla voitiin lopulta arvioida vesirakentamisen vaikutusta. Perustuen RI-indeksiin, usean joen vesirakentamisen vaikutuksia arvioitiin luokittelemalla vaikutukset vähäisiksi tai merkittäviksi.

Työssä tarkasteltiin ilmaston vaihtelun ja jokien virtaamaolosuhteiden vaikutusta järvien vedenpintoihin. Järvisimuloinnin tuloksia verrattiin puolestaan käyttäen indeksiä, joka kuvaa järvessä tapahtuvia muutoksia suhteessa hydrologisiin ja ilmastollisiin olosuhteisiin.

Väitöskirja käsittelee myös ympäristövirtaamien (EF) keskeisiä kysymyksiä: vedenkäytön jakautumista ja vuosittaisen virtaaman optimointia ympäristövirtaaman näkökulmasta. Työssä käytetään uutta hydrologista lähestymistapaa arvioimaan ympäristövirtaaman optimoitua kausivirtaamavaihtelua. Tässä lähestymistavassa vesivarastoaltaista lähtevää virtaamaa voidaan osittain täydentää tai kompensoida alapuoliselta valuma–alueelta tulevalla virtaamalla.

Väitöstyön tulokset lisäävät ymmärrystä vesivarojen kestävästä käytöstä. Lisäksi työssä kehitetyillä menetelmillä voidaan määrittää ja optimoida jokien ja järvien virtaamaolosuhteita erilaisissa tilanteissa. Väitöstyö tarjoaa uusia käytäntöjä päätöksentekoon liittyen ympäristövirtaamaolosuhteisiin ja -jakaumiin vesivoima- ja vedenkäyttökysymyksissä ottaen huomioon hydrologiset, morfologiset ja biologiset rajoitteet.

Asiasanat: hydrologisten vaikutusten arviointi, padot, säännöstely, vesirakentaminen, ympäristövirtaama

To the burned faces of Zayanderoud

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29 Oct. 2014 Ali Torabi Haghighi

Abbreviations

AAD	Available annual discharge at reference point (magnitude of flow)
A.Ma	Absolute maximum lake volume during 40–year simulation
A.Mi	Absolute minimum lake volume during 40–year simulation
AMR	Absolute maximum–minimum volume ratio
AIF	Annual inflow to dam
AOF	Annual outflow from dam
Aw	Tropical savannah climate according to the Köppen climate classification
Bsk	Cold semi–arid climate according to the Köppen climate classification
Bwh	Hot desert climate according to the Köppen climate classification
CAH	Closest annual hydrograph to natural flow after regulation at reference point
CIR	Capacity inflow ratio
CON	Consumption
Cs	Temperate with hot and dry summer climate according to the Köppen climate classification
Dfc	Cold without dry season climate according to the Köppen climate classification
DLW	Degree of lake wetness
DLW_1:	Degree of lake wetness based on lake geometry,
DLW_2:	Degree of lake wetness based on lake history,
EF	Environmental flow
FC	Flood control
IR	Irrigation
hm^3	Million cubic metres
HPP	Hydropower plant
MAF	Mean annual river flow
MIF	Magnitude impact factor
MMR	Maximum–minimum volume ratio
MRRP	Monthly river regime point
NAH	Natural annual hydrograph
NSP	Number of months in which outflow from lake occurred
RAH	Regulated annual hydrograph at reference point
Res	Residual

RI	River impact
ROR	Run of the river dam
RRI	River regime index
SAH	Standardised annual hydrograph
TIF	Timing impact factor
UP	Upstream
VAR	Variable
VIF	Variation impact factor
WS	Water supply

Original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:

I Torabi Haghighi A, Kløve B (2014) A sensitivity analysis of lake and wetland water level response to changes in climate and river regimes. Manuscript under revision.

II Torabi Haghighi A, Kløve B (2014) Development of optimal flow regimes for allocated environmental flow considering natural flow regimes and several surface water protection targets. Manuscript under revision.

III Torabi Haghighi A, Kløve B (2013) Development of a general river regime index (RRI) for intra–annual flow variation based on the unit river concept and flow variation end–points. Journal of Hydrology 503: 169–177.

IV Torabi Haghighi A, Marttila H, Kløve B (2014) Development of a new index to assess river regime impacts after dam construction. Global and Planetary Change 122: 186–196.

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1 Introduction

The increasing need for food and energy has put great pressure on the water supply in many regions, resulting in conflicts between different water users. Aquatic ecosystems are among the oldest water users, but are easily overlooked in decision making on water allocation. The modification of rivers by impounding flow for different purposes is the main reason for conflicts between water users. After many cases with severe consequences because water allocation for aquatic ecosystems was neglected, the environmental flow concept was introduced into integrated water resources management (Kashaigili et al. 2005, Carvajal–Escobar 2008). The overall aim of this thesis was to find pragmatic and scientifically sound solutions to assess the impact of dam construction on water bodies and improve existing methods for environmental flow assessment.

1.1 Background

The global population is increasing by about 80 million per annum, suggesting an increase in global water demand of about 64 billion cubic metres per annum (United Nation 2009). This means that the available water for aquatic ecosystems could be reduced by a corresponding amount, which is equivalent to the annual discharge from the Rhine river into the North Sea. This reduction must be considered in all water use scenarios and construction work in which water courses are regulated. It has been predicted that by the year 2025, more than 3.4 billion people will be faced with water shortages (Nayar 2013). Furthermore, based on (FAO 2012), more than 870 million people will face an insecure food supply. An increase in food production will require more water for irrigation, which will significantly reduce the flow to water systems and consequently also affect ecosystems. Furthermore, climate variability and climate change can increase the pressure on ecosystems on various temporal and spatial scales. Due to the current unprecedented overuse of water, a number of ecosystems are at future risk, including surface and groundwater systems as well as wetlands and other terrestrial ecosystems.

To supply the water needs of the population and cope with variations in water availability, dams are built and rivers are modified and regulated. Dam construction has been the traditional solution for securing water supply for 4500 years (Sternberg 2006). Around 170 of the world's 292 largest rivers have been modified by dams (Nilsson et al. 2005), with about two dams per day constructed throughout the second half of the 20th century (WCD 2000). Dams are essential for civil flood protection and domestic and industrial water needs, hydropower generation and food production (Brown et al. 2009, McNally et al. 2009). However, dams influence the water system and its ecology in many ways. For example, they prevent passage of migratory fish (Gorsky et al. 2012) and block the natural transport of sediments in rivers, resulting in upstream siltation and downstream erosion (Church 2002, Petts & Gurnell 2005). The reduced transport of material can also limit the food supply and influence ecosystems downstream (Ahearn & Dahlgren 2005). Moreover, changes in flood inundation patterns after regulation can have ecological impacts due to changes in riparian systems and stream bed interactions (Petts & Gurnell 2005). Indirect consequences of dam construction include changes in land use, microclimate and nearby communities.

In addition to the impacts arising from changes in land use, energy and food production, global warming and climate change can influence resources and their future management (Gleick 1998). Future climate change in terms of temperature, precipitation and evapotranspiration will result in changes in soil moisture, infiltration, recharge and runoff, which are fundamental components of the hydrological cycle. This could lead to significant effects on river flow and available water by changing e.g. peak flow amount, frequency and timing (from winter to spring), glacier melt patterns and amount, and base flow magnitude and drought frequency (Frederick & Major 1997). This will influence river systems, as flow regime is one of the vital requirements for the ecology of rivers and their associated aquatic ecosystem such as wetlands and floodplains (Poff et al. 1997, Puckridge et al. 1998, Naiman et al. 2002, Kashaigili et al. 2005). The fauna, flora and humans within these systems have adapted themselves to the particular water regime and any changes can therefore damage their reproduction and survival.

Making sustainable water allocations for different consumers is a key challenge in water resources management. Water allocation has impacts on the economy and the health and sustainability of societies. In general, future climate change would impose pressure on the two main faces of water resources, supplier and consumer. The supply–side pressures would include rising or decreasing amount of water, locally or regionally (Arnell 1999). Demand–side pressures could be linked to increasing temperature and associated increasing crop water demand. There are many uncertainties linked to both the supply and demand side. The main objective in the past was to provide water based on human demands, with minimal consideration of aquatic ecosystems (Kashaigili et al. 2005). However, following many reports world–wide of catastrophic depletion of important aquatic ecosystems, like the Aral Sea (Kamalov 2003, Zavialov et al. 2003, Glantz 2007, Erdinger et al. 2011) and Lake Chad (Guganesharajah & Shaw 1984, Coe & Foley 2001), another water demand issue, environmental flow, began to be considered (Kashaigili et al. 2005). It is now well known that various ecosystem services apart from food production, hydropower and flood protection functions need to be considered in management decisions. To achieve more environment–based or sustainable management of water resources, different agreements and legal commitments have been made, such as the Ramsar Convention (1971) to protect wetland and lakes; the Bonn Convention (1979) to protect migratory species and wild animals; the Helsinki Convention (1992) relating to environmental flow; the Mekong River Agreement (1995) and the UN Convention (1997, Articles: 5,6,7,8,9) to conserve and use rivers and achieve equitable utilisation of international water courses and riparian states; and the Convention on Biological Diversity (opened for signature at the Earth Summit in Rio de Janeiro, 1992)(Dyson et al. 2003). The conflicts between meeting the water requirements of ecosystems and supplying water to meet human needs have led to allocation of environmental flow (EF) being introduced as a concept in Integrated Water Resources Management (IWRM) to balance these two legitimate demands (Carvajal–Escobar 2008, Kashaigili et al. 2005).

Water allocation for environmental requirements is an important task in water resources management in order to maintain the supply of ecosystem services provided by aquatic ecosystems. Maintaining a balance between human water use and the needs of other stream ecosystem services is complicated due to the increasing global water demand and the limited amount of available freshwater, which is under pressure from climate change and pollution as well as the increasing consumption rate. Because of the many complex interconnections between different water resources stakeholders on local, national and international scale, EF assessment should be analysed in an IWRM framework.

1.2 Objectives, scope and key assumptions

The overall aim of the work presented in this thesis was to develop methods for assessing the river regime impacts of hydraulic structures such as dams. Different indicators and approaches that show changes in river and lake regime characteristics following dam construction are needed for water management, assessment and policy making. A starting assumption for the thesis was that river regimes possess five major characteristics of flow: magnitude, timing, rate of change, frequency and duration. It was also assumed that changes in these characteristics of flow will affect river and aquatic ecosystems, although ecology was considered not directly, but rather indirectly. The scope of the work was hydrological assessment and water resources engineering and the aim was to develop dimensionless approaches and indicators based on theories such as water balance and reservoir operation. For this purpose, river flows were scaled and virtual cases were generated and used. To cover a wide range of rivers and climates, it was decided to include different types of rivers and regulated systems, based on data availability. This was intended to allow a wider and more general comparison of river impact for different catchment sizes, climate scenarios and dam operation systems. However, the focus was on developing methods to assess the impacts of dams, land use and climate on river flow, not to study climate change or related impacts in a specific region.

For the research, three major research questions were formulated:

Research question 1: *How can changes to river regime be better included in hydrological indices for assesses the impacts of hydraulic structures*?

This question was examined in Papers III and IV. The main objective of Paper I was to quantify the monthly flow distribution using different non–dimensional indices applied to the annual hydrograph of rivers. The Nile river was used as a case study. The main objective of Paper II was to quantify the impact of dams on river regimes, in particular how dam operation policy can affect flow magnitude, flow timing and monthly variation of flow.

Research question 2: *What is the response of lake and water bodies to river regime and climate alteration?*

The main objective in Paper I was to develop a water resources system simulation based on the water balance equation and use it to analyse different sizes of lake combined with different flow regime and climates.

Research question 3: *What is the optimum environmental flow regime based on the layout of river modification and target points for recreation*?

One neglected point in hydrological environmental flow assessment is the monthly flow regime for allocated flow. Therefore the objective in Paper II was to develop a method for estimating the monthly distribution of EF and showing how this can be optimised in terms of basin layout and dam location.

2 Review of river regime indices and environmental flow methods

Different methods can be used to quantify changes in the hydrology of surface waters after river regulation, water use and climate change. The changes are evident in rivers and lakes as shifts in regime characteristics (timing and magnitude of flow and its distribution). The impacts of regulation can be modified using different methods applying environmental flow principles. The short review below describes methods for quantifying: a) hydrological alterations and b) environmental flow.

2.1 Indices for quantifying hydrological alterations

2.1.1 River regimes indices

A large variety goods and services are provided by rivers (Costanza 2003, Ripl 2003, Molden & Bos 2005, Gao et al. 2009), including irrigation water, generation of hydropower, drinking water, recreation, fisheries, transport etc. (Ripl 2003). Rivers are the main resource for fresh water bodies that support aquatic ecosystems and biological communities, species distribution and their adaptive capacity (Gao et al. 2009, Poff & Zimmerman 2010). River flow regime is vital for floodplains and wetlands (Tilmant et al. 2010) and habitats are easily affected by changes in flow and turbidity (Finger et al. 2006). Many functions in rivers, such as aquatic organisms, sediment transport and flood plain systems, are dependent on five attributes of flow, namely its magnitude, timing, rate of change, frequency and duration (Poff et al. 1997, Poff & Zimmerman 2010). For example, insect life cycle, flower feeding or egg hatching can be linked to the timing or size of floods and riparian ecosystems are related to the frequency or duration of flow (Poff & Allan 1995, Freeman et al. 2001, Marchetti & Moyle 2001, Humphries et al. 2002).

Natural flow patterns have changed over the past century due to changes in e.g. water resources use, land use and climate. Only about 15% of the world's rivers still flow in a natural regime due to construction of more than 45,000 dams with a height more than 15 m (Nilsson & Berggren 2000, Bejarano et al. 2010). According to (Graf 2006), in the USA such large dams reduce 67% of the annual maximum discharge and 64% of the daily discharge of rivers. However, dam operation can be manipulated to reduce the negative environmental impacts of changes in river flow (Yin et al. 2011). Irrigation and pumping of groundwater change base flow and increase the impact of droughts. Climate change is also a threat to river flow patterns, but in some cases the anthropogenic impacts dominate (Arrigoni et al. 2010). To understand the impacts of anthropogenic changes on the dynamics of natural rivers, simple indicators can be useful as management tools to quantify the various impacts caused by changes in water and land use.

Different methods have already been developed to assess the impacts of changes in river regimes due to human disturbance and climate variability and change. A number of methods are designed to show changes in river hydrology (Olden & Poff 2003, Gao et al. 2009) . The first of these river flow indicators were developed in the mid–1970s (Olden & Poff 2003). Other previously developed indicators are based on flow rate characteristics such as daily magnitude of flow (Richards 1989, Richards 1990, Clausen & Biggs 1997, Clausen & Biggs 2000), monthly flow magnitude, annual flow magnitude (Puckridge et al. 1998, Wood et al. 2000), low flow conditions (Clausen & Biggs 2000, Wood et al. 2000), base flow (Poff et al. 1996, Richter et al. 1997), maximum flow (Richter et al. 1996, Richter et al. 1997, Poff et al. 1997, Clausen & Biggs 1997, Clausen & Biggs 2000) duration of flow (Richter et al. 1996, Richter et al. 1997), timing of flow (Clausen & Biggs 2000) and rate of change of flow (Clausen & Biggs 2000). Among different methods to show seasonal effects, the Indicator of Hydrological Alteration (IHA; (Richter et al. 1996)) has been extensively used to assess river regime alterations, especially in dam construction issues, e.g. the River Roanoke in North Carolina (Richter et al. 1996), La Nga river in Vietnam (Babel et al. 2012), Tana river in Kenya (Maingi & Marsh 2002), Huaihe river in China (Hu et al. 2008) and River Karkheh in Iran (Madadi 2011). However, in most cases the use of these methods is time–consuming and they require daily flow data, which are not easily accessible in all regions.

2.1.2 Lake regime indices

Lakes, wetlands, estuaries and other aquatic ecosystems are water bodies that can also suffer from changes in climate, water and land use. In natural conditions, lake levels vary on different temporal scales from days to centuries (Riis & Hawes 2002, Chow–Fraser 2005, Hofmann et al. 2008, Wang & Yin 2008, Cui et al. 2010). These changes in lake water levels are due to many natural and anthropogenic pressures such as climate change, groundwater extraction or inflow regulation (Richter et al. 1997, Coops et al. 2003, Leira & Cantonati 2008, Aroviita & Hämäläinen 2008). A decrease in water level can influence the physical environment, biota and ecosystem (Leira & Cantonati 2008), with impacts on a number of lake ecosystem functions (Coops et al. 2003, Wantzen et al. 2008, Paillisson & Marion 2011). Severe impacts on ecological and socio–economic status have been reported for many large and small lakes worldwide, such as the Aral Sea in Asia (Kamalov 2003, Zavialov et al. 2003, Glantz 2007, Erdinger et al. 2011), Lake Chad in Africa (Guganesharajah & Shaw 1984, Coe & Foley 2001) and the Great Salt Lake (Stephens 1990, Bedford 2009) and the Salton Sea (Paillisson & Marion 2011, Khan et al. 2013) in the United States. Different lakes or part of lakes can display different responses to external impacts, with the littoral zone and its habitats typically being most easily affected (Coops et al. 2003, Aroviita & Hämäläinen 2008, Baumgärtner et al. 2008). There is an urgent need to gain a better understanding of the vulnerability of lake water levels to external pressures and to develop methods to relate catchment water use to changes in lake levels. In particular, the potential impacts of climate change must be better understood and predicted. Changes in lake level may also be a good measure for evaluating the consequences of flow alteration, as they could be determined e.g. by using satellite images in regions with a lack of reliable ground data.

The most common method for estimating lake levels is the water balance equation, where water input and output result in lake storage and water level changes (Crapper et al. 1996, Morrill et al. 2001, Tsubo et al. 2007, Soja et al. 2013, Bracht–Flyr et al. 2013). However, all water balance components cannot always be quickly assessed, such as evaporation due to expansion of irrigated areas or lake–groundwater interactions. A method that assesses general changes in lake level can be a useful tool in examining why different lakes have different lake level variation patterns and why the water disappears from some lakes. Assessment methods using climate data can provide important insights into variations in lake levels in different parts of the world (Bracht–Flyr et al. 2013).

2.2 Environmental flow

There is no single solution to restore or mitigate the negative impacts of flow changes in rivers or aquatic ecosystems. Environmental flow assessment can be considered as an approach to help reduce the impact or mitigate some parts of them. The objective for assessment could be set based on ecological, economic or social requirements. For instance, in a previous study in the central valley in Senegal the target was to maintain the flood plain area. In studies in the UK, in the Kennet river the aim was maintain the population of wild brown trout, in the Avon river it was protection of salmon migration and in Chippenham it was to protect the vegetation community. (Dyson et al. 2003).

2.2.1 Environmental flow concept

Environmental flow is the amount of allocated flow that is released to mitigate the negative consequences of dams and river constructions on the hydrological regime of the river in question in order to reduce the ecological impact of flow alteration (Poff & Matthews 2013). In addition to this definition, the EF concept has been defined by other organisations and research groups as:

- The amount of the original river regime that should run into downstream flood plains in order to preserve valuable and specified features of ecosystems (Tharme 2003).
- The flow that is required to sustain freshwater and estuarine ecosystems in coexistence with other water consumers (The Brisbane Declaration, 2007).
- The water regime provided within an aquatic ecosystem to maintain ecosystems and their goods and services (Dyson et al. 2003).

Among the different descriptions of EF, that developed by Poff & Matthews (2013) was used in this thesis.

2.2.2 Environmental flow assessment

A number of methodologies for environmental flow assessment have been presented over the years, e.g. by Tenant (1976), Arthington & Pusey (1993) and Tharme (1996, 1997, 2000). These approaches and methodologies include use of look–up tables, desk top analysis, functional analysis and habitat modelling (Dyson et al. 2003). Tharme (2003) found that at least 207 individual methods for estimating EF were used in 44 different countries and classified these into four categories, namely hydrological, hydraulic rating, habit simulation and holistic approaches.

More than 62 hydrological methods have been proposed to calculate EF. These methods are generally based on one of the characteristics of the flow regime (Tharme 2003) and almost all consider only flow magnitude (usually minimum flow), despite the irrefutable role of other flow rate characteristics such as timing, frequency and variability in aquatic ecosystem functions (Poff et al. 1997, Assani et al. 2010). Except for a few methods such as that developed by Tennant (1976), most suggest a fixed amount for EF (Tharme 2003). The Tennant method is used in more than 25 countries and is one of the most widely accepted in hydrological methodology (Tharme 2003). The main advantages of hydrological methods are that they are inexpensive and that estimation of EF is quick when the data are available (Dyson et al. 2003). Other methods are more detailed, requiring site information which can take more time and cost more.

Most EF methods are based on river in–stream demand (Tennant 1976, Tharme 2003, Kashaigili et al. 2007, Shang 2008, Cui et al. 2010). However, it is recommended that, in order to establish the lake’s goods and services, the water allocation for lakes must be close to the natural regime (Dyson et al. 2003).

3 Case studies: Rivers, lakes and dams

In order to test the applicability of the methods developed in Papers I–IV, data from different regions and climates were used. These included information on 19 rivers, four lakes and 19 dams world–wide (Fig. 1). However, the Kor river in Iran and the Nile rivers were the major case studies and therefore these are described in more detail below.

3.1 Nile river

The Nile has many tributaries flowing in different climate zones, such as tropical, savannah, mountain, semi–desert, desert and Mediterranean. It is also affected by many dams of different sizes (Fig. 2). The Nile is 6690 km long, with 3,007,000 km^2 drainage area. Within the Nile basin, the mean annual precipitation ranges from 36 mm in Egypt to more than 1800 mm in Rwanda. This variety in climate and rainfall distribution give different types of flow regime, from uniform flow in central Africa and near Lake Victoria to ephemeral tributaries in the east. This variety of flow regime is combined with different types of land use and landforms (e.g. waterfalls, marshes, wetlands) and requires different sizes of dams for collection of different river regimes. The Nile has two main tributaries, the Blue Nile and the White Nile. The furthest point from the Mediterranean outlet is in the White Nile at Kagera, 2800 m above sea level (asl) in the Burundi and Rwanda mountains. The River Kagera runs into Lake Victoria (1134 m asl) and Lake Victoria discharges into Kyoga Lake in a series of waterfalls (the Owen Falls Dam was constructed in 1953 to regulate the discharge). The Kyoga continues in an easterly direction to enter the Rift Valley and passes through wetlands interrupted by Murchison Falls. Here, the river passes over the Sudan border and meets the Sudd swamps, where it flows to the east and enters Lake No. The river Bahr el Ghazal also discharges into Lake No, from the opposite side. The Bahr el Ghazal is affected by some seasonal and permanent wetlands. The Sobat River joins the outflow from Lake No before Malakal Gauging Station. A tributary to the Sobat, the Baro, comes from the Ethiopian highland region (about 2000 m asl). Rivers in this region have wetlands and Machar Marshes. After Malakal Gauging Station, the river becomes the White Nile, which flows toward Khartoum. Before Khartoum, the Jebel Aulia Dam was constructed in 1937. The

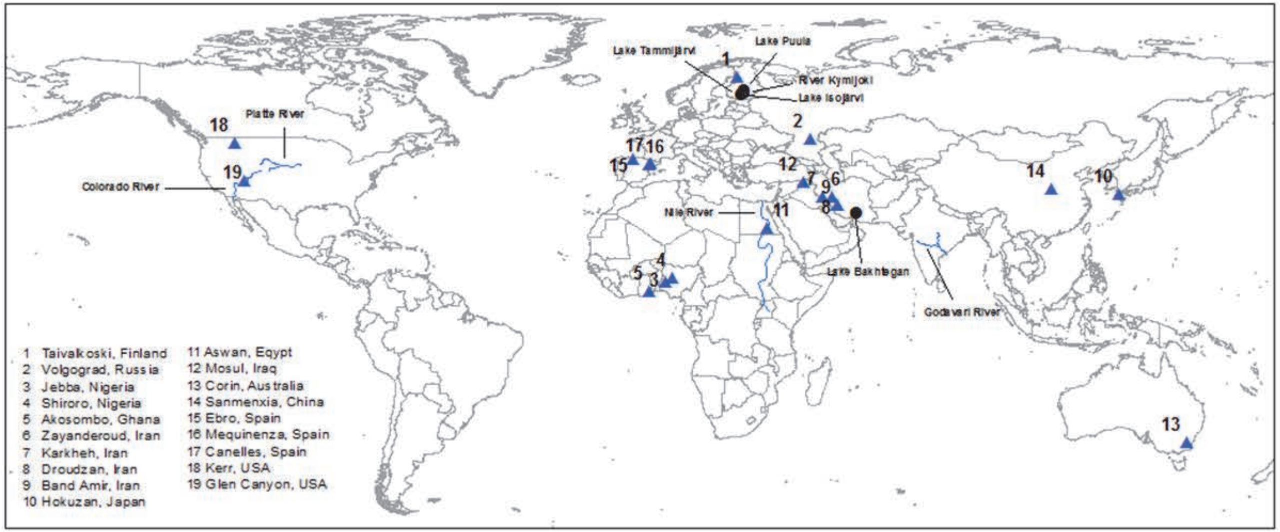


Fig. 1. Geographical location of case study rivers and dams used in Papers I–IV.

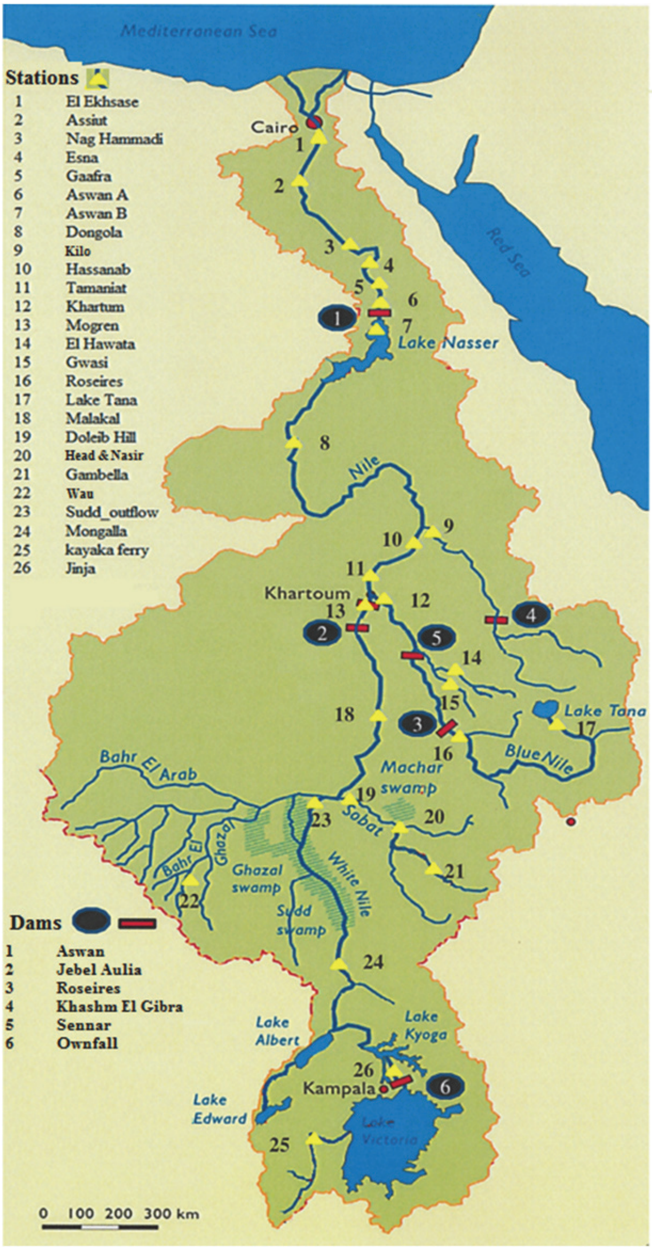


Fig. 2. Nile basin and its tributaries (Paper III). Image reprinted with permission from the Journal of Hydrology.

initial capacity was 3.2 km^3 (about 2.54 km^3 at present). The Blue Nile and its tributaries all rise on the Ethiopian Plateau, at an elevation of 2000–3000 m asl. (Sutcliffe & Parks 1999).

There are two dams, Sennar (1925) with 0.97 km^3 reservoir capacity and Rosaries (1966) with 3.35 km^3 before impoundment (Sutcliffe & Parks 1999, Tate et al. 2001). The river becomes the Nile or Main Nile after the Blue and White Nile junction near Khartoum (Fig. 2). The Atbara, the last tributary of the Nile, is a strongly seasonal river that enters the Main Nile about 325 km downstream from Khartoum. It is 880 km long and the majority of its catchment is located in Ethiopia and Eritrea. The Khashm El Gibra Dam, with 1.3 km^3 storage, was constructed on this river in 1964 (Karyabwite 2000). Finally, the Nile enters Egypt in Wadi Halfa. The Aswan High Dam, with 169 km^3 capacity for water storage, hydropower generation and river regulation, was constructed in 1971. A total of 26 major river gauge stations were selected for the case study and the annual river regime for 12 of these is shown in Fig. 3.

3.2 Kor river and Bakhtegan and Tashk lakes

Bakhtegan and Tashk lakes are located at the end of the Bakhtegan basin in Fars province, southern Iran (Fig. 4). In 1971 these lakes were included in the Ramsar Convention under the name ‘Lake Neyriz’, and in 1995 the lakes and their wetlands were registered as national parks (Afghahi 2010). The lakes are fed by the Kor and Sivand rivers. Due to climate change, dam construction and recent droughts, the lakes have partly vanished during the last 50 years, so EF allocation in this catchment is an important issue, as the demand for water for agriculture is high (Zarakani 2010). This area contains three large plains with an area of more than 110,000 hectares of irrigated fields and the three storage dams Doroudzan, Mollasadra and Sivand, which were constructed in 1972, 2006 and 2008 respectively, in upstream areas and have about 1583 million cubic metres (hm^3) of storage. Seven ancient diversion dams are also in use in the downstream agricultural region. After regulation of the river Kor by dams, EF can be allocated for two goals: Bakhtegan protection (as first possible target) and rehabilitation of the Kor river mesohabitat (as second possible target). In order to examine the effect of water allocation site on optimal EF regime, four gauging stations in the catchment were selected for this thesis (Fig. 4 and Table 1):

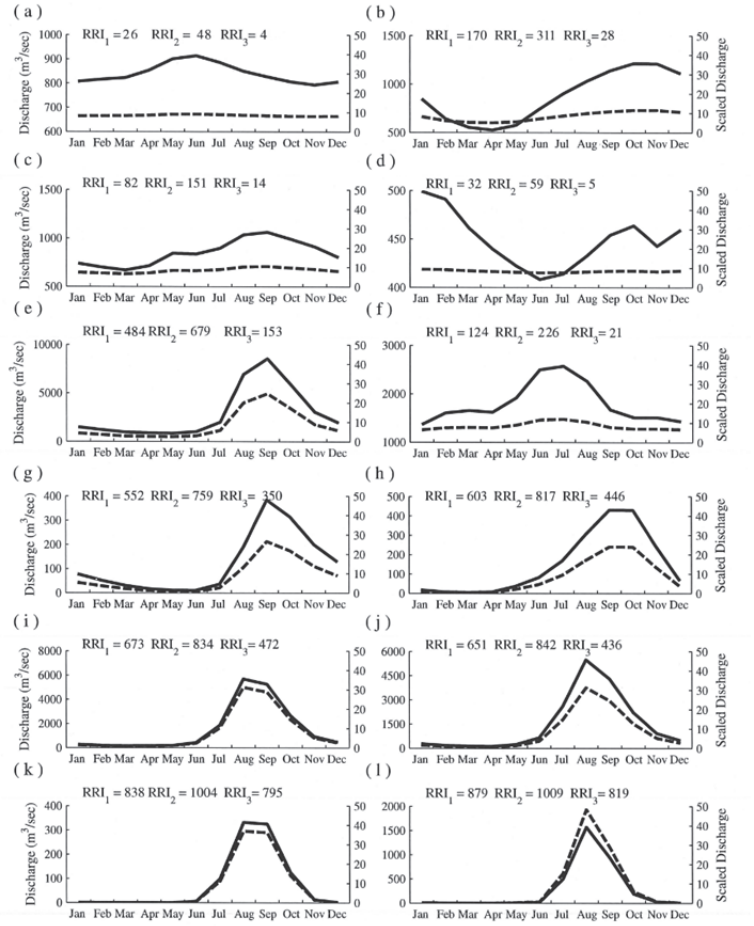


Fig. 3. Original (solid line) and scaled annual hydrograph (dashed line) and obtained the river regime index (RRI) models for selected stations in the Nile river basin: (a) Victoria at Jinja, (b) White Nile at Malakal, (c) Sudd wetlands inflow, (d) Sudd wetlands outflow, (e) Main Nile at Aswan before the Aswan Dam construction, (f) Main Nile at Aswan after the Aswan dam construction, (g) Blue Nile at Lake Tana, (h) Jur at Wau (i) Blue Nile at Khartoum, (j) Blue Nile at Roseires Dam, (k) Dinder at Gwasi, (l) Atbara at Kilo (RRI1, 2 and 3 are based on Models 1, 2 and 3, respectively). For scaling procedure, see section 3.3. (Paper III, reprinted with permission from Journal of Hydrology).

1. The Doroudzan dam, which is very important because it is the largest river flow regulator (993 hm^3 as initial storage volume) before Lake Bakhtegan.
2. The Mollasadra dam.
3. The outlet of the Shoor–Shirin catchment
4. The outlet of the Gavgodar catchment (Fig. 4).

Although there are no hydraulic structures present at gauging stations (3) and (4), they were selected in order to develop the methodology by examining the consequences of building dams there and the optimal form of the EF regime.

Table 1. Characteristics of sub–catchments and gauging stations in the Kor river case study (Paper I).

Sub–catchment	Gauging station	Area		Rainfall	Annual inflow		Reference point station	
		km2	%	mm/year	hm^3	%	River target	Lake target
Mollasadra	Tang Boraq	2300	17	432	381	21	Chamriz	Polkhan
Gavgodar	Dehkadeh sefid	1562	12	472	224	12	Mollasadra	Polkhan
Shoor–Shirin	Jamalbeik	548	4	519	255	14	Chamriz	Polkhan
Doroudzan	Doroudzan	4350	33	477	1194	65	Polkhan	Polkhan
Chamriz	Chamriz	3362	25	492	916	50	———	———
Polkhan	Polkhan	6980*	100	308	1833	100	———	———

* The area for Polkhan excludes the Sivand river sub–basin (with Sivand it would be 13,200 km^2).

In order to find the optimal EF intra–annual regime, two additional gauging stations, Chamriz and Polkhan, were selected for defining the reference hydrograph in the two EF target scenarios (Table 1). The Polkhan station is the last Kor river station before Lake Bakhtegan and has good quality, so it was selected as the reference point for the first protection target (lake protection). For the second target (river rehabilitation), the reference point selected was the best gauging station (in terms of data reliability) located immediately after the four main gauging stations (Doroudzan, Mollasadra, Shoor–Shirin and Gavgodar). Chamriz was the best station after Mollasadra and Shoor–Shirin, while Polkhan and Mollasadra were selected as the reference points for the Doroudzan and Gavgodar gauging stations, respectively (Fig. 4). The available data covered the period 1976–2008, but the data for 1976–2006 were used to eliminate the effect of the Mollasadra and Sivand dams on natural flow data at the target points. To find the natural flow regime at Polkhan, the gauging data were adjusted using Doroudzan dam outlet data. The natural regime generated for the Kor river at Polkhan (Fig. 5a) was used for defining the reference and standard hydrograph (Fig. 5b).

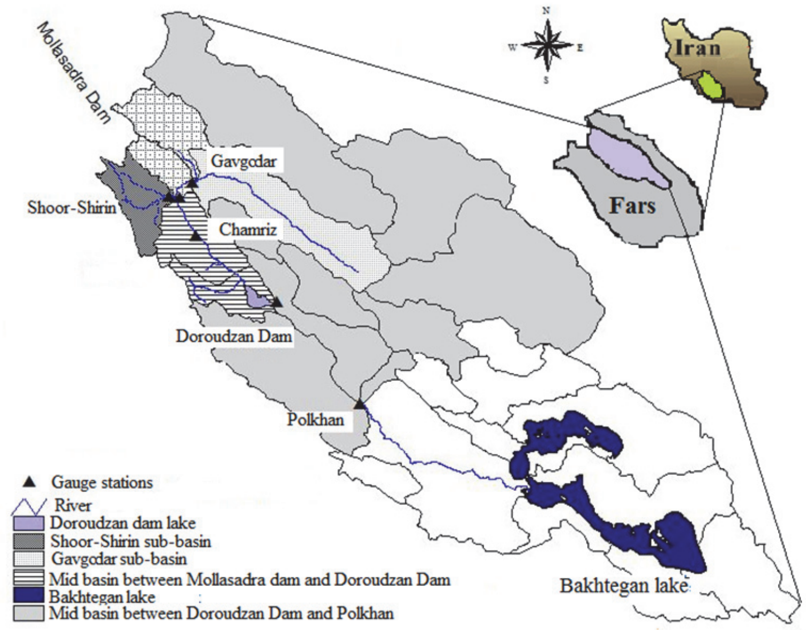


Fig. 4. Location of main dams and hydraulic structures in the Bakhtegan catchment area.

The intra–annual regime for EF was calculated for annual discharge at the Doroudzan, Mollasadra, Shoor–Shirin and Gavgodar stations as 20%, 30%, 40%, 50%, 60% and 80% of mean annual flow (MAF), i.e. the dam release policy was assumed to be 20%, 30%, 40%, 50%, 60% and 80% of MAF for these locations, as seen in Table 2.

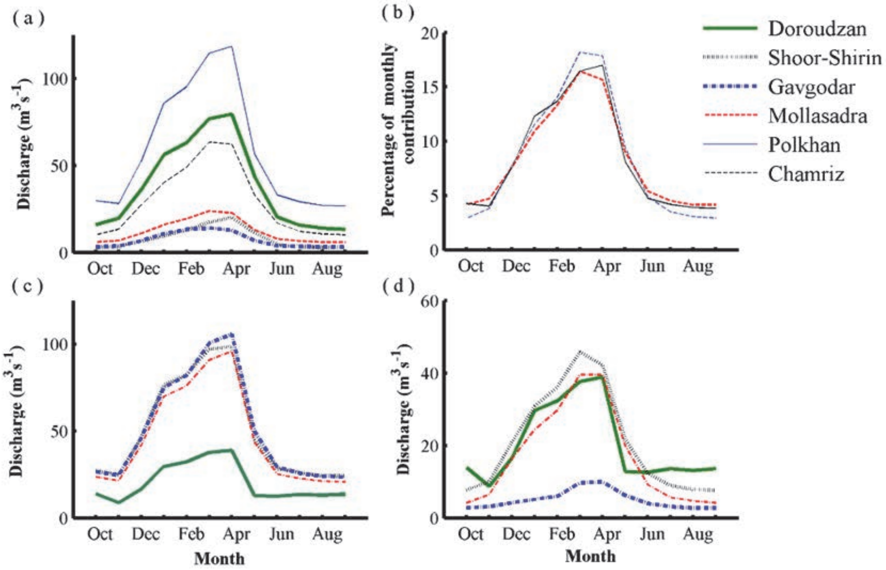


Fig. 5. Hydrographs at selected points in the Bakhtegan catchment. a) Mean monthly flow (m^3s^{-1}), b) monthly percentage distribution of flow at Mollasadra and Chamriz target points, c) residual hydrograph (see Section 4) based on lake conservation and d) residual hydrograph based on river conservation.

Table 2. Magnitude of annual flow in different allocation scenarios (EF as %MAF) at different points in the Bakhtegan catchment (hm^3).

	Location				
Allocation	Doroudzan	Chamriz	Shoor–Shirin	Mollasadra	Gavgodar
MAF	1194.30	916.41	254.61	381.15	224.38
80% MAF	955.44	733.13	203.69	304.92	179.51
60% MAF	764.35	586.50	162.95	243.94	143.61
50% MAF	611.48	469.20	130.36	195.15	114.88
40% MAF	489.19	375.36	104.29	156.12	91.91
30% MAF	391.35	300.29	83.43	124.90	73.53
20% MAF	313.08	240.23	66.74	99.92	58.82

3.3 River flow and climate data for sensitivity analysis of lake level

Lake levels were simulated with a water balance equation for values of different lake size (L1–L3), river flow (R1–R5) and effective precipitation (C1–C5). The simulations were carried out for 75 cases (3 lake sizes x 5 river flow regimes x 5 effective precipitation monthly time series). Each simulated scenario was denoted using the code RxCyLz, where R, C and L are as above and x represents the river regime type, y the type of climate and z the lake type.

Three lakes (L1–L3) differing in size, topography and area–volume–depth curve were selected as cases to test the methodology (Fig. 6). This approach of combining cases form different regions to create virtual cases is justified, as more than 60% of world rivers are modified by dams (Nilsson et al. 2005) and as after this modification, the river regime is dependent on dam operation policy and not only climate. Moreover, in many cases (especially large river basins such as the Nile) rivers pass through different climate zones or they result from tributaries originating from different climate zones.

The case rivers (R1–R5) were selected from five different climate zones to represent a wider range of river regimes and climate conditions (Table 3). Variations in the amount of inflow could have produced non–comparable simulation results, complicating the analysis of climate pattern and flow regime effects. Therefore in order to compare different river regimes, monthly discharge was scaled with a unit flow coefficient (η), defined as:

$$\eta = I' / I \qquad (1)$$

where I’ is the flow scaling unit (100 hm^3 per year or 3.1709 m^3s^{-1}) and I is the original mean annual flow rate of the river. After this scaling, each river has an annual flow of 100 hm^3 and small and large river flow regimes can be compared. This scaling (by a factor of 100) is convenient, as it allows fast assessment of monthly percentage of annual flow (total annual flow = 100; see also Paper III). The scaled annual hydrographs obtained using η are shown in Fig. 7b.

The Colorado and Kymi displayed a uniform hydrograph during the year, with low monthly fluctuation in annual discharge (standard deviation for scaled discharge 0.98 and 1.52, respectively), so these were classified as rivers with low variation in their intra–annual regime.

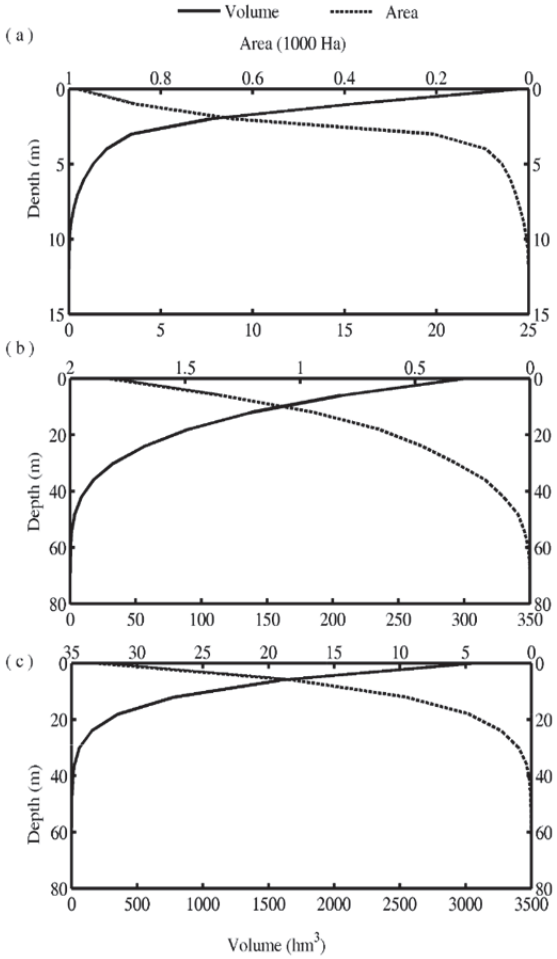


Fig. 6. Depth–area–volume curves for the lakes: a) Tammijärvi (L1), b) Isojärvi (L2) and c) Puula (L3) in Finland (http://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp).

The Godavari and Platte river hydrographs showed a strong seasonal pattern, with most discharge occurring from July–September (monsoon season) and April–July, respectively. The standard deviation for monthly scaled discharge for these rivers was 4.58 and 4.26, respectively. The Kor river regime also showed a seasonal intra–annual regime, but not as strong as that of the Godavari and Platte rivers, and its scaled annual hydrograph fell somewhere between seasonal and regulated (standard deviation for 40–year scaled monthly inflow data was 3.26) (Fig. 7b).

The climate in river regions varied in terms of mean effective precipitation depth (P–E) and temporal distribution of mean monthly precipitation within the year (Table 1 and Fig. 8a).

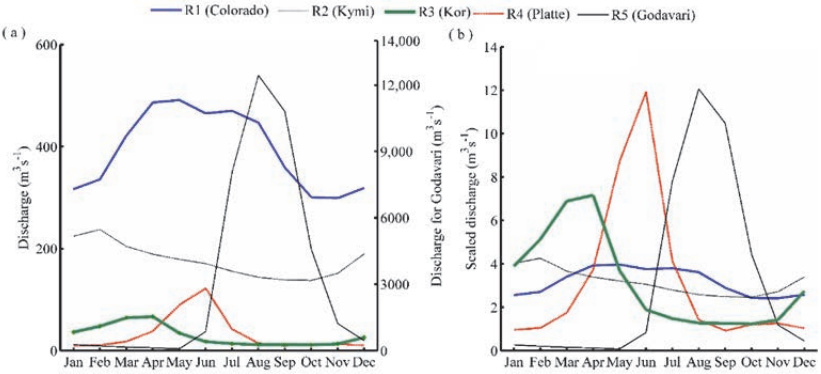


Fig. 7. Hydrological regime for different case studies with a) real discharge and b) scaled discharge.

As shown in Fig. 8a, the dry period for the Colorado and Kymi rivers is April–September, for Kor and Platte May–October and for Godavari December–May. To generate different water resource system cases (combination of river regime, climate and lake), each river regime (R1–R5) was placed upstream of each lake (L1–L3) in different climates (C1–C5). Monthly climate data for each river basin were used to obtain five series of monthly effective precipitation (P–E) for each climate zone. The wet period (the six consecutive months with the largest cumulative P–E) and the dry period (the other six consecutive months) were adjusted in time to fit the respective climate for each river. The original climate data are shown in Fig. 8a and the time–adjusted data considering the distribution of effective precipitation in Figs. 8b–d. For example, C3 (tropical savannah, Aw) climate data were obtained using as reference the monthly P–E data for the Godavari river (R5), for which the wet period is June–November. Therefore the wet period in other climate data was shifted to coincide with this period (e.g. data for Kymi were shifted forwards 4 months). This resulted in five monthly time series of different P–E, which were used to represent different climates found in tropical basins such as that of the Godavari (Fig. 8d). The effective precipitation values used for the Kymi and Colorado rivers are shown in Fig. 4b and those for the Kor and Platte rivers in Fig. 8c.

Table 3. Characteristics of the five river and five climate classifications used in simulations (Paper I).

River	Country	Available data years	Period use in simulation	Gauge stations	River system	Mean				Köppen climate type
						Inflow m^3s^{-1}	Prec. mm	Evap. mm	Temp. oC	
Kymi [a]	Finland	1900–2010	1968–2007	Pernoonkoski	Regulated	176.8	667	521	3.0	Dfc
Colorado [b]	USA	1934–2011	1968–2007	Below Hoover Dam	Regulated	392.6	155.4	3919	23.0	Bwh
Platte [c]	USA	1939–2011	1968–2007	AB Seminoe Reservoir	Seasonal	32.5	230	919	5.8	Bsk
Godavari [d]	India	1900–1975	1921–1960	Polavaram	Seasonal	3271.0	1087	2216	28.7	Aw
Kor [e]	Iran	1968–2011	1968–2007	Chamriz	Seasonal	29.5	550	2150	17.7	Cs

[a] River and climate data from http://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp.

[b] River data from http://waterdata.usgs.gov/nwis/monthly/; climate data from Climatography of the United States No. 20 and http://www.wrcc.dri.edu/htmlfiles/westevap.final.html.

[c] River data from http://www.sage.wisc.edu/riverdata/; climate data from http://www.tropmet.res.in.

[d] River and climate data from Fars regional water authority.

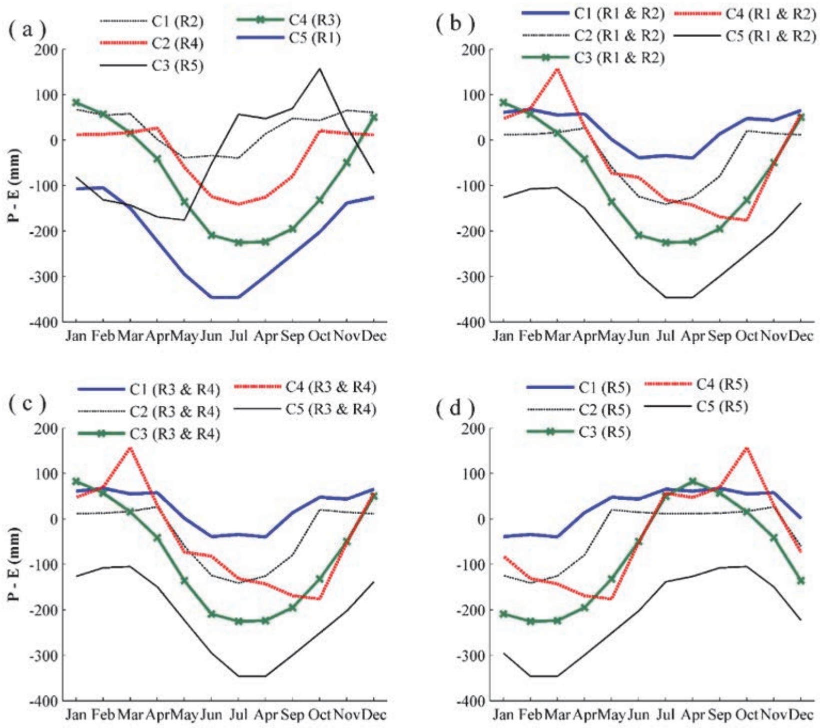


Fig. 8. Climate parameter ordering for different river systems. a) Original climate for different rivers, b) climate pattern data used for the Godavari river regime cases, c) climate pattern data used for the Platte and Kor river regimes cases and d) climate pattern data used for the Kymi and Colorado river regimes cases. C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer (Cs) and C5: hot, arid desert (Bwh).

3.4 Other case lakes and rivers

In addition to data on the Kor and Nile rivers, river flow data related to pre– and post– impact by dam for the Ebro river in Spain, Volga in Russia, Tigris in Iraq, Karkheh and Zayanderoud rivers in Iran, Kemijoki river in Finland, Yellow river in China, Cotter river in Australia, Niger and Kaduna in Nigeria, Kasegava river in Japan, Volta river in Ghana, Colorado and Feldhead river in USA were used for flow regime impact assessment (Fig. 9 and Table 4).

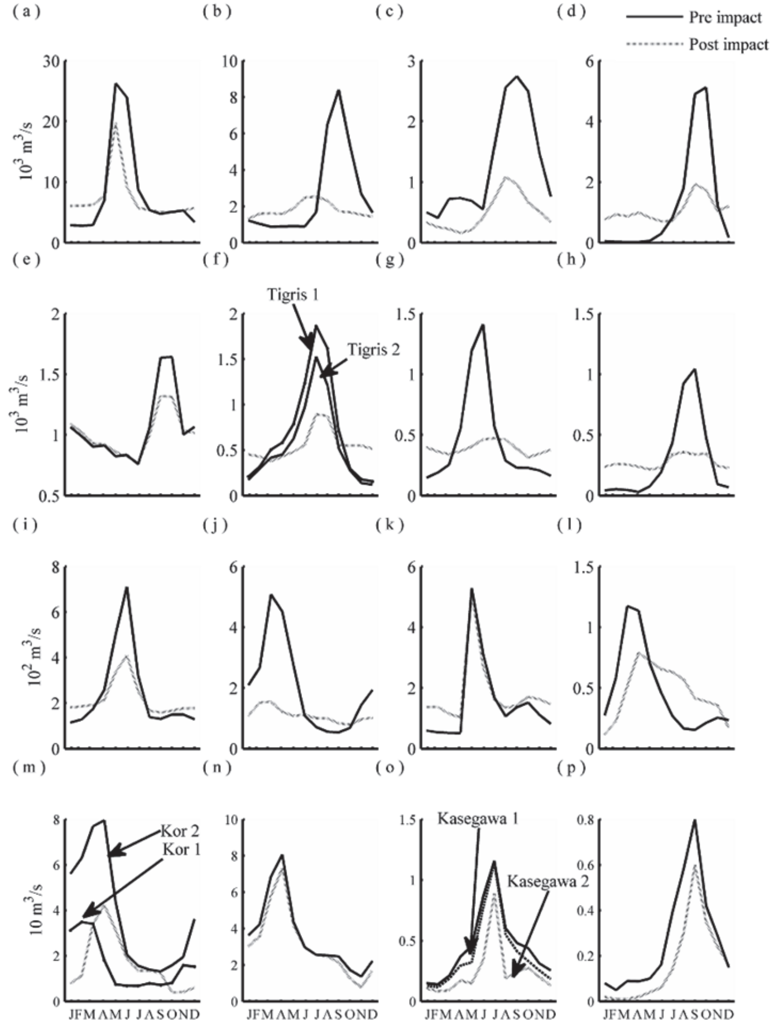


Fig. 9. Annual river hydrographs pre– and post–impact for the rivers: a) Volga, b) Nile, *c*) Yellow, d) Volta, e) Niger, f) Tigris, g) Colorado, h) Kaduna/Dinya, i) Flathead, j) Karkheh, k) Kemijoki, l) Zayanderoud, m) Kor at Doroudzan dam, n) Kor at Bande–Amir, o) Kasegawa and p) Cotter (Paper IV, reprinted with permission from Journal of Global and Planetary Change).

Table 4. Information on dams close to gauging stations for selected study rivers. IR = irrigation, WS = water supply, FC = flood control, HPP = hydropower) (Paper IV, reprinted with permission from Journal of Global and Planetary Change).

River	Country	Dam	Year opened	Dam height	Dam capacity	Dam area	Purpose(s) of dam				Coordinates		Period of impact		Flow data source
				m	km^3	km^2	IR	WS	FC	HPP	Lat.	Long.	pre	post	
Kemijoki	Finland	Taivalkoski	1975	25	0.05	16.5				x	65.93	24.71	1911–1950	1981–2013	1
Volga	Russia	Volgograd	1958	44	31.50	2613		x		x	48.83	44.68	1900–1935	1967–1980	22
Niger	Nigeria	Jebba	1976	40	3.60	360				x	9.14	4.79	1984–2010	1984–2010	3
Kaduna	Nigeria	Shiroro	1984	125	7.00	312				x	9.97	6.83	1990–2010	1990–2010	3
Volta	Ghana	Akosombo	1965	134	148.00	8482				x	6.17	0.2	1936–1963	1965–1979	2
Zayanderoud	Iran	Zayanderoud	1970	100	1.50	20.63	x	x		x	32.73	50.74	1972–2010	1972–2010	4
Karkheh	Iran	Karkheh	2001	127	5.60	166	x		x	x	32.49	48.13	1963–1999	2000–2009	5
Kor	Iran	Doroudzan	1972	60	0.99	55	x	x		x	30.21	52.42	1976–2008	1976–2008	6
Kor	Iran	Band Amir*	~900	9	0.001	0.01	x				30.21	52.42	1976–2008	1976–2008	*
Kasegawa	Japan	Hokuzan	1956	59	.020	1.7	x				33.43	130.24	B–dams**	A–dams**	7
Nile	Egypt	Aswan	1970	111	16.20	6500	x		x	x	23.97	32.88	1900–1970	1970–1981	2
Tigris	Iraq	Mosul	1985	22	3.50	122	x			x	36.61	42.46	1900–1937	1937–1984	8
Cotter	Australia	Corin	1968	76	0.075	2.5		x			–35.54	148.84	1911–1960	1969–1996	9
Yellow	China	Sanmenxia	1960	106	9.64	254.8	x		x	x	34.83	111.34	1958–1983	1984–2006	10
Ebro	Spain	Ebro	1945	34	0.54	54.3				x	42.97	–4.05	1913–1939	1975–1984	2
Ebro	Spain	Mequinenza	1966	81	1.53	47.8				x	41.37	0.27	1913–1939	1975–1984	2
Noguera Ribagorzana	Spain	Canelles	1960	150	0.68	11.3				x	41.98	0.61	1913–1939	1975–1984	2
Flathead	U.S.A	Kerr	1939	59	2.20	486.6				x	47.7	–114.2	1891–1939	1953–1995	2
Colorado	U.S.A	Glen Canyon	1963	216	2.50	120.7				x	36.9	–111.5	1921–1965	1965–2011	11

1: http://wwwp2.ymparisto.fi/scripts/oiva.asp , 2: http://www.sage.wisc.edu/riverdata, 3: (Olukanni & Salami 2012), 4: (Safavi et al. 2013), 5:(Madadi 2011),6: (Torabi Haghighi and Mohammadi, 2007), 7:(Supit & Ohgushi 2012), 8: (Al–Ansari et al. 2013, Saleh 2010), 9: (Nichols et al. 2006), 10: (Yang et al. 2012), 11: http://waterdata.usgs.gov/nwis.

*Data for Bande–Amir dam available at: http://www.frrw.ir/TabIndex.aspx?TabId=769, for other dams at: http://www.fao.org/nr/water/aquastat/main/index.stm, **No date mentioned in the source.

4 Methodology

To answer the research questions based on the river flow characteristics, several indices and methods were developed. First, a method for estimating the impact of dam construction on river regime was developed (Papers III and IV). Then a framework for analysing the sensitivity of water level fluctuations in lakes to climate and flow regime was established (Paper I). Finally, an approach to optimise EF regime was devised (Paper II).

4.1 Dam construction and river regime impacts

The impacts of dam construction on river regime can depend on the size of dams and the purposes of dam construction. Dams are constructed to work for single– or multi water purposes for municipal water supply, irrigation, flood control, hydropower etc. In general, the resulting impacts can affect any of the three main characteristics of monthly hydrographs: i) magnitude, ii) variability and iii) timing of flow (Fig. 10).

Water supply dams for domestic needs and irrigation consume water and can therefore have significant effects on the magnitude of flow (Fig. 10b). Water supply dams can also change the variability of flow (Fig. 10c). Dams for non–consumption purposes (like hydropower generation or for flood control) can have small effect on the magnitude of flow (because after changing the formation of the system from river to lake (reservoir), the rate of surface evaporation increases). These Dams can change the variability and timing of flow (Figs. 10c, d). Dams for irrigation purposes also alter the timing of flow if the season for water consumption is different from the high flow season of the river (Fig. 10d).

As shown in Fig. 10, the regime of rivers can be affected through the combination of these three functions. We therefore developed a river impact factor (RI) that considers all these parameters:

$$\mathrm{RI} = \mathrm{MIF} \times (\mathrm{TIF} + \mathrm{VIF}) \qquad (2)$$

where MIF, TIF and VIF are the flow magnitude, timing and variability impact factors, respectively.

The value of RI can range between 1 (natural river flow) and 0 (completely changed river flow). In equation (2), MIF is of equal importance to the sum TIF + VIF because flow magnitude is the controlling factor, i.e. if there is no flow there is no river and RI must be 0 (completely changed) if MIF is 0. The maximum impact of TIF or VIF is 0.5 and the sum is 1.

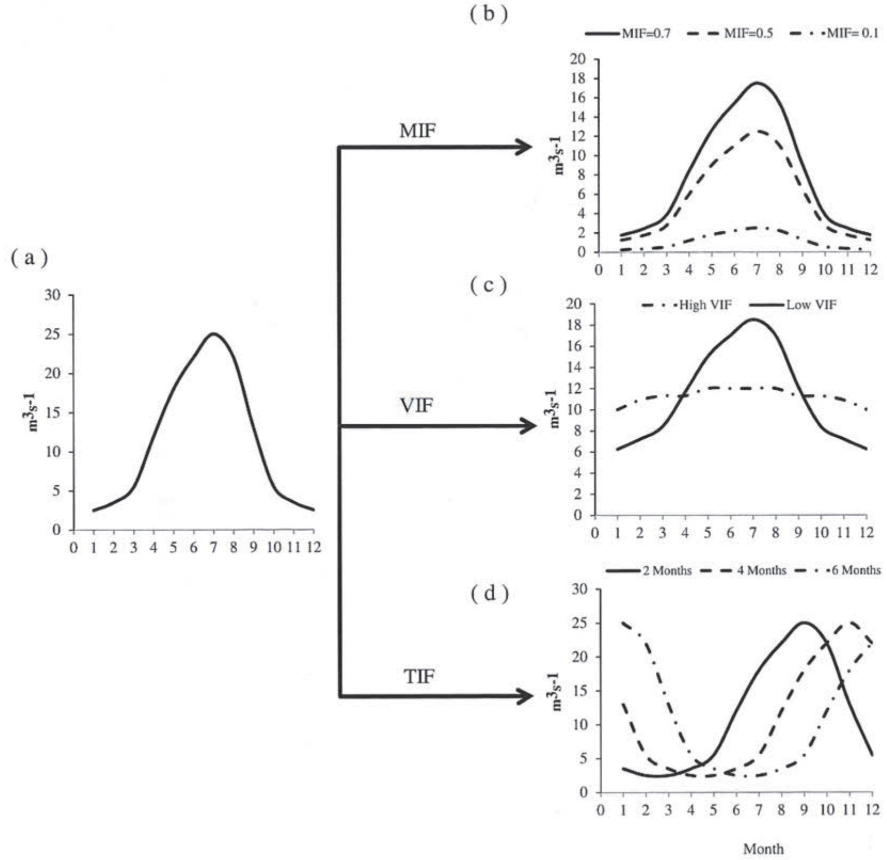


Fig. 10. Natural flow regime (a) and dam construction impacts on the flow hydrograph due to: b) the flow magnitude function (MIF), c) the flow regime alteration function (VIF), and d) the flow timing function (TIF) (Paper IV, reprinted with permission from Journal of Global and Planetary Change).

In some cases such as single purpose hydropower generation (HPP) dams, VIF is the most important factor, while in dams with irrigation or water supply, TIF is most significant alteration factor. In dams that have several purposes, the importance of these two factors is considered equal. TIF equals 0.5 when the timing has a maximum change (see Fig. 10d; the maximum change in timing is 6 months). VIF is 0.5 with the largest impacts in variability of flow.

4.1.1 Magnitude impact factor (MIF)

The flow magnitude impact factor (MIF) can be calculated as:

$$MIF_1 = AOF / AIF \tag{3}$$

or

$$MIF_2 = AF_{Post} / AF_{Pre} \tag{4}$$

where AOF is annual outflow from the dam (m^3 or $m^3\ s^{-1}$), AIF is annual inflow to the dam (m^3 or $m^3\ s^{-1}$), AF_{Post} is annual outflow from the dam after dam construction and AF_{Pre} is annual flow rate before dam construction. If the climate remains stable, MIF would be approximately the same for both the above calculations when a sufficient number of years is included in the pre– and post–construction periods. However, if the runoff record is variable, MIF_1 and MIF_2 will be different. By using Eq. 3, the sensitivity of the method to climate variability and differences in time series length can be removed. This is discussed further in the Results section, as the recommended IHA method uses the MIF_2 approach and this approach has some major weaknesses that are highlighted using the MIF_1 factor.

4.1.2 Variability impact factor (VIF)

The intra–annual flow variability factor (VIF) shows how the natural flow regime is changed after dam construction to more uniform flow (Fig. 10c). This impact factor is considered independent of flow magnitude. To enable comparison between different periods of impacted rivers in this regard, the intra–annual hydrograph of all rivers can be scaled to have equal flow rate of 100 hm^3 per year to produce whatcalls the unit river hydrograph. This parameter can be used to evaluate monthly flow directly as a proportion of annual flow (e.g. if July has 20 hm^3 flow, then its contribution to annual flow is 20%). The original monthly flow rate of a river is multiplied by the factor η, as defined in Eq. 1.

This scaling allows rivers of different sizes and discharge rates to be compared in terms of intra–annual regime, as demonstrated in Paper III using 12 annual river hydrographs for different parts of the Nile basin (Fig. 3). As can be seen in that diagram, the original monthly discharge for different rivers initially varied from 0 to 8900 m^3s^{-1} (left vertical axis), but after applying the unit river concept this variation changed to 0–60.

Variability of intra–annual flow regime can be altered between two extreme boundaries, a ‘uniform regulated river’ with constant monthly flow and a ‘dry river’ (ephemeral river) with all flow occurring during one month (Fig. 11). A ‘uniform regulated river’ has a monthly flow of exactly 8.333 hm^3 of total inflow (100 hm^3 divided by 12) and can be created by a reservoir with unlimited capacity. In the ‘dry river’ as defined here, all 100 hm^3 (or 100%) of annual flow occurs during one month and other months have 0 hm^3 flow, as is the case for ephemeral rivers (Fig. 11).

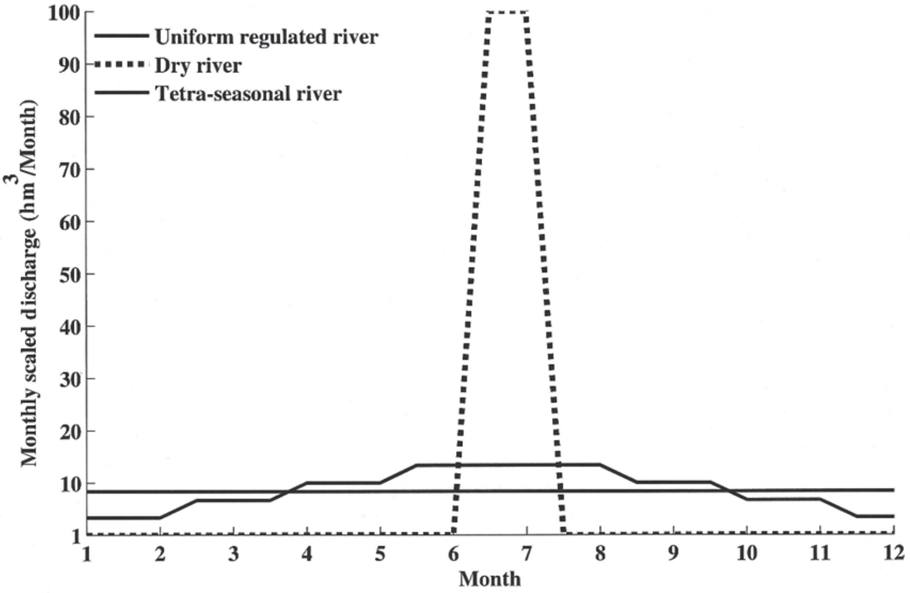


Fig. 11. Annual hydrograph for a uniform regulated river, a dry river and a tetra–seasonal river based on the unit river concept (Paper III, reprinted with permission from Journal of Hydrology).

Based on these two boundaries, the monthly river regime point (MRRP) was defined. The MRRP demonstrates how monthly flow deviates from a ‘uniform regulated river’ toward a ‘dry river’. Three extreme points were considered based on these two boundaries:

‘Uniform regulated river’ with constant discharge (Q) = 8.333 and MRRP = 0

‘Dry river’ with all flow occurring in one month: Q = 0 or Q = 100 and MRRP =100

where Q is the long–term average monthly unit flow rate for each month (based on the unit river concept explained above). To define the MRRP functions based on these endpoints three different models were developed and from those models, the following functions were selected as the best for assessing MRRP:

$$\text{If } 0 \leqslant Q \leqslant 8.333: \text{ MRRP} = -12 \times Q + 100 \tag{5}$$

$$\text{If } 8.333 < Q \leqslant 13.333: \text{ MRRP} = +12 \times Q - 100 \tag{6}$$

$$\text{If } 13.333 < Q \leqslant 100: \text{ MRRP} = 0.46 \times Q + 53.85 \tag{7}$$

Finally, the river regime index (RRI) can be obtained as:

$$\text{RRI} = \textstyle\sum_{k=1}^{12} \text{MRRP}(k) \tag{8}$$

where k is month number. An Excel calculator for determining RRI, developed using Visual Basic Programming, is attached as supplementary material in Paper III.

Based on this approach, RRI for the ‘dry river’ and ‘uniform regulated river’ is 1200 and 0, respectively. Thus it is possible to quantify a value between 0–1200 for each river hydrograph.

Comparison of annual river hydrographs pre– and post– impact can then clarify the effect of dams or other forcing factor (e.g. climate change) on the variability of flow rate due to impacts.

The intra–annual flow variability factor (VIF) is calculated based on following equations:

$$\text{VIF} = (50-0.5 \times \text{IRR})/100 \tag{9}$$

$$I_{RR} = \frac{ABS(RRI_{Pre} - RRI_{Pos})}{RRI_{Pre}} \times 100 \tag{10}$$

where RRI_{Pre} and RRI_{Pos} are the RRI index in the pre– and post– construction period (based on available data in different cases), respectively, ABS is the absolute value operator, and IRR is the percentage deviation in RRI. VIF is obtained by scaling IRR to a value between 0 and 0.5. The minimum value for

TIF +VIF is 0.25, as explained in the end of this section. The advantage of using the VIF function in comparison with using standard deviation of flow (post– to pre– change) is that VIF is independent of the magnitude of flow, while the standard deviation can be affected by the magnitude of flow.

4.1.3 Timing impact factor

Dams can also affect the temporal distribution of flow within a year. In many cases, the consumption season occurs in a different period of the year than the rainy season or high flow season. In hot and dry climates in particular, dams used for irrigation purposes store water in some months and release water in other months. For example, in Iran the majority of dams impound water during December–April and release it during March–October. This means that the seasonal order is changed totally, which can have effects on the ecology and geomorphology of downstream locations (Poff et al. 1997, Bowen et al. 2003, Gorski et al. 2011).

The flow timing impact factor (TIF) considers timing changes in maximum, minimum and timing of the 50% value of the discharge cumulative density function (cdf 50%; i.e. the point when cumulative discharge reaches the median):

$$\mathrm{TIF} = (50 - 0.274 \times \mathrm{TF})/100 \tag{11}$$

$$\mathrm{TF} = \frac{|DT_{Max}| + |DT_{Min}| + |DT_{Median}|}{3} \tag{12}$$

where DT_{Max} is the time shift in monthly maximum discharge, DT_{Min} the time shift in minimum discharge and DT_{Median} the time shift in cdf50 timing value (0–182.5 days), which can be obtained from the S–curve of monthly flow. The maximum TF value is thus 182.5. To scale the TIF to a maximum value if 0.5, the TF value must be multiplied by a constant, 0.274. The advantage of TF in comparison with the centre of gravity of post– to pre– change is that it considers the time of minimum and maximum flow, which are two important points for river geomorphology and ecology.

When VIF is 0, the impacted river flow has equal value for each month and there is no maximum or minimum value to be defined. The TIF function cannot be uniquely defined, as it can vary between 0 and 0.5 (no time lag or 6–month time lag). The minimum possible TIF for this case was therefore set as 0.25 (the average of 0 and 0.5).

Based on variation in impact factor, the range (0–1) can be grouped into five different impact classes (Table 5).

Table 5. Suggested values for river impact (RI) variations and boundaries (Paper IV, reprinted with permission from Journal Global and Planetary Change).

Range of RI	Impact class
$0 \leq RI < 0.2$	Drastic impact
$0.2 \leq RI < 0.4$	Severe impact
$0.4 \leq RI < 0.6$	Moderate impact
$0.6 \leq RI < 0.8$	Incipient impact
$0.8 \leq RI < 1$	Low impact

4.2 Lake regime index

The response of lakes to river flow regime changes could be considered as an indicator to evaluate the environmental impacts of river flow changes. In addition to being affected by flow regime, the lake response could also depend on the geometry of lake and the climate (especially in a hot, dry climate). The water level fluctuation was used here as the main criterion to assess changes in lake regime.

The water balance equation can be used to simulate lake water level response to changes in climate and river regime for different sizes of lakes assuming no groundwater exchange components (see Paper I).

$$S_{i+1} = S_i + (I' + 1.10^{-5} \times (P - c \times E) \times A - O) \tag{13}$$

$$A = (A_i + A_{i+1}) / 2 \tag{14}$$

where S_{i+1} (hm^3) is water budget on the first day of the next month in the lake, S_i (hm^3) is water budget on the first day of the current month in the lake (ith month of simulation), P (mm) is rainfall in the current month, E is pan evaporation in the current month, A (ha) is average lake area in the current month, I'(hm^3) is unit river inflow (Eq. 1), O (hm^3) is lake outflow that occurs after the lake water level exceeds the threshold capacity of the lake and c is a pan coefficient to convert the evaporation from pan to free water body surface. The recommended coefficient for class A land evaporation pan is 0.7 (Kohler et al. 1955, Webb 1966). Lake outflow (O) is dependent on the physical conditions of the lake–river connection point at the outlet of the lake. In different cases study, the lake outflow was calculated using the Kymi river rating curve when the lake level reached the threshold for outflow to occur.

The simulations were carried out for different lake initial conditions, assuming the lake to be full, semi–full and empty of water. The 'full' case represents the general situation for lakes in a cold, wet climate (e.g. in Finland, most lakes show low variations in annual water level) and the 'empty' case represents the situation in a hot, dry or moderate climate with extreme water use (e.g. Bakhtegan lake downstream of the Kor river in Iran shows high fluctuations in water level, drying out completely in October in some years). By considering these three states, we generated 225 different water resource systems to be simulated (3 lakes x 5 rivers x 5 climate types, resulting in 75 cases, multiplied by 3 initial states, giving 225 cases). The response in these lakes to different river and climate forcing was calculated using data from the five rivers with different regimes listed in Table 3.

In order to show the impact of river discharge on lake levels, the concept of capacity inflow ratio (CIR) was used. It is defined as the ratio of maximum lake capacity to mean annual river flow (Rami Reddy 2005):

$$\mathrm{CIR} = \mathrm{MLC}/\mathrm{MAF} \qquad (15)$$

where MLC is maximum lake capacity or volume (m^3) and MAF is mean annual river flow (m^3). Lake geometry can be represented as hypsographic (area–volume–depth) curves and maximum lake capacity can be calculated from topographical maps and lake area–volume–depth curves. By selecting 100 hm^3 as scaled flow, a good variation in CIR from below 1 to 30 was obtained. As CIR can also be interpreted as nominal or theoretical residence time (V/Q), the scaling produced residence times from 0.24–30 years, which is typical for a wide distribution of lakes (Albert et al., 2005).

In order to show the effect of different controlling factors (net precipitation and river flow) on lake hydrological status (e.g. as a habitat), the degree of lake wetness (DLW) was defined. Lakes can be divided into five wetness categories based on lake volume as a percentage of total volume or nominal volume as: dry (<20%), semi–dry (20–40%); normal (40–60%), semi–wet (60–80%) and wet

(>80%). Based on the simulation results or real data on past lake level fluctuations, the length or duration (number of months) of that water level in different zones can be calculated. Using the calculated distribution into different wetness categories, DLW is then calculated as:

$$DLW= (A_1\times10+A_2\times30+A_3\times50+A_4\times70+A_5\times90– 1000) / 8000 \qquad (16)$$

where the A1, A2, A3, A4, A5 variables are the percentage of time that the lake is in dry, semi–dry, normal, semi–wet and wet conditions, respectively (duration in months/total record, here total record was 480 months). The time percentage was obtained from the simulation results and based on the area–volume–depth curve. The DLW can vary between 0–1. If the lake experiences more than 80% of maximum capacity (A5=100 and A1–A4=0) in all months of the year, DLW is 1 (higher boundary condition for DLW). If the lake experiences less than 20% of maximum capacity (A1=100 and A2–A4=0) in all months of the year, DLW is 0 (lower boundary condition for DLW). The values 1000 and 8000 in Eq. 16 are two constants to scale the boundary conditions to 1 and 0 when DWL is calculated. DLW of a lake can be calculated based on historical lake operation data, estimated by aerial photo or satellite data for previous years or simulated based on time series data, as mentioned previously. For different cases, DLW was simulated based on 40 years of data. Based on DLW, the lakes were classified into five groups as shown in Table 6. The DLW index can be evaluated as an absolute value DLW_1 (zoning of percentage of total volume is considered based on lake geometry, with volume altering from 0 to maximum physical volume) or a or relative value DLW_2 (based on lake historical level fluctuation, with volume altering between minimum and maximum recorded in the lake). Both approaches were used in this thesis, but maximum level estimation for some closed lakes in hot, dry climates requires special effort to obtain past lake levels.

Table 6. Lake classification based on Degree of Lake Wetness (DLW).

Lake group	DLW range	Lake description
I	$0.0 \le DLW < 0.2$	Closed, predominantly dry lake
II	$0.2 \le DLW < 0.4$	Closed, temporarily dry lake
III	$0.4 \le DLW < 0.6$	Closed, intermittent lake
IV	$0.6 \le DLW < 0.8$	Open, temporarily wet lake
V	$0.8 \le DLW< 1.0$	Open, predominantly wet lake

In order to show the range of lake volume variation, the maximum–minimum and absolute maximum–minimum ratios can be calculated based on the long term simulation results as:

$$MMR=((Max_{volume}- Min_{Volume})/Mean_{volume}) \quad (17)$$

$$AMR=((AMax_{volume}- AMin_{Volume})/Mean_{volume}) \quad (18)$$

where Max_{volume}, Min_{Volume}, $Mean_{volume}$, $AMax_{volume}$ and $AMin_{Volume}$ are mean annual maximum volume, mean annual minimum volume, mean volume, absolute monthly maximum volume and absolute monthly minimum volume during long–term simulations, respectively.

Another important parameter that can show lake historical performance is the amount and duration of outflow (NSP). Occasionally, due to a high amount of inflow or low lake capacity, some part of inflow is conveyed out of the lake system. Thus at the end of simulations, the number of months when spilled water occurred (NSP) shows how long the lake has been connected to the downstream.

4.3 Environmental flow regime

To develop the optimum environmental flow regime, a modified catchment with a dam in upstream and downstream residual catchment was assumed (Fig. 12). Then a certain amount of water was allocated for EF. The optimum annual distribution for these allocated flows was determined based on the two predetermined targets for aquatic ecosystem protection. For the first target, the goal for EF release (reference point) was at the end of the catchment (point A in Fig. 12 or the lake). The residual area for this point was taken to be equal to all the area downstream of the dam. For the second target, the goal for EF allocation was river re–creation at point B. The residual area for this case was an area downstream of the dam, between the dam and point B (Fig. 12). The reference points for both targets in the Bakhtegan catchment are listed in Table 1. Based on this assumption, the optimal EF intra–annual regime as follows:

The natural annual hydrograph (NAH) was defined from monthly average discharge (Q) values at the gauging stations used as reference points and the EF release points in natural conditions before any regulation as the following matrix (for case study points see Fig. 5a):

$$[Q_{NAH}] = [Q_1\ Q_2 \ldots.\ Q_i \ldots Q_{11}\ Q_{12}] \quad (19)$$

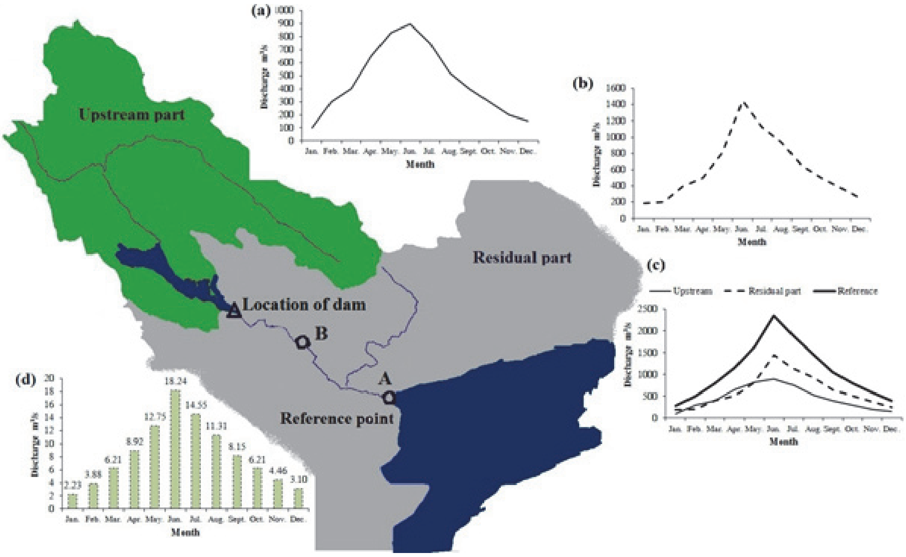


Fig. 12. Characteristics of the basin after construction of the main reservoir for hydropower and irrigation needs. a) Upstream hydrograph, b) residual hydrograph, c) reference hydrograph, and d) monthly percentage of annual flow hydrograph.

This was scaled to a standardised annual hydrograph for reference points (PR_{SAH}) to show the percentage of monthly flow at target points (Fig. 5b) as:

$$[\,PR_{SAH}\,] = [PR_1\ PR_2 \ldots\ldots PR_i \ldots\ldots PR_{11}\ PR_{12}] \tag{20}$$

where

$$PR_i = \frac{Q_i}{\sum_{i=1}^{12} Q_i} \tag{21}$$

with Qi being monthly discharge in month i.

Based on the location of a reference point and dam position in basin layout, the annual natural flow ($[Q_{NAH}]$) at the reference point was divided into two parts, the first belonging to upstream of the dam (Q_{up}), which would be regulated in the future, and the rest belonging to downstream of the dam (Q_{RES}), which could remain in pristine condition after dam construction and regulation (Fig. 5a–c):

$$[Q_{NAH}] = [Q_{up}] + [Q_{RES}] \tag{22}$$

where $[Q_{up}]$ is the natural flow hydrograph at the EF release location (for this case study the Doroudzan, Shoor–Shirin, Mollasadra and Gavgodar gauging stations;

see Fig. 5a) and [Q_{RES}] is the residual hydrograph based on the target points and EF release location (Figs. 5c, d).

Based on real data and using Eq. 22, the residual hydrograph for the two target points could be defined (Figs. 5c, d). However, hydrological models could be used to develop Q_{NAH} and Q_{up} in cases where gauged data are lacking.

After regulation, the upstream parts of the annual hydrograph [Q_{up}] at the reference location were changed to a regulated or variable part that is released by the dam and the new hydrograph at the reference point changed to RAH:

$$[\, Q_{RAH} \,] = [\, Q_{VAR} \,] + [\, Q_{RES} \,] \tag{23}$$

Part of the regulated flow can be consumed for downstream needs such as irrigation (Q_{CON}) and the rest would be the allocated flow for other purposes such as flood control, hydropower (with the release water considered non–consumed water) and environmental flow (Q_{EF}). Therefore the regulated flow was:

$$Q_{VAR} = Q_{EF} + Q_{CON} \tag{24}$$

The magnitude of available annual discharge (Q_{AAD}) at the reference point was:

$$Q_{AAD} = Q_{VAR} - Q_{CON} + Q_{RES} = Q_{EF} + Q_{REF} \tag{25}$$

The monthly natural distribution of Q_{AAD}, assuming similar natural hydrological characteristics at the reference point (upstream and residual catchments), could then be estimated using Eq. 26:

$$[Q_{CAH}] = Q_{AAD} \times [PR_1\ PR_2 \ldots\ldots PR_i \ldots\ldots PR_{11}\ PR_{12}] \tag{26}$$

Finally, the intra–annual regime of EF was calculated as:

$$[\, Q_{EF} \,] = [\, Q_{CAH} \,] - [\, Q_{RES} \,] \tag{27}$$

The optimal environmental intra–annual flow regime is obtained when Q_{AAH} is close to the natural flow regime at the reference point.

In some cases, due to the location of the dam and the area of the residual sub–catchment, for some months Q_{RES} can exceed Q_{AAH}. Thus it is recommended that the EF intra–annual regime be optimised based on the following condition:

$$\text{Minimise } \sum_{i=1}^{12} (Q_{CAH}\, i - (Q_{EF} i + Q_{RES} i)$$

$$\text{when } (Q_{CAH}\, i - (Q_{EF} i + Q_{RES} i) > 0 \tag{28}$$

The optimisation could also include additional limitations, such as ecological criteria:

$$Q_{EF}i \geq Q_{EMIN}i \quad (29)$$

where Q_{EMINi} is the minimum discharge requirement in month i, based on ecology, geomorphology, dam restrictions or other environmental requirement if desired and the data are available. Based on these two conditions (Eqs. 28 and 29), the reduction in monthly flow at the reference point will be compensated for by the optimised EF regime which is released by the dam.

In the present thesis this optimisation was carried out using the Solver box in Microsoft Excel, but it is also possible to use simplex linear programming or the GRG (Generalized Reduced Gradient) algorithm as a powerful non–linear programming method.

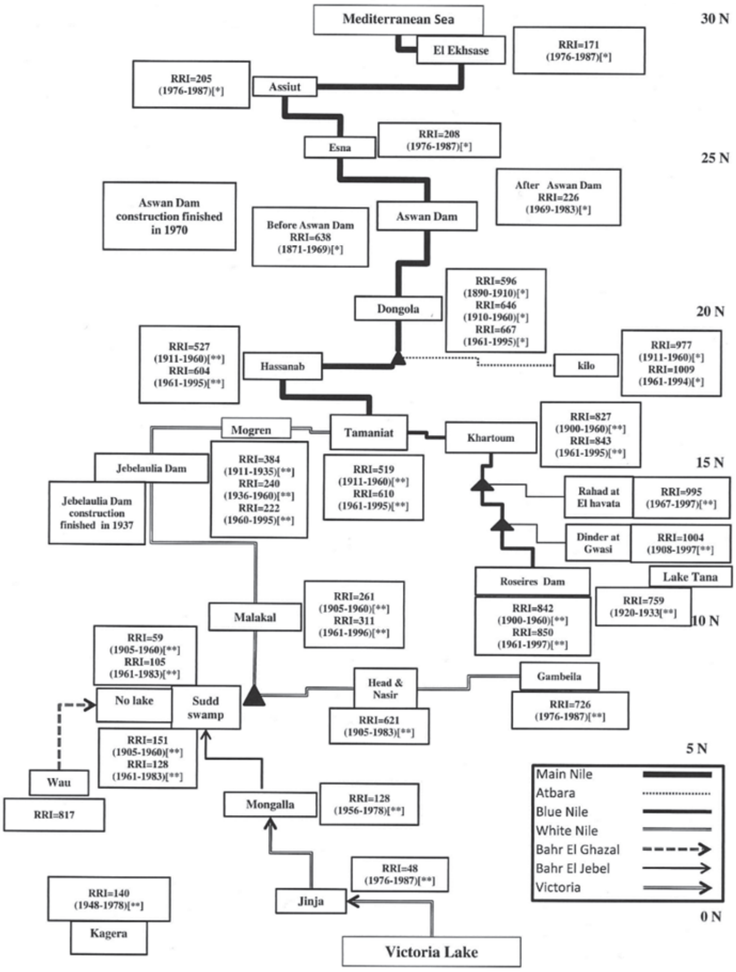
5 Results

The key results obtained in this thesis as regards the four main areas studied: i) river regime, ii) impact of river regime, iii) lake regime and iv) environmental flow regime, are presented in the following sections. More detailed results can be found in Papers I–IV.

5.1 River regime index

There was a clear impact on RRI in the Nile basin after construction of the Aswan, Jebel Aulia, Khashm El Gibra and Roseires dams (Fig. 13). After construction in 1971 of the Aswan dam (capacity 169 km^3, or approx. 2.5 times the annual Nile flow rate of 68 km^3), the RRI changed from 638 (for the period 1871–1969) to a regulated river with low fluctuation in intra–annual regime (RRI = 226 for the period 1969–1983) (see Figs. 3e, f).

The RRI at Morgan station, immediately after the Jebel Aulia dam on the White Nile, was 384 before dam construction (1911–1935) and 222 after dam construction (1936–1960). The other dams on the Nile river do not have such significant effects as the Aswan and Jebel Aulia dams, as their capacity is lower than the annual river discharge. The Roseires and Khashm El Gibra dams do not have any significant effect on river regime, as their capacity is much lower than annual river discharge (e.g. the capacity of Roseires dam is 3 km^3, compared with annual flow of 44 km^3 in the Blue Nile). The RRI is affected by wetlands, marshes and other land uses or changes due to mixing of different river tributaries. The RRI for Baro river (tributary of White Nile, Gambeila and Head & Nasir gauging stations in Fig.13) is reduced from 726 to 621 because of meeting the Sobat wetlands and Machar Marshes. The RRI of Bahr el Jebel, another tributary of the White Nile, before and after Sudd wetlands is 151 and 62, respectively. These two examples show that wetlands reduce flow fluctuations and that when wetland size decreases, an increase in flow fluctuations can be expected. The Malakal gauging station (RRI=261, see Fig. 3b) is located after the confluence of the Bahr el Jebel and Baro tributaries, resulting in RRI of 261 at that station. The Baro river at Gambeila (Fig. 13), the Wau river at Jur in the White Nile headwaters (see Fig. 3h) and some headwaters of the Blue Nile, such as Tana Lake, are almost pristine and affected by a monsoon and savannah climate, and the RRI obtained for these rivers was 600–800 (Fig. 13). In the hot arid and semi–arid zone, for example the regions in the north–east of the Nile



*: Global River Discharge Database2010, [Homepage of center for sustainability and the global environment], [Online]. Available: http://www.sage.wisc.edu/riverdata/

**: Sutcliffe. J. V, Parks. Y. P. 1995, The Hydrology of the Nil, IAHS

Fig. 13. RRI in different tributaries of the Nile. For Nile river stations, Aswan A and B refer to RRI calculated after and before Aswan dam construction, respectively, while Morgan and Dongola A and B refer to after and before Jebel Aulia dam construction, respectively. (Paper III, reprinted with permission from Journal of Hydrology).

basin, the river regime tends to be seasonal and ephemeral and these rivers have a high RRI (more than 900), as shown here for the rivers Atbara, Rahad and Dinner (Fig. 13). The lowest RRI in the Nile basin area was found at Jinja station, which is affected by the flow–regulating effect of Lake Victoria, in addition to climate. In this area, the river regime comprises uniform flow during the year due to the even distribution of annual precipitation. A full analysis of longitudinal changes in RRI along the Nile river can be found in Paper III.

RRI as a quantitative parameter can be calculated for different time slots, and by comparing RRI for different periods the effect of climate change and climate variability on intra–annual flow regime can be evaluated. This is done in Fig. 13 for the Atbara at Kilo, the Blue Nile at Khartoum, the Roseires dam and the inflow and outflow of the Sudd wetlands, where RRI was calculated for two time periods.

5.2 Quantification of the impacts of different types of dams on river regime

The analysis of rivers in different regions showed that those most affected by dams were the Nile at the Aswan dam, the Karkheh at the Karkheh dam, the Kor at the Doroudzan dam and the Lower Yellow at the Lijin gauge station. The Aswan, Karkheh and Doroudzan are large multi–purpose dams. For the Lower Yellow and Kor rivers, the low RI impact index resulted mainly from a considerable decrease in flow magnitude (MIF = 0.39 and 0.44, respectively; lowest of all cases) and only minor alterations in flow timing and variability. In the Nile, the Aswan dam changed the flow magnitude, timing and variability, but in the Karkheh the magnitude and regime were altered by the Karkheh dam (Table 7 and Fig. 14).

The RI index showed a moderate impact of dam construction on the Colorado, Volta, Kaduna, Volga, Kasegawa and Cotter rivers. The dams in question (except in the Volga) are all single–purpose dams (see Table 4), with those in the Colorado, Volta and Kaduna providing hydropower and those in the Kasegawa and Cotter supplying irrigation and water supply systems. The Kor at the Bande–Amir dam and the Kemijoki were classified as having a low impact on river monthly flow regime. The Bande–Amir is a diversion dam with a small reservoir for irrigation, while the Kemijoki river is affected by fairly low–capacity reservoirs compared with the annual flow as run–of–river (ROR) hydropower.

The Zayanderoud and the Tigris at the Mosul dam were classified as incipient impact rivers (Fig. 14).

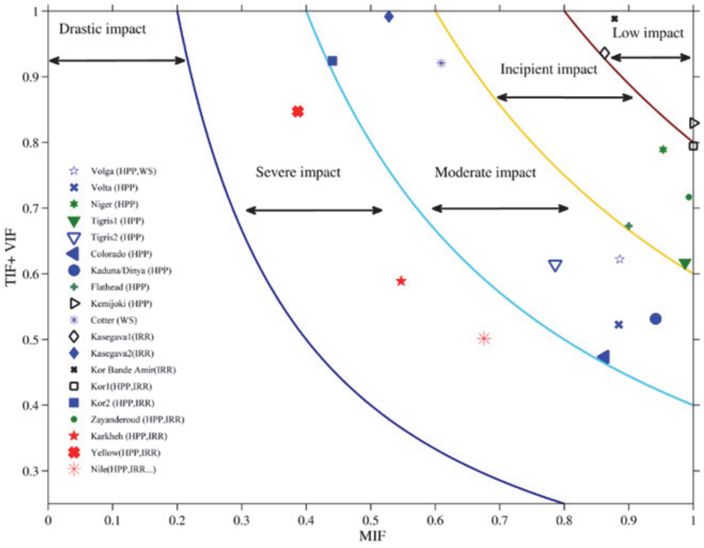


Fig. 14. River regime impact classification for 15 international rivers (Paper IV, reprinted with permission from Journal Global and Planetary Change).

The boundary lines in Fig. 14 were generated by combining Eq. 2 and Table 5. The RI index showed a low impact of ROR dams with small reservoirs, even when the river network was affected by many dams, e.g. the Kemijoki in Finland, while other single purpose dams for hydropower or flood control (non–consumer dams) with a huge reservoir could have a greater effect on river regime, e.g. Akosombo dam on the Volta in Ghana. For single–purpose dams used for water supply (e.g. urban water supply), the RI will be more or less equal to the magnitude factor (MIF). An example of this is the dam in the Cotter river in Australia, which was constructed to supply water to Canberra. In dams for irrigation purposes, the impact of single–purpose dams is more dependent on irrigation timing and season and the magnitude of irrigation demand, whereas for diversion dams the impact is mainly dependent on water consumption. If consumption is less than 20%, then the dam can be classified as a low impact dam (e.g. the Bande–Amir dam in Iran). The overall impact mainly depends on inflow magnitude, storage capacity, demand and operating policy.

Table 7. Impact factors for other international rivers. MIF, VIF, TIF = magnitude, variability and timing impact factors, RI = river impact (Paper IV, reprinted with permission from Journal Global and Planetary Change).

River	Station or dam location	Impact factors				Impact class
		MIF	VIF	TIF	RI	
Volga	Volgograd	0.89	0.27	0.35	0.55	Moderate
Nile	Aswan	0.68	0.17	0.33	0.34	Severe
Yellow	Lijin	0.39	0.44	0.41	0.33	Severe
Volta	Akosombo	0.88	0.17	0.34	0.45	Moderate
Niger	Jebba	0.95	0.33	0.46	0.75	Incipient
Tigris1	Mosul	0.78	0.20	0.41	0.48	Moderate
Tigris2	Mosul	0.99	0.21	0.41	0.61	Incipient
Colorado	Lees Ferry	0.86	0.11	0.37	0.41	Moderate
Kaduna/Dinya	Shiroro	0.94	0.12	0.41	0.50	Moderate
Flathead	Kerr Dam	0.90	0.29	0.39	0.61	Incipient
Karkheh	Karkheh	0.55	0.17	0.42	0.32	Severe
Kemijoki	Taivalkoski	1.00	0.33	0.50	0.83	Low
Zayanderoud	Zayanderoud	0.96	0.47	0.33	0.77	Incipient
Kor 1	Doroudzan	1.00	0.47	0.32	0.79	Incipient
Kor 2	Doroudzan	0.44	0.47	0.45	0.41	Moderate
Kor 3	Bande–Amir	0.88	0.49	0.49	0.86	Low
Kasegawa 1	Hokuzan	0.86	0.44	0.50	0.81	Low
Kasegawa 2	Kase Dam	0.53	0.49	0.50	0.52	Moderate
Cotter	Corin dam	0.61	0.44	0.48	0.56	Moderate

5.3 Response of lakes to climate and river regimes

The results showed that the lake response to water balance changes is dependent on: i) effective precipitation or climate, ii) size of lake, iii) river regime and iv) initial condition of lake level/capacity. The response time (Fig. 15) for lake level to reach dynamic equilibrium for the three different lake initial conditions (full, medium, empty) depends on the CIR. The equilibrium time is obtained from the

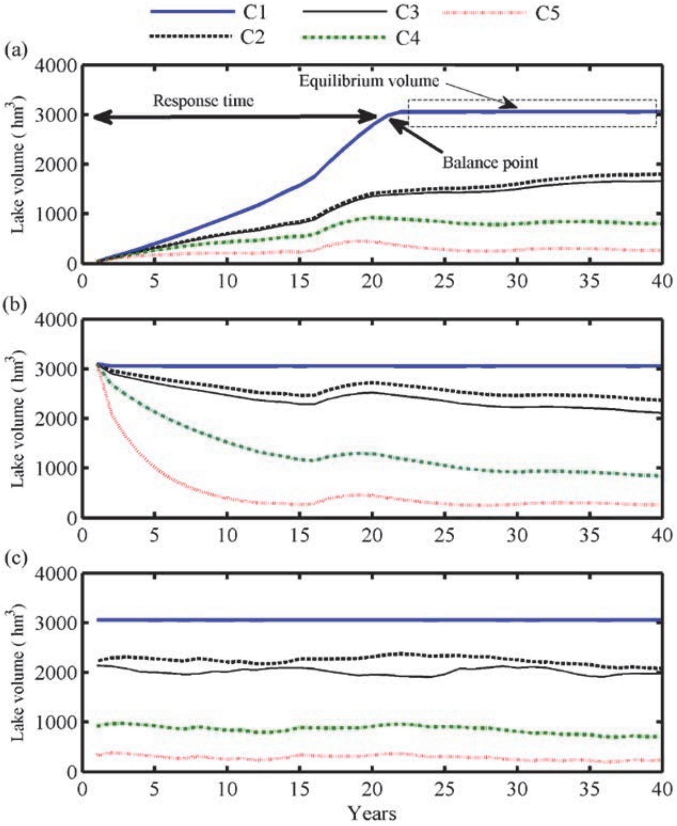


Fig. 15. Lake volume fluctuation for lake L1 (CIR=30) with River R2 (Regulated river system Kymi regime) in different climates. a) Rising state (volume at start point is empty), b) falling state (volume at start point is full) and c) stable state (volume at start point is intermediate). C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer (Cs) and C5: hot, arid desert (Bwh).

mean of final volume for initial conditions full and empty. It took from several months for low CIR to several years for high CIR when the initial volume was full or empty (high and low water level, respectively). For example, the results for three initial conditions for lake model L3 (Puula lake with CIR=30) with the Kymi river inflow regime R2 (R2C1L3, R2C2L3, R2C3L3, R2C4L3 and R2C5L3; Figs. 15a–c) showed a long response time of about 20 years for the lake to reach dynamic equilibrium for empty (Fig. 15a) or full (Fig. 15b) initial conditions, respectively. For the third initial condition (lake in dynamic equilibrium, Fig. 15c), the response time was short (almost zero). The response time was slowest for small lake systems, i.e. about five years for a lake with CIR=3.0 (L2), and less than one year for a lake with CIR=0.24 (L1). When the initial condition was close to steady state, there was no response time. Fig. 15a could represent an example of an impacted (vanished) lake projected for recreation with 100 hm^3 flow rate (e.g. as environmental flow allocation). As the diagram shows, the equilibrium volume would be obtained after 20 years in that case. In contrast, Fig. 15b could be considered a natural lake supplied by a river subjected to several constructions (dams), reducing the flow to 100 hm^3, so it has started to shrink and the final impacted state of the lake would be observed after about 20 years.

The final steady state equilibrium lake volume in different months depends on climate and river regime (Figs. 16, 17). The lake levels fluctuate around an equilibrium volume, as seen in Fig. 16. For example, a lake with high CIR (e.g. L3 Puula) and with a regulated river inflow regime (e.g. R2 Kymi) would have a different volume in different climates, varying between 286 hm^3 for a hot, arid desert climate to 3000 hm^3 for a cold, wet climate (C1). For lakes with low CIR, the equilibrium lake volume can be defined as the maximum water capacity of the lake, e.g. for L1 and L2, the major parameter defining the equilibrium volume of the lake is the maximum physical volume, which is 300 and 24 hm^3, respectively. Following a change in CIR or climate pattern, the lake level will find a new equilibrium volume, although as the results in Fig. 15 show, this can take more than 20 years for large lakes.

Lakes in a cold, wet climate have the smallest annual water volume changes (Figs. 16, 17). The monthly lake volume fluctuation increases when the CIR increases, as seen e.g. from water volume simulations for R3C5 (Fig. 16).

The monthly lake volume variation also increases as the flow regime changes from uniform to seasonal, as seen by comparing e.g. cases R1C4, R2C4, R3C4, R4C4 and R5C4 (different river regimes in climate C4). In the uniform flow regime (low fluctuation in monthly discharge; e.g. R1 (Colorado) and R2 (Kymi) with SDED = 0.96 and 1.52, respectively), the lake monthly variation (R1C2–R1C5 and R2C2–R2C5, see Fig. 7) follows the climate pattern (Fig. 8), while in a highly seasonal flow regime like that of R5 (Godavari) and R4 (Plate) (SDED = 4.85 and 4.26, respectively), the pattern of monthly distribution of lakes (R5C1–R5C5 and R4C2–R4C5; Fig. 16) is similar to the flow regime pattern (Fig. 7).

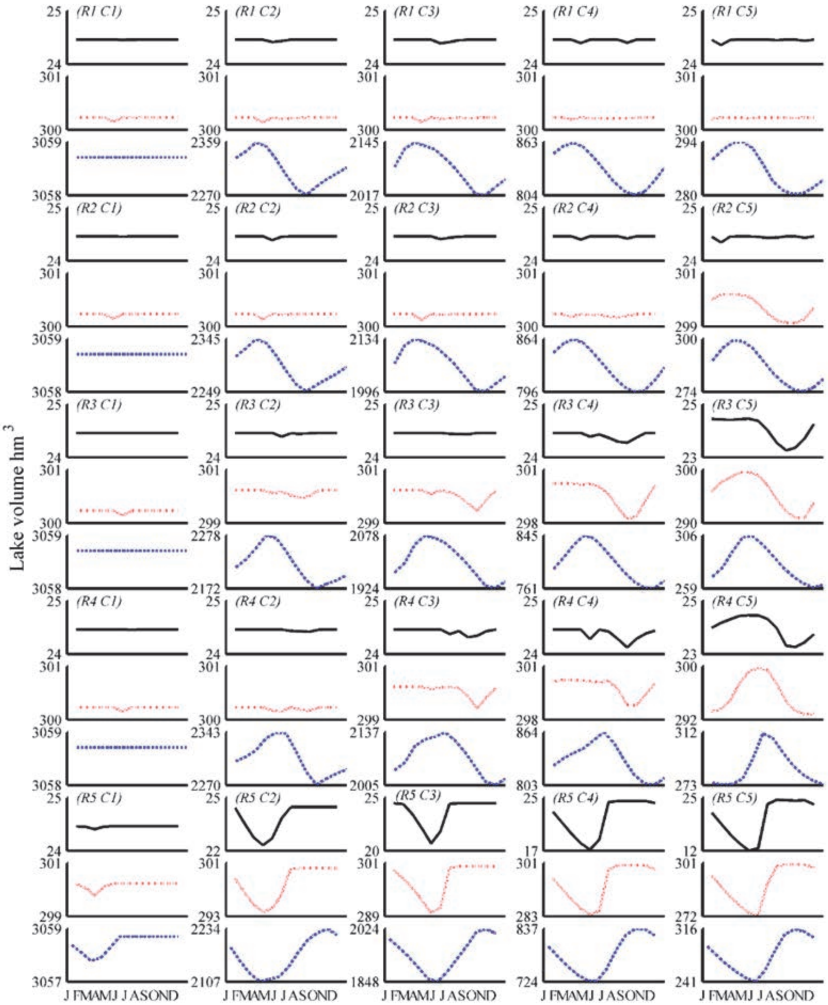


Fig. 16. Long–term monthly average (40 years) for different lake systems based on the third initial condition. Black solid line: lake L1 CIR=0.24, red dashed line: lake L2 CIR=3, blue dotted line: CIR=30. R1: Colorado river regime, R2: Kymi river regime, R3: Platte river regime, R4: Kor river regime, R5: Godavari river regime, C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer (Cs) and C5: hot, arid desert (Bwh).

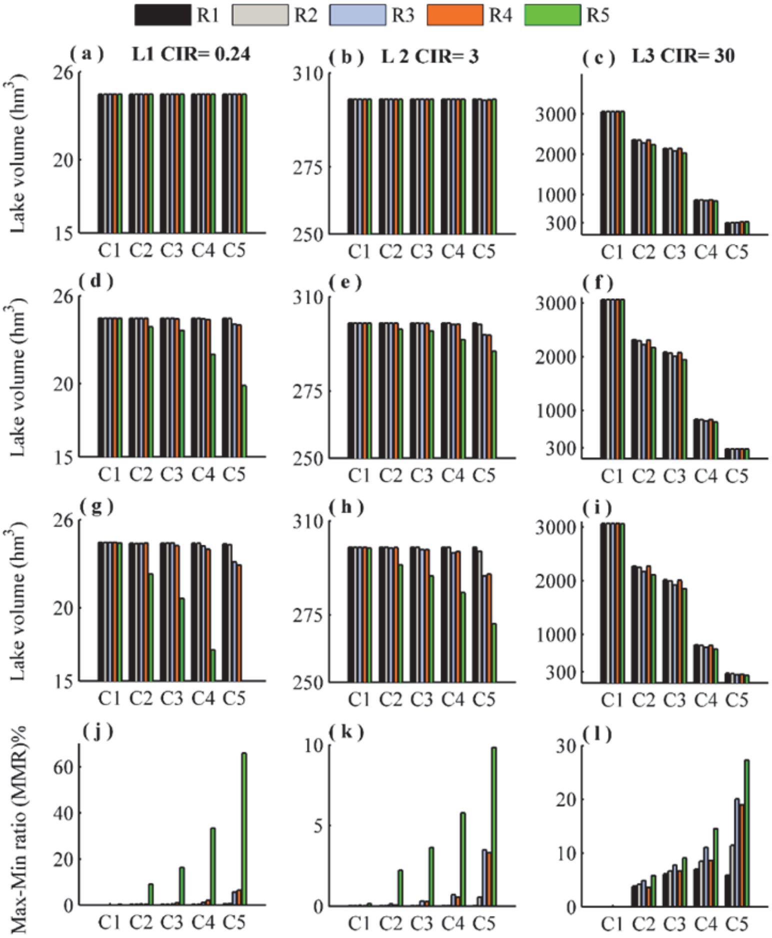


Fig. 17. Summary of the simulation results for different lake systems. a–c) Mean monthly maximum lake volume, d–f) mean monthly lake volume, g–i) mean monthly minimum lake volume and j–l) max–min ratio (MMR), R1: Colorado river regime, R2: Kymi river regime, R3 Platte river regime, R4: Kor river regime, R5: Godavari river regime, C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer (Cs) and C5: hot, arid desert (Bwh).

The simulation results showed that for lakes with small CIR (L1 and L2 cases), the maximum annual lake volume is quite similar for different climate and inflow regimes (Figs. 17a, b). These lakes reach the maximum water level every year and outflow (spill) occurs. The minimum water level in these lakes depends on the flow regime in climates C2–C5 (Bsk, Aw, Cs, and Bwh), but not in climate C1 (Dfc) (Figs. 17g, h). For lake L3 with CIR=30, the maximum, minimum and mean lake water volumes are mostly dependent on climate and only slightly on river regime (Figs. 17 c, f, i). The maximum–minimum (MMR) and absolute maximum–minimum ratio (AMR) in lakes L1–L3 are dependent on climate (increased from C1 to C5) and flow regime (increased from R1 to R5) (Figs. 17 j–l, Tables 8–10). The difference in MMR and AMR increases when the flow regime shows high monthly variation from uniform (R1) to seasonal (R5), as seen in Tables 8–10.

The lake level change indicator developed here, DLW, is sensitive to changes in lake hydrology, climate and river regime. DLW_1 provides general results where lakes are compared and DLW_2 provides an indicator to show past historical stages. For lakes with CIR=30, DLW_1 is 0.00 (‘Closed predominantly dry lake’), 0.25 (‘Closed temporarily dry lake’), 0.72 (‘Open temporarily wet lake’), 0.75 ‘Open temporarily wet lake’) and 1 (‘Open predominantly wet lake’) for the climates C5–C1 (Bwh, Cs, Aw, Bsk and Dfc, respectively). Using DLW_2, lake systems with CIR=30 are classified as ‘Open predominantly wet lake’ for a cold, wet climate with continuous discharge surplus. For other climates and river regimes they are classified as ‘Closed intermittent lake’ (Table 8). With DLW_2, lake systems with CIR=3 are classified as ‘Open predominantly wet lake’ for all river regimes in C1 climate and most other cases except for rivers R3 and R4 in C5 climate and river R5 in other climates, which are classified as ‘Open temporarily wet lake’ (Table 9). With DLW_2, lake systems with CIR=0.24 are classified as ‘Open predominantly wet lake’ for all cases except river R5 in all climates C2–C5 (Bsk, Aw, Cs and Bwh), which is classified as ‘Open temporarily wet lake’ (Table 10).

Given a certain climate and flow regime, the lake type (as open or closed) is controlled by the CIR. Lakes in a cold, wet climate are always open (have an outlet), but for lakes in other climates this depends on CIR. The amount of discharge or spill (NSP) shows that lakes with high CIR in a cold, wet climate spill water in 98–100% of the simulated months (480 months), whereas in other climates the lakes with high CIR are closed lakes. Smaller lake systems with CIR=3.00 discharge water most of the time when the river regime is regulated and have a uniform flow regime (see first eight rows in Table 9). For medium–sized lakes with uniform flow in a temperate or hot, arid climate (R2C4L2 and R2C5L2), the lakes are occasionally closed, as NSP is less than 480 months. For seasonal river regimes (R3–R5), the NSP is lower than for uniform regimes. The smallest lake (CIR=0.24) has the highest NSP (Tables 8–10).

Table 8. Summary of simulation results for lake L3 (CIR=30) in different river regimes and climates.

Case	DLW_1	DLW_2	NSP	Ave	A.Max	A.Min	Max	Min	MMR	AMR
R1C1L3	1	1	480	3059	3059	3059	3059	3059	0.00	0.00
R1C2L3	0.80	0.56	0	2314	2562	2042	2358	2270	0.04	0.22
R1C3L3	0.73	0.56	0	2082	2367	1767	2144	2017	0.06	0.29
R1C4L3	0.25	0.51	0	833	1038	667	863	804	0.07	0.45
R1C5L3	0.00	0.43	0	287	397	218	296	279	0.06	0.62
R2C1L3	1.00	1.00	480	3059	3059	3059	3059	3059	0.00	0.00
R2C2L3	0.75	0.57	0	2295	2468	2049	2345	2250	0.04	0.18
R2C3L3	0.74	0.56	0	2067	2304	1776	2134	1996	0.07	0.26
R2C4L3	0.25	0.54	0	829	989	661	865	795	0.08	0.40
R2C5L3	0.00	0.49	0	286	413	184	303	271	0.11	0.80
R3C1L3	1.00	1.00	480	3059	3059	3059	3059	3059	0.00	0.00
R3C2L3	0.75	0.46	0	2220	2411	2074	2279	2170	0.05	0.15
R3C3L3	0.75	0.50	0	2002	2204	1818	2078	1922	0.08	0.19
R3C4L3	0.25	0.46	0	800	997	658	846	757	0.11	0.42
R3C5L3	0.00	0.49	0	281	437	174	307	251	0.20	0.94
R4C1L3	1.00	1.00	480	3059	3059	3059	3059	3059	0.00	0.00
R4C2L3	0.77	0.55	0	2307	2534	2041	2350	2267	0.04	0.21
R4C3L3	0.74	0.56	0	2073	2325	1752	2141	2002	0.07	0.28
R4C4L3	0.25	0.52	0	832	1042	647	869	797	0.09	0.48
R4C5L3	0.00	0.52	0	285	440	167	314	260	0.19	0.95
R5C1L3	1.00	0.99	475	3058	3059	3022	3059	3058	0.00	0.01
R5C2L3	0.75	0.47	0	2168	2385	2029	2234	2108	0.06	0.16
R5C3L3	0.73	0.52	0	1942	2172	1772	2024	1849	0.09	0.21
R5C4L3	0.25	0.49	0	782	1014	644	838	724	0.15	0.47
R5C5L3	0.00	0.47	0	280	454	196	317	241	0.27	0.92

R1: Colorado river regime, R2: Kymi river regime, R3: Kor river regime, R4: Platte river regime, R5: Godavari river regime. C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer, C5: hot, arid desert (Bwh). DLW_1: Degree of lake wetness based on lake geometry, DLW_2: Degree of lake wetness based on lake history, NSP: Number of months in which water spill occurred, Max and Min: Mean maximum and minimum volume during 40–year simulation, Ave.: Average volume during 40–year simulation, A.Max and A.Min.: Absolute maximum and minimum volume during 40–year simulation, MMR: Maximum–minimum ratio, AMR: Absolute Maximum–minimum ratio.

Table 9. Summary of simulation results for lake L2 (CIR=3) in different river regimes and climates.

Case	DLW_1	DLW_2	NSP	Ave	A.Max	A.Min	Max	Min	MMR	AMR
R1C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C2L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C3L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C4L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C5L2	1.00	1.00	480	300	300	299	300	300	0.00	0.00
R2C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R2C2L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R2C3L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R2C4L2	1.00	0.92	473	300	300	299	300	300	0.00	0.00
R2C5L2	1.00	0.89	412	300	300	290	300	299	0.01	0.03
R3C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R3C2L2	1.00	0.93	448	300	300	296	300	300	0.00	0.01
R3C3L2	1.00	0.92	429	300	300	295	300	299	0.00	0.02
R3C4L2	1.00	0.86	383	300	300	290	300	298	0.01	0.03
R3C5L2	1.00	0.69	227	296	300	269	300	289	0.03	0.11
R4C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R4C2L2	1.00	0.92	475	300	300	298	300	300	0.00	0.01
R4C3L2	1.00	0.92	437	300	300	295	300	299	0.00	0.02
R4C4L2	1.00	0.88	404	300	300	291	300	299	0.01	0.03
R4C5L2	1.00	0.64	200	296	300	265	300	290	0.03	0.12
R5C1L2	1.00	0.89	390	300	300	299	300	300	0.00	0.00
R5C2L2	1.00	0.64	245	298	300	293	300	294	0.02	0.03
R5C3L2	1.00	0.72	239	297	300	288	300	289	0.04	0.04
R5C4L2	1.00	0.64	192	294	300	281	300	283	0.06	0.06
R5C5L2	1.00	0.64	161	290	300	266	300	272	0.10	0.12

R1: Colorado river regime, R2: Kymi river regime, R3: Kor river regime, R4: Platte river regime, R5: Godavari river regime. C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer, C5: hot, arid desert (Bwh). DLW_1: Degree of lake wetness based on lake geometry, DLW_2: Degree of lake wetness based on lake history, NSP: Number of months in which water spill occurred, Max and Min: Mean of maximum and minimum of volume during 40–year simulation, Ave.: Average volume during 40–year simulation, A.Max and A.Min.: Absolute maximum and minimum volume during 40–year simulation, MMR: Maximum–minimum ratio, AMR: Absolute Maximum–minimum ratio.

Table 10. Summary of simulation results for lake L1 (CIR=0.24) in different river regimes and climates.

Case	DLW_1	DLW_2	NSP	Ave	A.Max	A.Min	Max	Min	MMR	AMR
R1C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R1C2L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R1C3L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R1C4L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R1C5L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R2C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R2C2L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R2C3L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R2C4L1	1.00	0.89	480	24	24	24	24	24	0.00	0.01
R2C5L1	1.00	0.93	476	24	24	23	24	24	0.01	0.05
R3C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R3C2L1	1.00	0.94	477	24	24	24	24	24	0.00	0.02
R3C3L1	1.00	0.94	477	24	24	24	24	24	0.00	0.04
R3C4L1	1.00	0.94	458	24	24	21	24	24	0.01	0.15
R3C5L1	1.00	0.86	388	24	24	17	24	23	0.06	0.30
R4C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R4C2L1	1.00	0.98	476	24	24	23	24	24	0.00	0.07
R4C3L1	1.00	0.93	454	24	24	22	24	24	0.01	0.10
R4C4L1	1.00	0.91	447	24	24	20	24	24	0.02	0.18
R4C5L1	1.00	0.84	382	24	24	16	24	23	0.06	0.35
R5C1L1	1.00	0.96	456	24	24	24	24	24	0.00	0.02
R5C2L1	1.00	0.72	295	24	24	21	24	22	0.09	0.16
R5C3L1	1.00	0.78	321	24	24	19	24	21	0.16	0.25
R5C4L1	0.93	0.67	216	22	24	16	24	17	0.33	0.39
R5C5L1	0.84	0.65	184	20	24	10	24	11	0.66	0.75

R1: Colorado river regime, R2: Kymi river regime, R3: Kor river regime, R4: Platte river regime, R5: Godavari river regime. C1: cold without dry season (Dfc), C2: cold, arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, dry summer, C5: hot–arid desert (Bwh). DLW_1: Degree of lake wetness based on lake geometry, DLW_2: Degree of lake wetness based on lake history, NSP: Number of months in which water spill occurred, Max and Min: Mean of maximum and minimum of volume during 40–year simulation, Ave.: Average volume during 40–year simulation, A.Max and A.Min.: Absolute maximum and minimum volume during 40–year simulation, MMR: Maximum–minimum ratio, AMR: Absolute Maximum–minimum ratio.

5.4 Environmental flow regime

The optimal monthly distribution of EF depended on how much water was allocated, the location in the catchment and the target for allocation. The monthly distribution of EF ranged from low (20% of MAF) to high (80% of MAF) (Figs. 18–23). The distribution of EF also varied depending on the location in the catchment. For example, when 30% of MAF was allocated, the allocation during April was 10.5%, 13.3%, 18.7% and 27.6% for the Mollasadra, Gavgodar, Doroudzan and Shoor–Shirin locations, respectively (Fig. 23d). The distribution of flow between months was more uniform with high allocation and was closer to the natural flow regime, as can be seen on comparing the natural flow hydrograph for Doroudzan (Fig. 5a) with the optimal EF regime (Fig. 21).

When the EF was allocated in an optimal way considering river or lake as the target, different monthly discharge was obtained when the residual term was considered. The intra–annual flow regime showed different monthly distributions for the river and lake targets (see Figs. 18–20). This was seen for all EF allocations (20–80% of MAF). For example, when 30% of MAF was allocated for EF for Mollasadra, the maximum monthly release occurred in March and was 5.87 and 7.8 m^3s^{-1} for the lake and river targets, respectively (Fig. 19). This difference was due to the two target points having differing residual area. The residual area for Mollasadra with the lake protection target was about 4680 km^2 as it included the downstream unregulated catchment, while the contributing area for the river target point was the dam catchment of Mollasadra, comprising 1062 km^2.

By increasing the EF allocation, the difference between the optimal regime hydrographs of the lake and river targets was reduced. This can be seen by comparing the monthly allocation of 80% and 20% for the river and lake targets (Figs. 18–20). For example, at Shoor–Shirin, the maximum difference between the river and lake EF hydrographs was 6.1 %–units (from 27.0 to 20.9%) of allocated flow in May (Figs. 22e and 23e), while the maximum difference for 80% allocation (203 hm^3) was 0.45 %–units (18.5 to 18.05%) for March (where 18.5 and 18.05 % are the optimal EF portion in April for the lake and river, respectively).

For river stations at different locations in the catchment, the optimised intra–annual flow regimes showed different monthly distribution for a given allocation when the residual term was included (compare parts a in Figs. 18–20). For example

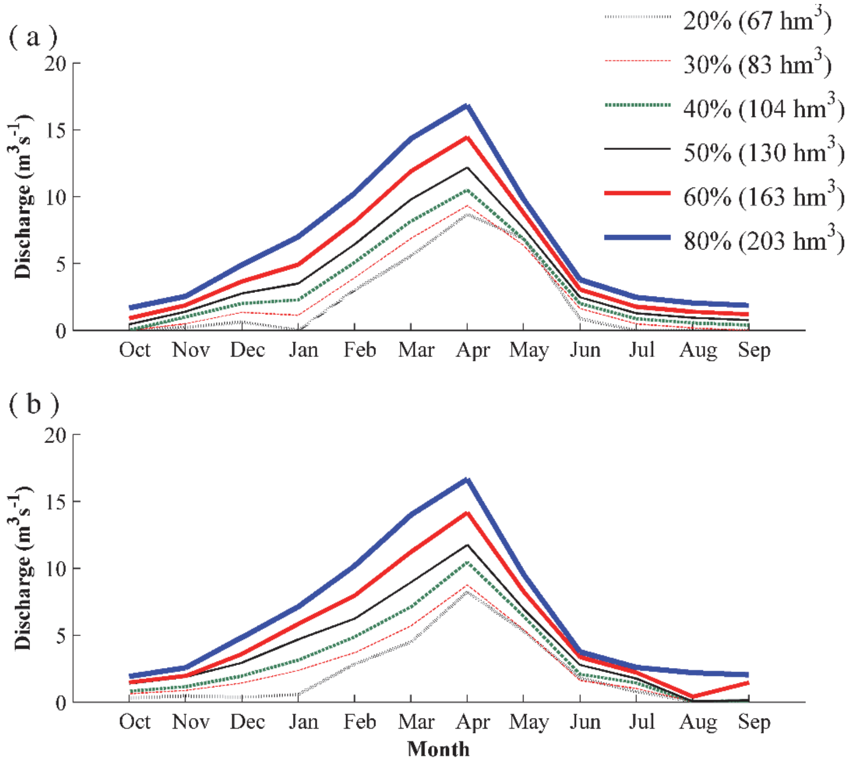


Fig. 18. Annual EF hydrograph for the Shoor–Shirin gauging station for a) lake conservation and b) river conservation for different EF allocation rates (20 to 80% of MAF).

the maximum release for the EF requirement of Doroudzan and Shoor–Shirin was in April, but for Gavgodar and Mollasadra it was in February. The optimal flow regime seemed to depend on local climate, as in the catchment the rainfall increases from south to north and from west to east (e.g. from Gavgodar with 472 mm to Shoor–Shirin with 519 mm; Table 1). With the higher rainfall at Gavgodar, the optimal regime showed maximum EF demand in January–March (Fig. 20), while at Shoor–Shirin EF demand was greatest in March–May (Fig. 18).

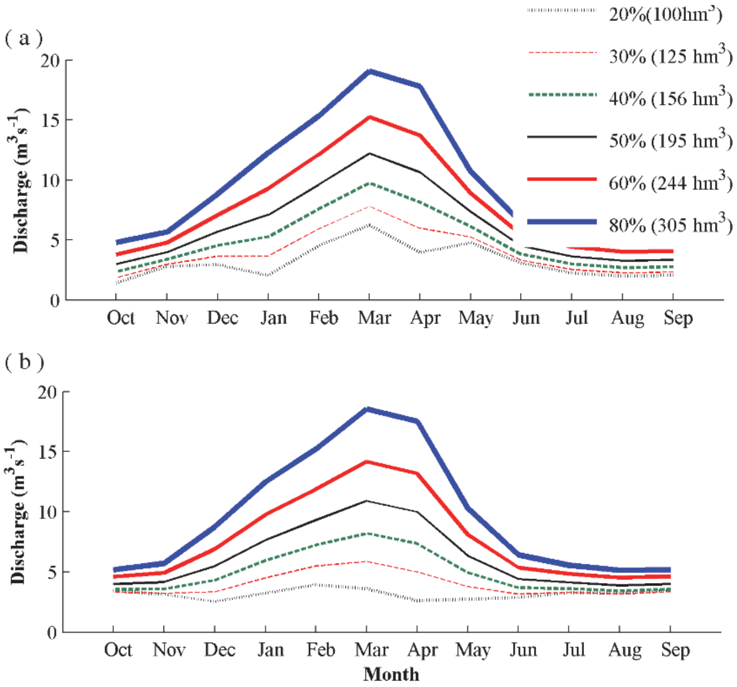


Fig. 19. Annual EF hydrograph for the Mollasadra dam for a) lake conservation and b) river conservation for different EF allocation rates (20–80% of MAF).

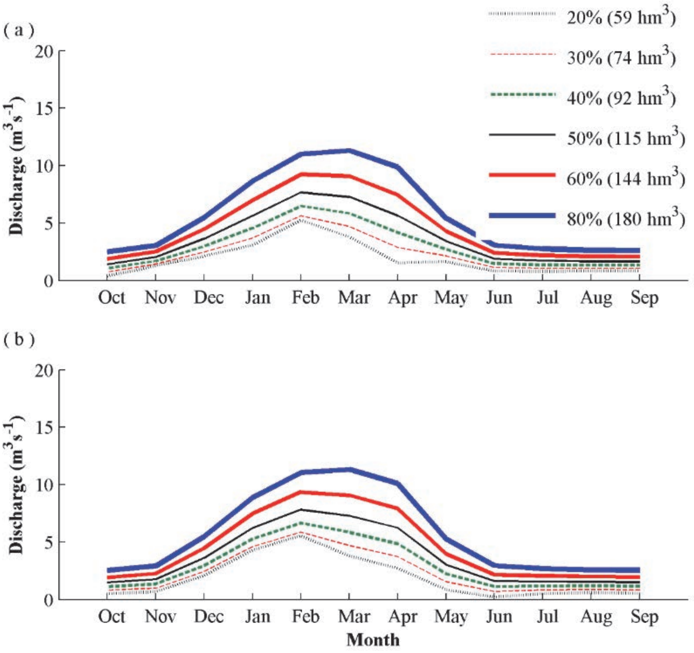


Fig. 20. Annual EF hydrograph for the Gavgodar gauging station for a) lake conservation and b) river conservation for different EF allocation rates (20–80% of MAF).

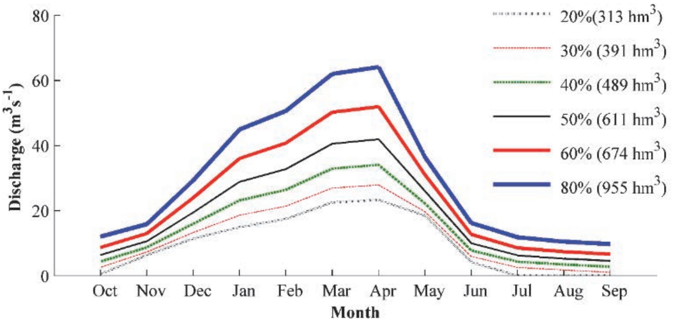


Fig. 21. Optimal annual EF hydrograph for the Doroudzan dam for Lake Bakhtegan and Kor river conservation for different EF allocation rates (20–80% of MAF).

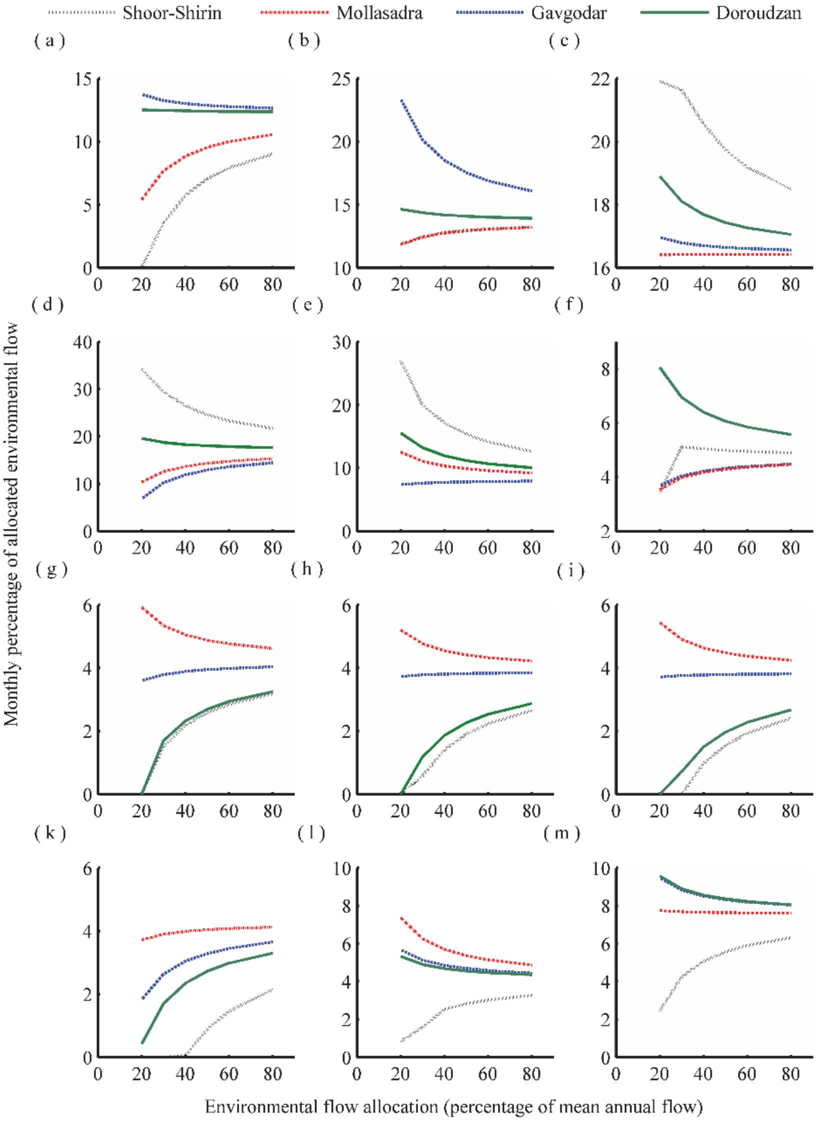


Fig. 22. Monthly percentage of allocated EF at different percentage allocation rates for lake conservation (20–80% of MAF) at different locations in a–m) January–December.

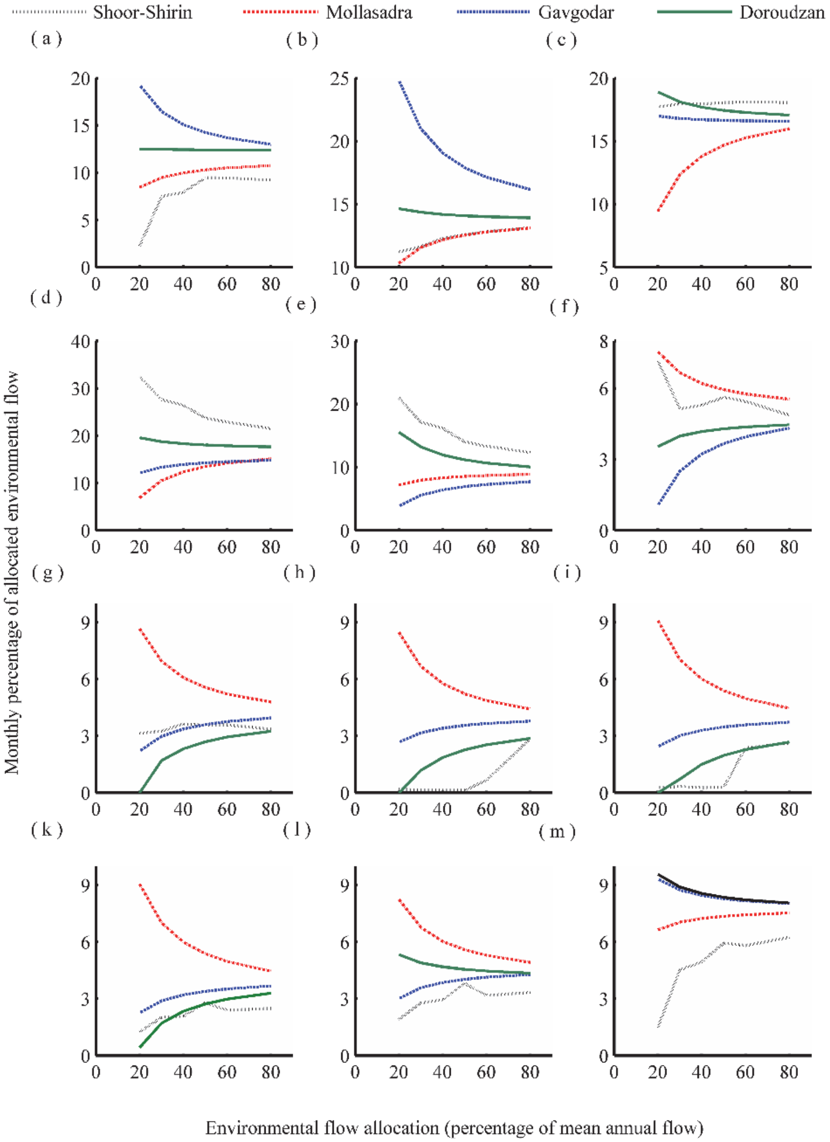


Fig. 23. Monthly percentage of allocated EF at different percentage allocation rates for river recovery (20–80% of MAF) at different locations in a–l) January–December.

6 Discussion

The main outputs are discussed below in relation to river regime impact due to dam construction. The newly developed method is compared to other commonly used methods in flow regime alteration analysis. The sensitivity of lake regimes to climate and flow regime is discussed and new inputs to analysis of EF regimes are presented.

6.1 Assessment of river regime impact

Dam construction, climate and land use changes can alter flow regime in many ways and assessment of the overall impact on the river regime is complex. For dam construction impacts, the essence and scale of the impact differs between rivers, dam purposes and operating strategies and has diverse effects on different ecosystems and end–users, e.g. lakes, wetlands, fisheries and farmers. For example, altering the flow regime can affect fisheries by changing spawning and growing conditions, which depend on the timing of flow and instream velocity distribution (Bailly et al. 2008, Balcombe & Arthington 2009, Bowen et al. 2003, De Mérona et al. 2005, Freeman et al. 2001, Grabowski & Isely 2007, Oscoz et al. 2005, Trifonova 1982, Welcomme & Hagborg 1977). For lakes, the magnitude of flow is more important, as reduced inflow results in lake level decline, which can have a major impact on ecology (Amoros & Bornette 2002, Miranda 2005, Thomaz et al. 2007).

Analysis of monthly flow data is useful, since unlike annual flow data, it gives information on flow seasonality. Analysis of daily flow data can show changes in river flow regimes in more detail, but in most cases such data are not as available as monthly flow data. As shown in Fig. 9, the annual hydrographs for pre– and post–construction can show the impacts on river regime due to different types of dams. The most commonly used approach in assessment of flow river alteration is the IHA method (Richter et al. 1996), which is based on daily flow data. This method provides 33 different parameters to evaluate pre– and post–construction impacts, while the new approach presented here uses a combination of three important attributes in one single index. The benefit of the new RI index in comparison with IHA is that the attributes are physically sound and logical consequences of dam construction. A drawback is that the RI index method does not account for the effects of short–term regulation (hourly or daily water regulation), which is typical for hydropower and can considerably affect local habitats, for example that in the Kemijoki river. However, the RI index method provides important information on overall changes in river flow regimes at monthly time scales. This is the first method to quantify the flow regime alteration within the year based on intra–annual river regime characteristics.

In the past, seasonal variations in river flow regime have been assessed by estimating the amount of flow for different seasons, such as the mean three–monthly river flow for March–May or June–August (Alba Solans & LeRoy Poff 2012, , Döll & Schmied 2012, Hannaford & Buys 2012, Arnell & Gosling 2013). The RRI method developed in this thesis is a better tool for showing such seasonal changes in regime, as it does not depend on predefined calendar months. In addition, RRI is a single index and can better integrate the seasonal regime into a single, dimensionless value. It is therefore recommended that RRI be used to assess natural regimes or the impacts of river regulation, land use and climate, as discussed further below.

The RI index can quantify the effect of different types of dams on flow. Typically, single–purpose dams constructed for hydropower, flood control or navigation have little or no effect on flow magnitude, as water is not consumed, e.g. for irrigation. For example, in the Volta, Kaduna/Dinya, Tigris and Colorado rivers, the flow magnitude did not change after dam construction. Although these rivers have been affected by considerable reservoirs (Table 4), according to the RI index these were classified as having a moderate impact on flow (Fig. 14). Several dams and hydropower constructions built on the Middle Volga river during 1935–1967 have changed the natural flow regime of the lower Volga after Volgograd (Fig. 9a). This alteration has also been reported in previous studies (Asarin 1986, Ratkovich et al. 2003, Hans et al. 2005, Van de Wolfshaar et al. 2011, Górski et al. 2011). While the reduction in magnitude at Volgograd is 0.89 (MIF in Table 7), due to the fairly small alteration in river regime (VIF=0.27) and timing (TIF=0.35), the combined RI index indicated that the Volga has been moderately affected by dams and related water regulation.

By using the proposed methodology, it is possible to show the impact of rivers and determine the effect of water resources development in different periods and construction phases. In the Kasegawa river in Japan, the first dam construction at Hokuzan (1956) resulted in a low impact (Kasegawa 1 in Fig. 14), but after construction of the Kasegawa dam, the river was re–classified as suffering a moderate impact (Kasegawa 2 in Fig. 14). Many previous studies have demonstrated the effect of regulation structures on river flow regimes, but only a few have been performed in rivers affected by many dams in series or parallel

(Nichols et al. 2006). The RI index shows the effects of dams at each point of the river channel network based on annual hydrographs pre– and post–construction, as shown here for the Lower Yellow river in China and the Volga in Russia (Table 1). The RI index can also be useful for showing the impact of climate change on river regimes by comparing the RI for different time slots typically used in climate change assessment.

In many cases, the consumption season can be totally different from the rainy season or high flow season. In hot, dry climates in particular, dams used for irrigation purposes store water in some months and release water in other months. Most storage dams (e.g. the Zayanderoud dam; Fig. 9l) are built to store water through the wet season and release it in the dry season for irrigation, resulting in an effect of the dam on timing (Fig. 10d). This means that the seasonal order is changed totally, which can affect the ecology and geomorphology of downstream locations (Poff et al. 1997, Bowen et al. 2003, Gorski et al. 2011). Thus the RI index method could be used to determine the sensitivity of ecological processes to different flow attributes.

The impacts of dams based on river flow can be assessed: i) by considering the change in inflow and outflow of the dam MIF_1 (e.g. the Niger at Jebba; see Table 1) or ii) by using river flow data from two different periods, before and after dam construction MIF_2 (e.g. 1900–1935 and 1967–1980 for the Volga, or 1958–1983 and 1984–2006 for the Yellow river, as shown in Table 4).

The use of data from before and after dam construction is problematic, as the river flow also changes due to variations in climate. This can be seen by inspecting the flow hydrographs for the Tigris before ($Tigres_1$ in Fig. 9f) and after construction, where the flow magnitude was higher after dam construction. This makes flow magnitude difficult to assess, as it results in different impacts for pre–impact ($Tigres_1$ in Fig. 9f) and post–impact data compared with the use of inflow ($Tigres_2$ in Fig. 9f) and outflow data. Based on the Tigris1 hydrograph (different periods for pre– and post–impact) the RI is 0.61 and the impact class is incipient (Fig. 14), while based on the Tigris2 hydrograph (same periods for pre– and post–impact) the RI is 0.48 and the river impact class is moderate (Fig. 14). Similarly, for the Kor river the period before dam construction (Kor_1 in Fig. 9m, 1957–1972) is drier and has lower flow magnitude than the period after dam construction, with water being consumed for irrigating 110,000 hectares of agricultural land. Thus when using the Kor_1 hydrograph (different periods for pre– and post– impact) the RI is 0.79 and the impact incipient, while when using the Kor_2 hydrograph (same periods for pre– and post– impact) the RI is 0.41 and the impact moderate. These examples clearly show that using pre– and post–impact periods belonging to different hydro–climatic conditions (e.g. wet and dry periods) can sometimes show a higher impact than in the actual conditions (Tigris river) and sometimes a lower impact (Kor river). Therefore the MIF_1 approach results in a more realistic assessment for river impacts. Clearly the inflow and outflow data are more accurate to show the effects of dam construction on water losses. MIF_1 can be calculated based on dam policy operation to estimate the impacts of dams during initial planning phases. The IHA method (which uses data from before and after construction) may therefore not be suitable for regions with high natural climate variability.

6.2 Comparing the new RI method with the IHA method

The method most commonly used to date to assess flow changes is the IHA method, which uses daily data to define 33 different parameters that are classified into five different groups. The RI index method presented in this thesis assesses the overall impact of dams on rivers using monthly data to find changes in magnitude, timing or intra–annual flow regime. While the IHA is useful for many purposes, the benefit of the new RI index method is that: i) it uses monthly flow data, which are more easily available for users than daily flow data; ii) it determines the change in magnitude using the MIF factor, which is independent of climate variation; and iii) it defines the change in inter–annual flow regime using the VIF factor in a unique way.

The novel aspect of the RI index in comparison with the IHA index is how it deals with flow variability. One of the main functions of dams, especially those used for hydropower production, is a change in intra–annual flow (as seen in Fig. 4c). The IHA method shows this hydrological alteration as changes in monthly or seasonal flow magnitude before and after dam construction. However, instead of comparing changes in different months, the RI index method quantifies the intra–annual flow regime using a unique variability impact factor (VIF). This is important, as the flow regime is a good characteristic of the overall hydrological system of the river. For example, based on the IHA method, the average monthly flow alteration for Volga (Fig. 3a) is 65% (maximum 116% flow increase in February to –61% flow reduction in June). For the Karkheh river (Fig. 3j), the IHA method gives an average monthly flow alteration of –15% (–73% flow reduction in April to +80% flow increase in August). This monthly assessment using IHA indicates more severe changes in the Volga than the Karkheh, although comparing pre– and post– impact hydrograph for these two rivers (Fig. 3a and 3j) clearly shows that more changes have occurred in the Karkheh. Using the variability impact factors (VIF), the impact was calculated to be 0.27 and 0.17 for the Volga and Karkheh, respectively, i.e. with more impact in the Karkheh (no impact in inter–annual regime occurs with VIF = 0.5). For the Cotter river too (Fig. 3t), there was a –50% alteration in average monthly flow (from –6% to 89%) according to the IHA index, despite minor alterations in the shape of the annual hydrograph. The VIF value obtained for the Cotter dam was 0.44, which agrees better with the actual data. Therefore, it can be concluded that VIF is a more robust and exact measure of inter–annual flow regime changes than the IHA index.

The RI and IHA index both use a similar approach to assess changes in flow timing (date of minimum and maximum discharge for pre– and post– impact periods). In the IHA method, this is assessed in the third group of parameters. In the RI index method, the TIF value is based on two IHA parameters (minimum and maximum discharge for pre– and post– impact periods) and the change in date of the 50% value of the discharge cumulative density function is also considered. For example in the Karkheh river, the IHA parameters show that the date of maximum and minimum discharge changed from –44 to –52 days after dam construction (Madadi, 2011). This minor change agrees with the TIF factor, which shows a change from 0.5 to 0.42 (Table 7).

6.3 Sensitivity of lakes to climate and river regimes

The simulation show that lake equilibrium volume is mainly controlled either by climate or by CIR (lake hydraulic properties). For large CIR, the steady state lake level (equilibrium lake volume) depends on climate and to some extent also on river regime. For small CIR, the lake volume depends on the lake hypsometric characteristic (area–volume–depth curve). For example, a lake with high CIR and with a regulated river inflow regime has a different equilibrium volume in different climates, varying between 286 hm^3 for a hot, arid desert climate to 3059 hm^3 for a cold, wet climate. For lakes with low CIR, the equilibrium volume can be defined as the maximum water capacity of the lake. Following a change in inflow (CIR) or climate pattern, the lake level will find a new equilibrium volume, although as the results in Fig. 15 show, this can take more than 20 years for large lakes. These results can be used in climate change studies to estimate expected response times, which may be long, following the impacts of land use and climate change.

The sensitivity of lakes to climate and river regimes also depends on timing of runoff and evaporation. In most hydrological conditions runoff is low when net precipitation is low (ET is high) except for mountainous regions with considerable snowmelt during summer. This can be seen from case studies for the Kor and Platte rivers (Figs. 7 and 8). In a cold, dry climate as in Platte (Wyoming State, USA), runoff peaks in summer months due to snowmelt in the mountains. The combination of high runoff and high evaporation make mountainous lakes less sensitive to water level variation caused by summer dryness (Fig. 7, for Kor (R3) and Platte river (R4)).

For lakes in a cold climate, the difference between maximum and minimum water levels is small. Thus in future the water level in these lakes will stay at the maximum possible level and changes in river flow regime will not have a major effect on lake levels. Lakes in a warm climate are sensitive to changes in water quantities. As the water use in these regions is under high pressure for agriculture and hydropower, lake level changes have already occurred. Further water level changes can be expected for lakes with high CIR, whereas lakes with low CIR may experience only a very slight change, despite intensive water use and regulation. The method developed here could be used on a regional scale to map lakes that are sensitive to water and land use.

The DWL index developed in this thesis could be used as a simple index to describe the hydrological regime of any lake. The DLW index represents a statistical characteristic of the lake based on the lake volume in past times series of data and classifies the lake on a scale that can vary from ‘open’ to ‘closed’. In the past, water level fluctuation within years and between years has been considered a key factor in lake and wetland management (Coops et al. 2003, Paillisson, 2011). However, using water level data alone does not summarise the lake status. The major merit of the DLW index is that it helps to quantify lake responses to changes in different components of the water balance equation. The use of the DWL index could help decision makers to better understand how lake hydrology changes due to different water allocation scenarios. DLW can be used to quantify climate change effects and the impacts of hydraulic structures on lake regimes. For example, it can be calculated in two main periods, before and after dam construction, and the results can be used for quantifying the impact of the dam on the water body. DLW can also be used in allocation of environmental flows to lakes and wetlands as an index to calculate the lake status after impact.

Of the two approaches presented here for calculating DLW, the second approach is suggested for evaluating the possible change in lake regime system. In addition, the lake distribution is better fitted by the DLW_2 index. As shown, all lakes with CIR=30 in their regime in any climate except for a cold, wet climate are classified as ‘Closed moderate lake’ and any change in climate or flow regime would be reflected by deviation from moderate conditions.

6.4 Environmental flow regime

The approach presented here is a new method for determining the monthly release in allocated EF in an optimal way. The method considers the water provided by the unregulated catchment downstream of the dam, in what is referred to in this thesis as the ‘residual hydrograph’. In many cases, decision makers allocate EF on an annual amount basis, without considering the natural flow regime. Hydrological methods used to date do not take the natural regime into account, although the importance of considering the natural regime in aquatic ecosystem EF allocation is widely documented (Smakhtin et al. 2004, Cui et al. 2010). The new method presented here allows for allocation on a monthly basis, so that the natural regime is better maintained. This is a clear improvement on existing methods, as the main criticism of the hydrological EF assessment methods currently in use is that they ignore the natural regime of river flows (Richter et al. 1996, Poff et al. 1997, Arthington et al. 2006,).

The new method uses a catchment–scale release policy that takes into account the location of reservoirs and the residual hydrograph. This is not considered in other hydrological methods, many of which also do not consider the layout of the catchment and its fragmentation into different sections due to the presence of dams. However, without considering the location of dams, the allocated EF is clearly not used in the most efficient way. This is especially important in dry climates with high pressure on water resources, such as the study region in Iran used in this thesis and other regions in Asia.

The monthly release of EF has previously been included in some hydrological methods, such as that proposed by Tennant (1976), where water is released in two different six–month periods (October–March and April–September). Our new method is more precise and allocates water for each month based on the natural flow regime at the target point and the site of water release. It is therefore in better agreement with the natural flow regime, as this varies between months. Thus it can be expected to be more optimal from an ecological perspective, as river flow is similar to the past pattern to which the ecosystem is adapted. Moreover, the new method distributes the flow depending on how much water can be allocated for EF. This is important because the residual water can be used for base flow when only a small amount can be allocated to EF. In addition, water is not released unnecessarily when the residual hydrograph can supply enough water for aquatic ecosystem demands.

Sometimes different priorities may need to be set between different aquatic systems in the catchment for EF use. The target point could be a river, lake or wetland depending on the conservation target. The new method presented in this thesis allows setting of different ecological target points which can be distributed at different locations in the catchment. This is not considered in other hydrological methods. An additional advantage of the new method is its flexibility with regard to ecological flow constraints (habitat requirements). Additional information on water requirements can easily be included.

7 Conclusions and suggestions for future studies

A new index based on the physically sound unit river concept was developed in a framework of monthly river regime point (MRRP) and river regime index (RRI). Using RRI, it is possible to quantify river regimes by a single non–dimensional index showing the distribution of monthly river flow within a year. This index is sensitive to the impacts of climate and land use. RRI values are low in areas with stable discharge, such as around the equator, downstream of large dams and around natural systems such as wetlands, waterfalls and lakes. The RRI is very suitable for assessing seasonal changes due to climate change, irrigation or river regulation, e.g. it is altered considerably by construction of hydraulic structures such as dams, which change the river flow regime in large rivers such as the Nile. RRI varies between 0 to 1200 and it can be used for classifying rivers because it increases with changing river regime from uniformly regulated to seasonal. Based on the work in this thesis, RRI be recommended for use as one of several reference methods for environmental flow and environmental impact assessment in order to determine the effect of hydraulic structures on intra–annual river regime.

The RI index evaluates the effect of dam construction in terms of three characteristics of river regime: magnitude, timing and intra–annual alteration. The RI index is based on monthly river flow data from periods pre– and post– impact by dams and can be used in river impact assessment and classification (to classify rivers from low to drastic impact). Using this method, the effect of different types of dams with different sizes and purposes on 16 selected rivers across the globe was quantified in this thesis. The method was found to be suitable for use in environmental impact assessments of rivers that have been modified by dams or affected by changes in land use or climate. It is based on monthly data, which are more accessible than the daily data required e.g. in the IHA method. Use of inflow and outflow data to demonstrate the impacts of dams proved more accurate than only using river flow data collected before and after dam construction. This was demonstrated here for the Kor and Tigris rivers, where data for the pre– and post–periods (as in the IHA method) were affected by climate change in two different periods, while this effect was eliminated by the RI index. The RI index method can be considered an overall method to assess river regime changes, especially rivers affected by climate change, climate variability, land use change or dam construction. For dams with hydropower generation as their main purpose, e.g. the Jebba, Shiroro, Akosombo and Taivalkoski in this thesis, the main environmental impact is generally seen as changes in water level fluctuations downstream of the dams due to the change in intra–annual regime, without any significant alteration in flow magnitude. With the RI index method, the change in inter–annual flow variation between the pre– and post– construction periods is quantified using the robust variation impact factor (VIF), which shows the changes in annual river hydrographs.

Environmental flow is important for water bodies and aquatic ecosystems that are under pressure and have important ecosystem services. The new approach presented here finds the optimal water release considering the intra–annual regime, the layout of catchment based on the location of dams, gauging station arrangement and the selected target point (river or lake). The method is based on three annual hydrographs at main points of the catchment: that at the water diversion (dam) point (upstream hydrograph), that at target points (reference hydrograph), and the residual hydrograph, which is related to the unregulated runoff excess of the catchment between the dam and the target point. The method is flexible depending on the availability of input data and requirements. Hydrological data can give a first approximation of the optimal intra–annual regime. Biological, geomorphological or other requirements can be added to the hydrological data and used in the optimisation procedure, which is a main advantage of the method. The method also takes into account the main characteristics of natural flow when setting the hydrograph for EF. It can thus be used in any new water development or construction project to protect existing aquatic ecosystems or restore damaged water systems. The method can also be used in designing hydraulic structures to find the optimum capacity for outlet structures and design the rule curve for dam operation to reduce the impact of flow regime alteration. The method complements previous EF methods which only use magnitude of flow.

In future research, the RRI method could be developed for seasonal classification of rivers. The RI index could be improved with more river characteristics, which would make it possible to link river impact classes to the environment impact that has occurred in aquatic ecosystems. The framework developed for lake and DLW index could be used in real case studies to obtain feedback from real conditions and thereby develop the method further. This could provide better decision support for environmental flow allocation of lakes. Lake assessment could also consider interaction with groundwater and this interaction could be added to the water balance equation. The residual hydrograph concept could be combined with some ecological concepts to develop a hydro–biological framework to estimate environmental flow regime.

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