CHAPTER

Human influence*

10

Anne F. Van Loon[1], Niko Wanders[2], John P. Bloomfield[3], Miriam Fendeková[4], Cosmo Ngongondo[5] and Henny A.J. Van Lanen[6]

[1]*Water & Climate Risk Group, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, the Netherlands;* [2]*Physical Geography, Utrecht University, Utrecht, the Netherlands;* [3]*Groundwater Science, British Geological Survey, Wallingford, Oxfordshire, United Kingdom;* [4]*Department of Engineering Geology, Hydrogeology and Applied Geophysics, Faculty of Natural Sciences, Comenius University Bratislava, Bratislava, Slovakia;* [5]*Department of Geography, Earth Sciences and Environment, School of Natural and Applied Sciences, University of Malawi (UNIMA), Zomba, Malawi;* [6]*Hydrology and Quantitative Water Management Group, Environmental Sciences Group (ESG), Wageningen University & Research, Wageningen, the Netherlands*

Chapter outline

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10.1 Introduction

In many places around the world, low flow and hydrological drought are strongly influenced by human interventions. For example, the Netherlands is at the downstream end of three major European rivers, and navigation, industry, recreation, drinking water supply, electricity production, water quality, agriculture and ecology are all affected when there is less water in the Rhine, Meuse and Scheldt Rivers. Water levels and discharge in these rivers depend on what happens upstream, in response to different drivers, both natural processes, such as rainfall, snowmelt and groundwater storage, as well as human interventions, such as abstraction, reservoir management and drainage. Drought impacts in a downstream country, such as the Netherlands cannot be understood without including effects of up-stream human interventions (e.g., in Germany, France and Belgium). As another example, California regularly faces extreme multi-year droughts and a recurring question in the media is “How much rain is needed to end the drought”? However, the answer to this question strongly depends on human-affected water flows, since the water system in California is highly engineered and managed with, for example, massive abstractions, reservoirs, water transfers, irrigation systems and artificial recharge. The question of when a hydrological drought will end can only be answered if these interventions are taken into consideration.

Globally, the human footprint on the water system is massive, and sustainably managing our water resources is a major challenge. Including human-water interactions in drought studies is vital (Lloyd-Hughes, 2014), as most areas around the globe are affected by either water abstractions for irrigation, industry or domestic water use, or have their hydrology altered by land use change or the construction of reservoirs. In most of the world, hydrological drought and low flow develop as a result of both natural processes (Chapter 3) and human interventions and are modified by land characteristics reshaped by human interventions. For example, surface and subsurface water abstraction lower water levels in groundwater and surface water (rivers and lakes) and deforestation and urbanisation change water pathways and fluxes. Low flow can be increased or decreased in response to human interventions, and hydrological drought can be aggravated or alleviated.

It is important to take these human influences into account when analysing low flow and hydrological drought. Only then can we make accurate drought predictions and design effective drought management actions in our human-dominated era, the Anthropocene. Accounting for the influence of humans on hydrological drought analysis adds complexity and leads to challenges with data and modelling, but it also opens up a new range of opportunities and makes the analysis more relevant to society.

In this chapter, the concepts and processes of human interventions on low flow and hydrological drought are introduced and explained (Section 10.2 and 10.3). We then have a look at different methodologies that can be used to study these interactions and analyse the influence of human interventions on low flow and hydrological drought (Section 10.4). In a number of examples, these human interventions and methodologies are explored further (Section 10.5).

This chapter does not discuss the effects of anthropogenic climate change on hydrological drought, which is covered in Chapter 11. It also does not cover impacts of hydrological drought on society and ecosystems, which are discussed in Chapter 12. Human interventions influence water quality as well as water quantity, but the effect on water quality is not dealt with in this textbook because of its comprehensive nature. The reader is instead referred to specific literature on this topic (e.g., Van Vliet et al., 2017).

10.2 Concepts

Human interventions influence low flow and hydrological drought in various ways and subsequently impact different sectors, such as agriculture and livestock farming, wildfires, waterborne transportation and freshwater ecosystems (Fig. 12.1). To analyse and understand the influence of human interventions (further called 'human influence'; for short), it is useful to have a consistent terminology and categorise droughts with respect to their origin.

Hydrological drought in a region with human interventions can be categorised as climate-induced, human-induced or human-modified. Fig. 10.1 shows a hypothetical time series of groundwater levels, surface water levels or river discharge. When these water levels or discharge fall below the drought threshold, a hydrological drought occurs (Section 5.4.1). The yellow areas in the figure indicate (the fraction of) hydrological drought that is caused by natural processes, and the red areas indicate (the fraction of) hydrological drought that is caused by human interventions. Climate-induced hydrological drought is caused by natural processes only (first event of the four shown), and human interventions do not influence the drought event (neither positively nor negatively). Human-induced hydrological drought is caused by the human influence only (second event of the four shown). This event would not

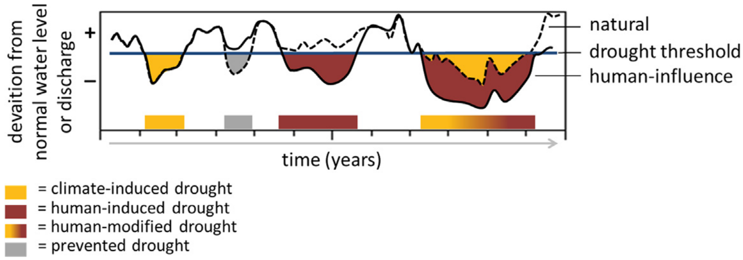

FIGURE 10.1

Hydrological drought events categorised with respect to their drivers as climate-induced drought, human-induced drought and human-modified drought. Observed water levels or discharge (*solid black line*) that are influenced by both natural processes and human interventions are compared to naturalised (natural simulated) water levels or discharge (*dashed line*). Note that human-modified drought can be aggravated or alleviated with respect to the natural situation.

Modified from Van Loon et al. (2016a).

have occurred in the absence of human interventions. Human-modified hydrological drought is caused by a combination of natural processes and human interventions. A natural hydrological drought can then be either aggravated or alleviated compared to the situation without human interventions. Fig. 10.1 shows an example of aggravation (last event of the four shown), where the total deficit results from a combination of natural and human causes. Finally, human influence can completely alleviate hydrological drought, preventing drought events even to occur (second event of the four shown in Fig. 10.1).

For human-induced changes in low flow, the word ‘hydrological alteration’ is often used (Richter et al., 1996). The term was first introduced in ecological research, where the human influence on aquatic ecology has been studied since the mid-20th century. If the human influence is extensive and continuous, water levels and discharge can drop dramatically without recovering. ‘Overexploitation’ is defined as the “long-term overuse of water resources resulting in a gradual decrease in water availability” (Van Loon et al., 2016b). For overexploitation of groundwater, the term ‘depletion’ is often used (AghaKouchak et al., 2021). Two famous examples are the Aral Sea in Central Asia and the Colorado River in the United States, which both have dried up (almost) completely in the past due to abstraction for irrigation. Such extreme, often irreversible, cases are not discussed further in this chapter.

10.3 Human interventions influencing low flow and hydrological drought

Human interventions can influence low flow and hydrological drought in a myriad of ways (Fig. 10.2), adding to the already complex relationship between meteorological and hydrological drought (Fig. 1.2). Anthropogenic climate change (Section 11.4) and land use change affect the climate input (forcing) to the hydrological system, that is, precipitation and potential evapotranspiration and also snow storage and snow and ice melt. Subsequently, soil water storage is influenced by these changes in inputs, in addition to direct interventions, such as soil and water conservation measures and irrigation. Changes in soil water storage further affect recharge into shallow and deep aquifers as well as overland flow and throughflow to the surface water system. These fluxes and states of the hydrological system

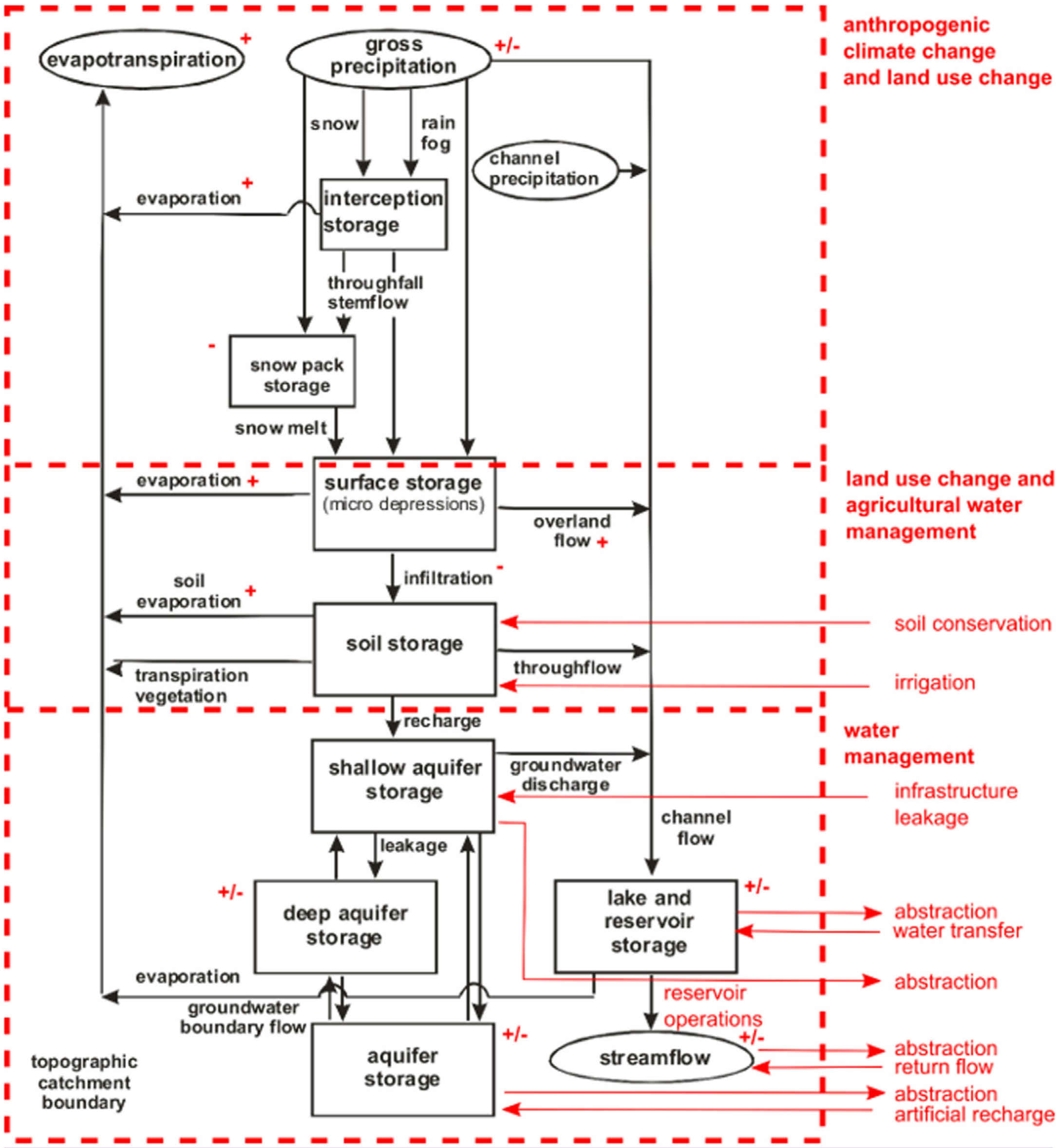

FIGURE 10.2

Hydrological drought generation processes including human water pathways and interventions (adaptation of Fig. 3.2). The three *red dashed boxes* illustrate how human interventions may influence different stages in the drought propagation. The red arrows represent human additions and removal of water from different parts of the hydrological cycle. The *red pluses and minuses* denote how fluxes are expected to increase (+) or decrease (−) under human influence. Anthropogenic climate change and land use change influence meteorological and soil moisture drought processes (*upper red box*), land use change and agricultural water management influence recharge and soil moisture drought processes (*middle red box*), and water management influence hydrological drought processes (*lower red box*).

are strongly influenced by water management interventions, such as abstractions, reservoir management, water transfers (diversions) and return flows (Fig. 10.2).

Water abstraction (Section 10.3.1) is an important direct human influence on low flow and hydrological drought. Water can be abstracted directly from the river, from groundwater or from (existing) reservoirs, which have different effects on the fluxes and states of the hydrological system. Water can be abstracted for different purposes, with different spatio-temporal patterns and intensities of abstraction that may influence low flow and hydrological drought in various ways. Reservoirs (Section 10.3.2) can be used for water supply, but also for other purposes (e.g., hydropower production and flood alleviation). Many reservoirs have been built to reduce flow variability, so to overcome dry periods (seasons or years) and reduce flood peaks. Return flows, that is, abstracted water that later returns to the river or subsurface, may alleviate the effect of abstractions depending on the fraction of water returned, the time lag and the location where the water is returned. Water can also be added to surface water via interbasin transfers and to groundwater stores via artificial recharge.

These human interventions are not static, but change over time. Drought management (Section 13.2), for example, includes various measures that influence water storage, abstraction and availability on long and short timescales. In the long term, to prevent or limit hydrological drought, water storage can be increased artificially by building (more) reservoirs, increasing groundwater recharge (managed aquifer recharge, MAR), developing water transfers from other (wetter) regions and by holding back water upstream in lakes and wetlands or in soils (water conservation). In the short term, during a drought, water abstraction can be restricted, water demand can be managed, and water can be transferred from areas that are less affected by drought; measures that are all aimed to alleviate the impacts of drought and thereby often resulting in a human modification of the hydrological drought.

The human influences on low flow and hydrological drought can be a direct result of active water management decisions or a side effect of interventions intended for a different purpose. Unintended side effects may result from developments, such as urbanisation, where the conversion of natural or agricultural land to residential areas or industrial, commercial estates, changes water pathways and therefore indirectly influences the propagation of drought (Fig. 10.2, Sections 2.3 and 3.3−3.5). By changing evaporation, infiltration and surface runoff, these land use changes alter the relationship between meteorological and hydrological drought.

Terrier et al. (2021) present an overview of how human interventions affect river flow and how these can be detangled from the disturbed hydrograph (naturalisation, Section 4.3.9.1). They report on the effect of reservoirs and their associated storage, water withdrawal, water release, land-use and land-cover change, and a combination of interventions. In addition to the examples of human interventions presented below, Van Loon et al. (2022) describe tens of cases across the world. They found that aggravation of streamflow drought due to human intervention is dominant and alleviation due to water management and water inputs was limited in this broad set of cases. In the following sections, we provide a more detailed discussion on the effects of three common human interventions, that is, water abstraction and return flows (Section 10.3.1), reservoirs (Section 10.3.2) and land use change (Section 10.3.3) on low flow and hydrological drought.

10.3.1 Water abstraction, transfer, return flow and artificial recharge

Early human societies settled in close proximity to rivers or other water resources and reliable access to water is still critical for human development around the world. Global water demand has been

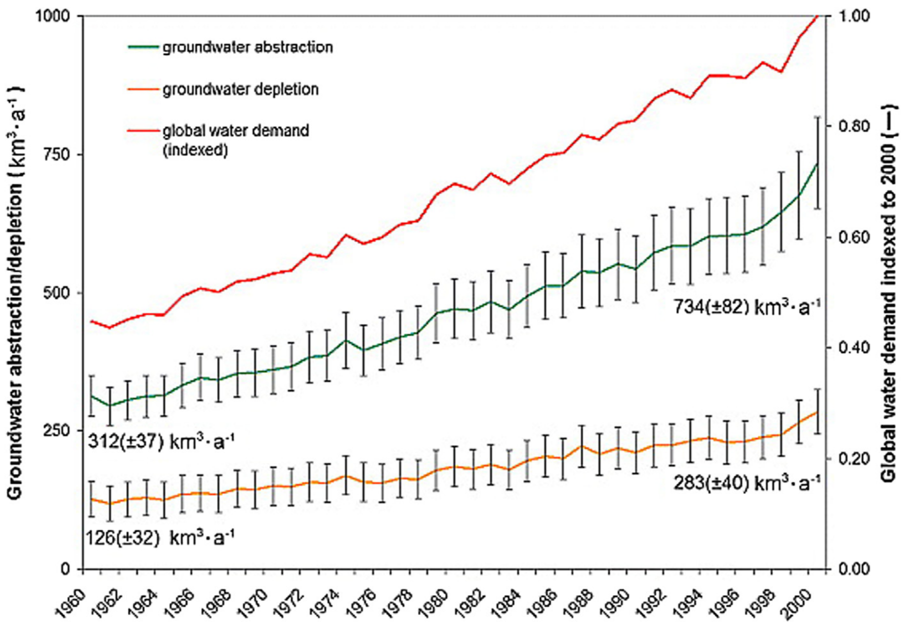

FIGURE 10.3

Increase in global groundwater abstraction (left axis; km^3 year^{-1}) and global groundwater depletion (left axis; km^3 year^{-1}) over the period 1960–2000. Increase in global water demand (–) relative to the year 2000 (right axis). Groundwater abstraction and depletion show a similar increasing rate as total water demand.

Modified from Wada et al. (2010).

increasing steadily for decades (Fig. 10.3), mostly related to an increase in population, but also to changes in diet and an increase in domestic water use per capita. Water can be abstracted from natural water bodies including rivers, lakes and groundwater, but also from artificial water bodies, such as reservoirs. The latter is discussed in Section 10.3.2.

10.3.1.1 Surface water abstraction, transfer and return flow

Surface water is mainly abstracted for agricultural irrigation and industry, but also for drinking water. A large part of the agricultural and drinking water use is consumptive, meaning that little water returns to the river or groundwater. Industries, however, often use water for cooling or other processes that have a high return flow fraction. The influence of surface water abstraction on low flow and hydrological drought therefore differs depending on the fraction of water that is returned.

The influence of surface water abstractions on low flow and hydrological drought depends on the location, timing and amount of water being abstracted (Clausen et al., 1994). Larger abstractions lead to a higher influence, but the influence depends on the size and hydroclimate of the catchment being affected. For example, if the same volume of abstraction takes place in a smaller river, the effects at the catchment outlet will be larger than in a bigger catchment. Similar, if the same volume of abstraction takes place in a wet catchment, this abstraction constitutes a smaller part of the water balance, and its effects on the river flow regime will be less. Surface water abstractions can be concentrated at a specific location, for example, drinking water abstractions from a lake to provide water for a city, or the abstractions can be distributed over many points, for example, inlets for irrigation along a river. The timing of the surface water abstractions strongly influences its effects on low flow and hydrological drought. If the abstraction is continuous throughout the year, which is often the case in industry, then the overall flow regime will experience lower flows. If the abstraction is highly seasonal, which is the case for irrigated agriculture that needs most water during the growing season (when precipitation is often low and evaporation high), then this already dry season may experience even lower flows, while the high flows may be less affected. Both continuous and seasonal abstraction can lead to lower low flow and more severe hydrological drought.

Droughts in surface water can also be alleviated, for example, by water transfers or return flow (from e.g., sewage water) being discharged into a river. In case of water transfers, the overall flow regime in the receiving catchment will experience higher low flow and alleviated hydrological drought. For return flows, if water is abstracted for cooling water in industry or electricity production and is returned to the river immediately after use, hydrological drought would not be impacted (although it would have a marked effect on water temperature and probably also on aquatic ecology). However, if only a fraction of the water abstracted is returned, the alleviating effects will be less and if return flows are diverted to another catchment, no alleviation takes place in the abstraction catchment. Irrigation aims to enhance vegetation growth and thus transpiration increases, which reduces recharge to groundwater and drainage to surface water systems, and hydrological drought can be strongly affected. Water abstracted for domestic water use is mostly returned as (treated) sewage water, but often at a different location or even catchment from where it was abstracted (Section 9.4.3). Thus, the effluent of sewage water treatment plants can increase low flow and alleviate hydrological drought in other catchments or downstream, depending on the delay from when it is being abstracted to it is returned (if within the same catchment).

10.3.1.2 Groundwater abstraction and artificial recharge

Fig. 10.3 shows that global groundwater abstraction during the second half of the twentieth century has grown rapidly due to an increasing population combined with higher water use per capita and the uptake of technology, such as efficient pumps and the electrification of rural communities. Estimated global groundwater abstraction almost doubled between 1960 and 2000, from about 312 to 734 km^3 $year^{-1}$ (Wada et al., 2010). Similar to surface water, groundwater is used for drinking water, agricultural irrigation and by industry. For example, in Europe, about 75% of EU inhabitants depend on groundwater for their domestic water supply, and worldwide, most of the groundwater abstracted is for irrigation (43% of irrigation water comes from groundwater, Siebert et al., 2010).

Groundwater abstraction lowers groundwater levels and can therefore cause a human-induced or human-modified groundwater drought. Groundwater is in most catchments strongly connected to surface water, and consequently, groundwater abstraction also influences river flow. The principle of groundwater ‘capture’ (Lohman, 1972) stipulates that groundwater abstraction leads to a combination of a lowering of groundwater levels, an increase in groundwater recharge (from surface water or water that would otherwise run off the surface as overland flow or reduced actual evapotranspiration in areas with shallow groundwater tables) and a decrease in groundwater discharge to surface water. Following a change in abstraction, this process continues until a new equilibrium is established in the hydrological system (Section 3.4). Thus, in most cases, groundwater abstraction decreases low flow and may cause or aggravate streamflow drought.

Groundwater abstraction often has a large spatial footprint, depending on aquifer characteristics. Abstractions located far away from a surface water body have less effect on low flow and streamflow drought than abstractions located close to a river or lake (e.g., Clausen et al., 1994; Peters et al., 2006). The influence of abstractions can cross catchment boundaries, as major aquifers often underlie several topographic catchments (Section 3.4.2).

Managed aquifer recharge, which is a form of artificial recharge (often abstracted from rivers), is an approach that is increasingly used to increase groundwater storage (Dillon et al., 2019). Its effects on hydrological drought (in groundwater and river flow) remain to be investigated in more detail. Irrigation losses that infiltrate into the aquifer also artificially recharge groundwater. Although often not intended, reducing irrigation losses decreases groundwater recharge and therefore aggravates groundwater droughts (Dench and Morgan, 2021).

10.3.1.3 Water abstraction during drought

During a drought, groundwater and surface water abstraction often increase. Water abstraction for domestic water supply can be higher during a drought or a heatwave (which often co-occurs with meteorological and soil moisture drought), when more water is used for watering plants and filling swimming pools. Water abstraction for irrigation also usually increases during meteorological drought in response to lower soil moisture, to support plant growth according to their need. Because groundwater generally responds slowly to a lack of precipitation (Sections 3.3.4 and 3.4.2), groundwater is often used as alternative water resource during drought. However, if the drought continues for a long time across seasons or even years (multi-year drought), wells may run dry or reach critically low levels because of the combination of climate-induced drought and human-induced drought (due to increased abstraction). If funding is available, deeper or more wells can be dug to continue abstraction, with increasing negative effects on groundwater and streamflow drought. A lower groundwater table may also cause a range of related impacts, such as reduced crop yields, land subsidence and ecosystem degradation (Section 12.2) and may reduce or prolong recovery after drought.

In well-regulated settings, abstraction may be reduced during major droughts, for example, when restrictions are placed on groundwater abstraction for agricultural, domestic and/or industrial purposes. Groundwater management focuses on sustainable groundwater use with the aim to reduce impacts of abstraction locally or elsewhere in the hydrological system, for example, if groundwater abstraction leads to more severe streamflow drought downstream. Measures that can be implemented are a reduction in abstraction rates, either through licences and restrictions or through awareness campaigns, or an increase of artificial recharge.

10.3.2 Reservoirs

Surface water reservoirs have a large influence on the hydrological cycle and river regimes as they store water during wet periods and release it later in time. The global impact of the current 6000+ large reservoirs (Lehner et al., 2011) is huge as they alter 23% of the global river systems (rivers with a discharge larger than 10 $m^3 s^{-1}$). Fig. 10.4a shows that the effect is largest and most widespread in the United States and Europe, but is also considerable on other continents, especially in the large river systems, such as the Nile and the Amazon. Both the number of reservoirs (Fig. 10.4b) and their combined storage volume (Fig. 10.4c) have increased over time, especially in the 1960s and 1970s. Reservoirs have a wide range of purposes, ranging from flood alleviation, to hydropower production, to

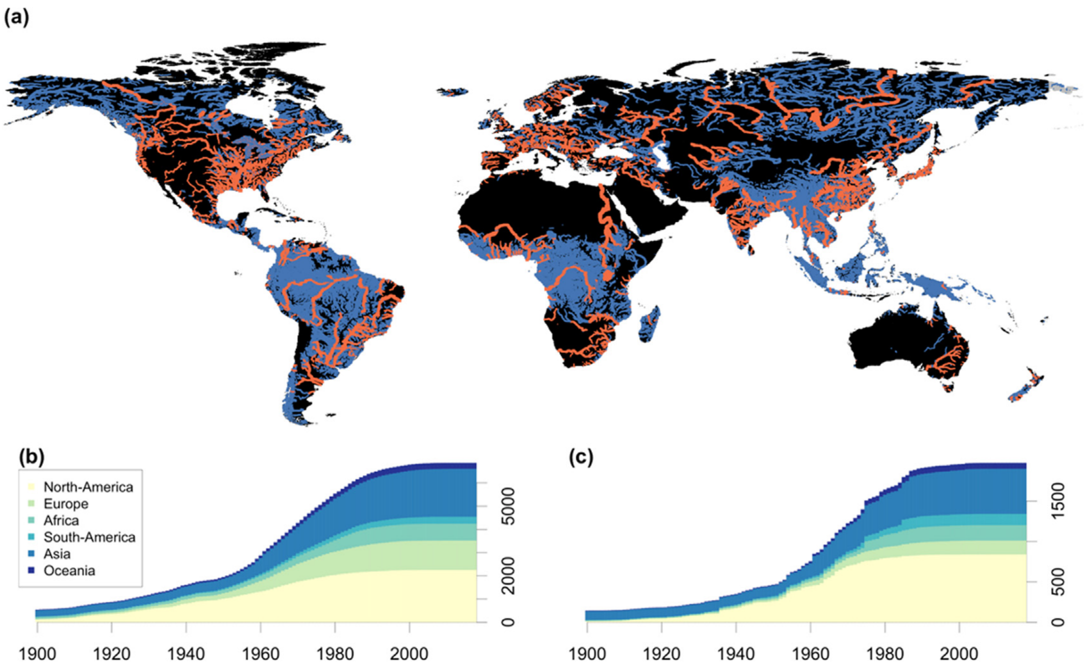

FIGURE 10.4

Impacts of reservoirs: (a) rivers affected by reservoirs around the world (river stretches in blue are unaffected by reservoirs, river stretches in red represent the downstream effects of reservoirs along the full downstream length of the river), (b) number of reservoirs per continent, and (c) total reservoir storage per continent over the period 1900–2020.

Data derived from GRanD database (Lehner et al., 2011).

water supply. Many reservoirs are multi-purpose, which means that the operating rules for the reservoir have to balance out various management needs. Accordingly, the influence of the reservoir on low flow and hydrological drought can be complex. Moreover, reservoir managers are commonly required to sustain a certain minimum flow during drought conditions for environmental purposes, often referred to as environmental flow. This requirement sometimes even increases low flows downstream of a reservoir as compared to the natural condition.

Reservoirs used for water supply often have a large influence on the flow regime and thus on low flow and hydrological drought. Water can be taken directly from the reservoir and not returned to the river system, or it can be released to the river for use further downstream. In the first case, discharge to the river downstream of the reservoir is significantly reduced, low flow is decreased, and streamflow drought may develop or be aggravated. In the second case, water is often released during dry periods to sustain abstraction for irrigation or water supply downstream, or for environmental flow requirements, which may increase low flows and alleviate streamflow drought.

Hydropower reservoirs release water for electricity production and often result in a more stable hydrological regime with less seasonality and less extreme high and low flows downstream.

Accordingly, reservoirs often increase low flows and alleviate hydrological drought downstream. Especially, during heatwaves when demand for energy is high, it may happen that the release of water to the downstream river is higher than normal, partly or fully compensating for the reduced natural flow. Sometimes, hydropower production leads to irregular river flow pulses downstream. This may cause many, but short-lived streamflow droughts downstream of the hydropower reservoir. In a drought analysis, we can consider to exclude these minor drought events (Box 5.2).

One of the side-effects of reservoirs is that by increasing surface water area, evaporation increases. This can reduce the overall water balance and thus, water availability, especially in dry climates and during prolonged drought and heatwaves. Therefore, sand dams are built in some regions (Lasage et al., 2007), which are small dams in sandy rivers that encourage sediments to settle behind the dam so that water can be stored within the sand and evaporation reduces. Another example is the employment of shade balls that cover the surface of the reservoir and thereby reduce evaporation (Haghighi et al., 2018).

It is important to note that due to reservoir management, human decisions control when and where hydrological drought occurs in human-modified catchments. Political and economic factors drive demand and release policies, which, together with natural processes, determine reservoir storage and release to the river and, hence, influence hydrological drought development downstream.

10.3.3 Land use

Changes in land use often have unintended consequences for water pathways and water balance components that may influence low flow and hydrological drought. Conversion of forest into agricultural land or vice versa (deforestation and afforestation) affects evapotranspiration, infiltration and consequently surface runoff, soil moisture, groundwater levels and river flow. How these changes again affect low flow and hydrological drought depend on the agricultural and forest practices, for example, whether irrigation is applied (where and when) and whether it varies over time. Evapotranspiration is an important factor because trees have higher evapotranspiration rates than grass or crops, and they maintain transpiration for longer during meteorological drought (Teuling et al., 2010). This is due to a combination of higher interception losses and easier access to soil water through deeper root systems. Studies indicate that afforestation can decrease low flow and increase hydrological drought, but over time, it also restores soil and recharge processes creating slower flow paths, higher base flow and therefore increased low flow (e.g., Van Meerveld et al., 2019, 2021).

When natural or agricultural land is converted to urban area, the increase in impermeable surface results in less infiltration and more surface runoff. This leads to a flashier hydrological regime (Sections 3.4.2 and 5.3.3), with lower low flows and a higher number of streamflow droughts. However, urban areas may also experience an increase in water input to the hydrological system and thus an increase in mean river flow. This may, for example, be due to a reduction in evapotranspiration, the release of (treated) sewage into urban rivers or leakage from water supply or sewage pipes recharging the groundwater (Lerner, 1990).

Overall, the effects of urbanisation on low flow and hydrological drought are not consistent and can vary considerably between urban areas depending on their specific design and measures taken. Recent developments in urban planning towards green or ‘sponge cities’ are aiming to reduce the effects of urbanisation on the water balance. There is, however, limited quantitative research on the influence of land use change on low flow and drought and contrasting results are reported between modelling studies (Tallaksen, 1993; Querner and Van Lanen, 2001; Hurkmans et al., 2009) and observation-based studies (Price et al., 2011; Eng et al., 2013).

Another land use change that influences hydrological pathways is the draining of land, which aims to permanently reduce water levels. As wetlands and other areas with high groundwater levels tend to support high evaporation rates (Bullock and Acreman, 2003), drainage may also lead to reductions in evapotranspiration and consequently higher recharge and low flow. However, wetlands dampen the flow regime (both high and low flows) and drainage will lead to a flashier regime and thus reduced low flow. The overall effect on low flow and hydrological drought (increase or decrease) will depend on the specific region and degree of drainage in the individual catchments.

10.3.4 Drought management and adaptation

Compared to floods and other natural hazards, droughts are often long lasting, which means that there is ample time for management responses during a drought event that will subsequently influence the hydrological drought hazard itself and its impacts. We will not discuss drought management in detail here, the reader is referred to a number of excellent books on drought management, for example Wilhite and Pulwarty (2018), UNCCD (2019) and URL 10.1. However, we do need to briefly mention the effects of drought management on hydrological drought. Drought management should implement a pro-active approach, including drought early warning, rather than a reactive one (Section 13.2). This includes demand-side and supply-side measures and should also imbed both long-term strategies and emergency responses to prepare for and mitigate hydrological drought.

Supply-side measures include water transfer from an area that is less affected by drought or from an area that does not have a high demand for water. Water transfer (diversion) decreases the hydrological drought in the receiving catchment, but increases the hydrological drought in the donor catchment. Another option to increase water supply is via desalination of saline water from oceans and (inland) seas. This may have indirect consequences for low flow and hydrological drought when the desalinated domestic water later is released to rivers and streams as treated sewage water.

The most common demand-side measure is a change in abstraction. Abstraction rates are often increased during drought to prevent or limit impacts, although in some cases, they are reduced to preserve water. The latter is often achieved through awareness campaigns and legal water use restrictions, or it happens inadvertently when reservoirs or wells run dry. In Cape Town (South Africa), restrictions in domestic and agricultural water use in 2018 prevented 'Day Zero' (the day when no water would be available anymore; Enqvist and Ziervogel, 2019). A prolonged increase in abstraction rates can have large impacts on hydrological drought. For example, in California (USA), groundwater abstraction increased dramatically during the multi-year drought (2011–16), which caused problems with land subsidence (Tortajada et al., 2017).

Some human interventions are meant to reduce water excess (flood prevention measures), but unintentionally contribute to hydrological drought development (Ward et al., 2020). In some areas land drainage may be such an example. On the other hand, some human interventions aim to improve the water situation for certain users during low flow and by that alleviate hydrological drought. An example is navigation. Ships require a minimum water depth, which is maintained by sluices and weirs, water transfers or reservoirs.

Interestingly, most drought management options shift the drought or the impacts to influence other components of the hydrological cycle, occur in a different region, manifest at a different time, or affect different water users. So, current short-term drought crisis management is often about prioritising and levelling among users and areas affected, that is, where and when it is optimal for a hydrological drought to occur to better deal with the impacts. However, long-term drought management requires pro-active measures to be taken to reduce possible drought impacts (always and everywhere) across sectors. And this should be based on adequate hydrological drought monitoring and forecasting (Chapter 13) and a good understanding of the human influences on hydrological drought.

10.4 Approaches to analyse human-drought interactions

To understand and quantify the effects of human interventions on the river flow regime and on hydrological drought, we can use a number of different approaches that complement each other (Table 10.1). These can be separated into approaches aimed at system understanding and those aimed at quantification of the effects of human interventions. Secondly, they can be classified in observation-based and model-based approaches, in which the observations can be either qualitative or quantitative data. We further distinguish between catchment-scale versus large-scale approaches (Table 10.1).

Quantification approaches aim to disentangle the natural processes and human influence on low flow and hydrological drought and quantify their individual contribution to these events. It is not straightforward to distinguish between natural variability and human influences mainly because droughts are rare cases, every drought event is different, necessary data are difficult to obtain, and rarely only one type of human intervention is present in a catchment. In addition, effects of natural processes and human interventions may counteract each other and therefore obscure the individual effects.

Common to the quantification approaches is the type of indices used to detect possible changes in low flow and hydrological drought among time series with and without the human intervention. For example, drought analysis of disturbed and undisturbed time series can show whether hydrological drought frequency, duration and/or severity have increased or decreased due to the human intervention. Some studies also look at differences in propagation from meteorological drought to hydrological drought between the disturbed and undisturbed situation. The comparison can be done between

Table 10.1 Overview of the approaches to analyse human interventions influencing hydrological drought.

		Catchment scale	Large scale (regional – global)
Quantification of human influence	**Observation-based**	**a)** Paired-catchment **b)** Upstream-downstream **c)** Observed-naturalised **d)** Pre-post-disturbance	Large-sample screening
	Model-based	Scenario modelling	Scenario modelling
System understanding	**Observation-based**	Analysis of qualitative data	
	Model-based	Socio-hydrological modelling	

different model scenarios, between observed (disturbed) and naturalised (undisturbed) data, and between a human-influenced (disturbed) and a control (undisturbed) catchment.

If the interest lies particularly with the human influence on low flow, we may look at differences in the flow duration curve (FDC; Section 5.3.1), its slope and in particular values in the lower range, for example, the Q_{80} or Q_{90} (Box 5.1). In ecological studies, it is common to define the areas between the disturbed and undisturbed FDCs as an 'eco-deficit' when it is negative and 'eco-surplus' when it is positive (Vogel et al., 2007). Additionally, Indicators of Hydrologic Alteration (IHA) developed in the 1990s by nature conservation organisations to assess human-induced changes to river flow regimes (Richter et al., 1996; Mathews and Richter, 2007) are used. In total, 33 variables that characterise the hydrological system are suggested, including the annual minima and number of no-flow flow days (Sections 5.3.2 and 5.4.2, respectively). IHAs are often used by water managers to determine environmental flow recommendations or requirements.

System understanding approaches aim to understand the complex interactions between drought and society, either using analysis of qualitative data (Section 10.4.5) or using socio-hydrological modelling (Section 10.4.6). These are often done on smaller, local scales, for example, one catchment, city or community.

The approaches presented in Table 10.1 are explained in more detail in the next sections, including their advantages and disadvantages. Section 10.5 gives examples of applications of these approaches, and Section 10.6 provides some guidelines on how to choose the most appropriate approach in a specific case.

10.4.1 Catchment-scale, observation-based methods

Quantifying the human influence on hydrological drought is often done on the catchment scale using observations (Van Loon et al., 2022). The basis of these catchment-scale and observation-based approaches is finding a natural benchmark (not influenced by the human intervention) against which the human-influenced river flow data can be compared. This natural benchmark (i.e., analogue or donor catchment, Section 4.3.9) can be taken from a period before the disturbance (pre- and post-disturbance approach), from a benchmark catchment nearby or upstream (paired-catchment and upstream-downstream approach) or from naturalised time series obtained by modelling (observed-naturalised approach).

Low flow indices, including those derived from FDCs, can be compared directly between the human-influenced time series and its natural benchmark. For drought analysis, a fixed or variable drought threshold (Section 5.4.1) is commonly calculated from the benchmark dataset ('benchmark threshold') and applied to both the benchmark and the human-influenced time series to calculate drought characteristics (Fig. 10.5). The benchmark and human-influenced drought characteristics are then compared to find the relative influence of the human intervention on hydrological drought. Note that these influences can be both positive (alleviating hydrological drought) and negative (aggravating hydrological drought). The reason for using the benchmark threshold for both time series is to exclude any human influence on the threshold. If the threshold is calculated from the disturbed and undisturbed time series independently or standardised indices are used (normalising each time series separately, Section 5.5), changes in the regime are not taken into account and the human influence is underestimated (Rangecroft et al., 2019).

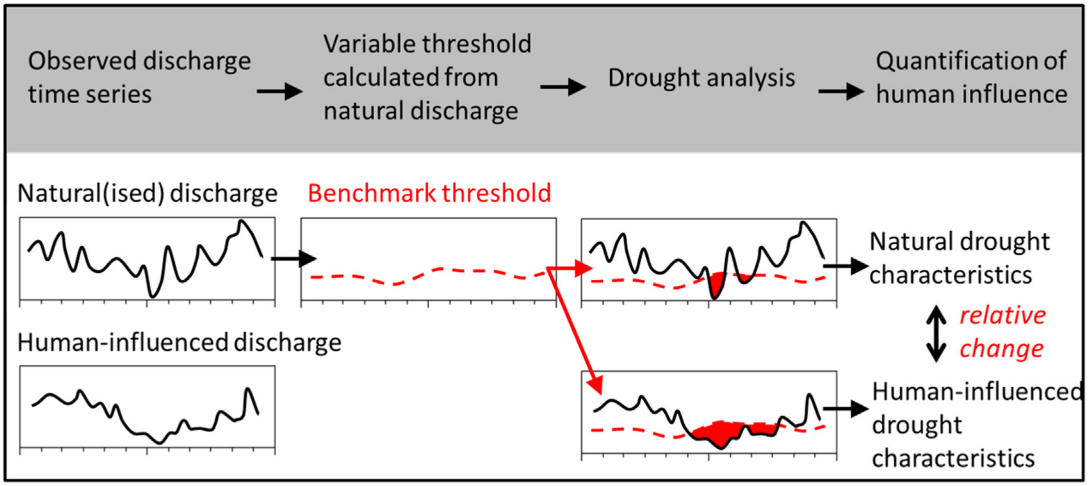

FIGURE 10.5

Illustration of the quantification of human influence on hydrological drought in observation-based approaches. The benchmark threshold (threshold calculated from the time series of the natural or naturalised discharge) is used to calculate drought characteristics in both the natural and human-influenced time series, which can then be compared.

Modified from Van Loon et al. (2019).

10.4.1.1 Paired-catchment approach

The paired-catchment approach has its roots in experimental hydrology. In the original setup (Bates, 1921), two adjacent catchments are investigated, one is kept natural and the other is disturbed intentionally (e.g., drained, afforested or deforested), and differences in water fluxes are compared. The approach has also proved useful for pre-existing human influences as long as the site selection is done carefully (Van Loon et al., 2019). The catchments should have climate and catchment characteristics (e.g., topography, soils and hydrogeology) as similar as possible, the only difference being the human intervention under study. Most studies using the paired-catchment approach focus on effects of land use change on annual and high flow, but the effects of other human interventions on low flow and hydrological drought can also be analysed using this approach.

10.4.1.2 Upstream-downstream approach

The upstream-downstream approach is a special case of the paired-catchment approach. It compares observed river flow downstream of a human intervention with the observed flow upstream (natural benchmark). Human interventions can be of any kind affecting river flow (e.g., urbanised area, extensive irrigated area, large groundwater abstractions), but is mostly used to investigate the impact of reservoirs within a river basin (e.g., López-Moreno et al., 2009; Rangecroft et al., 2019). Again, the upstream and downstream catchment characteristics need to be as similar as possible except for the human intervention. The effects of the intervention on low flow and hydrological drought are then determined by comparing low flow or streamflow drought characteristics derived from the time series of observed river flow downstream of the intervention to those upstream. The paired-catchment and upstream-downstream approaches work well for streamflow drought, but are less suitable for studying the effects of human interventions on groundwater drought because of the spatially diverse character of groundwater level and groundwater abstraction.

10.4.1.3 Observed-naturalised approach

The observed-naturalised approach is based on the comparison of low flow and hydrological drought characteristics of two time series of hydrological data (groundwater or river flow) at the same location, an observed time series and a naturalised time series. Sometimes naturalised data are provided by national agencies (Section 4.3.9). Otherwise, naturalised time series can be obtained by applying a process-based hydrological model (Fig. 10.6) or a statistical model based on regionalisation (Zimmerman et al., 2018; Section 7.2). For a process-based model, a predisturbance period is often required to calibrate the model (Section 9.3.3) and for statistical approaches, sufficient undisturbed data points are needed to train the model (Section 7.2). The observed-naturalised approach is a well-known approach; for example, it has been used to quantify effects of human influences on hydrological drought in river basins in China, including impacts of water withdrawal in the Yellow River (Yuan et al., 2017) and reservoirs in the Jinjiang River (Wu et al., 2017).

10.4.1.4 Pre-post-disturbance approach

The pre-post-disturbance approach compares the low flow and hydrological drought characteristics in the period before and after the human intervention started. This can be a good approach in cases where

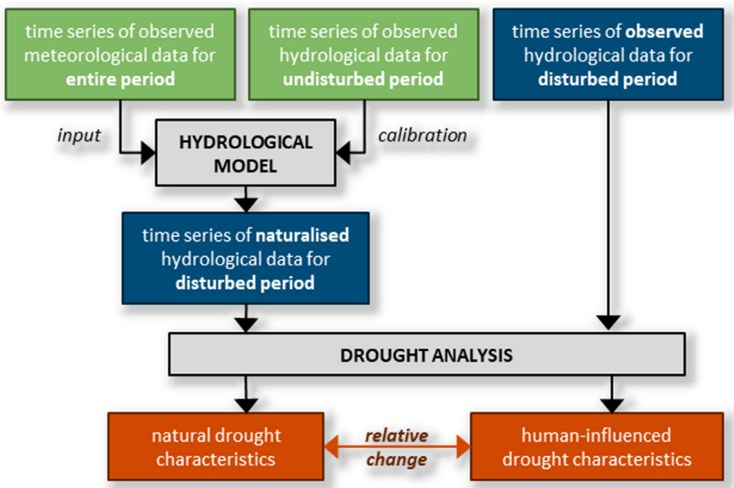

FIGURE 10.6

Illustration of the observed-naturalised framework. A hydrological model is used to naturalise the discharge data for the disturbed period using hydrological data of the undisturbed period for calibration. Drought characteristics of both naturalised and observed time series for the disturbed period can then be compared, representing natural and human-influenced drought characteristics (Fig. 10.5).

Modified from Van Loon and Van Lanen (2013).

the human intervention started at a specific point in time (e.g., reservoir building) or changed significantly (e.g., the groundwater abstraction rate) and where data are available from before and after the intervention. It is less used for analysing the effects of land use change, which tends to happen more gradually. In the latter case, the record can be split into several time periods and differences in low flow and hydrological drought characteristics between the time slices can be analysed. Alternatively, a sliding time window can be used, for example, a 20-year time window is moved in steps of one year. This sliding-window approach is particularly suited for analysing gradual changes, such as land-use changes and nonstationarity due to, for example, climate change. If the exact time of the intervention is not known, methods to identify inhomogeneities and breakpoints in the time series can be useful. Detecting and quantifying sudden changes in time series is known as change-point detection and the point in time when the change occurs is often referred to as a breakpoint. Several statistical methods to identify such breakpoints are available as elaborated in Section 7.4.3 (see also Worked Example 7.3). In Section 10.5.1.3, an example using the double mass analysis — a simple graphical method — is provided. Metadata (information about potential influences) can be used to attribute the step changes to the human influence and/or other influences. The pre-post-disturbance method is best suited for rather long time series to ensure time slices of sufficient length both prior to (pre) and after (post) the intervention. Examples of the pre-post-disturbance approach include Quesada-Montano et al. (2018) for the Po River in Italy, Kang and Jiang (2019) for the Yangtze River in China, and the Göta River (Figs. 7.9—7.14).

10.4.2 Large-sample screening

To understand relationships between human interventions and hydrological drought across a wide range of hydrological regimes and over a variety of spatial and temporal scales, we can use ‘comparative hydrology’ (Falkenmark and Chapman, 1989) or ‘large-sample hydrology’ (Gupta et al., 2014). These are approaches that aim to balance an understanding of the unique behaviour of individual catchments with the quantification of hydrologic similarity between catchments across larger regions (Section 8.2.1). This is done through statistical analysis of large-sample datasets. It relies on the availability of datasets with large numbers of catchments with common data procedures to ensure that the data are comparable. Large-sample hydrology or large-sample screening is potentially a powerful approach to disentangle and better understand human influences on low flow and hydrological drought, particularly when additional qualitative data are available to support the interpretation of the patterns seen in such a large sample of catchments.

Large-sample screening has been used to investigate the human influence on low flow (e.g., Price et al., 2011; Eng et al., 2013) on river flow (e.g., Sadri et al., 2016; Tijdeman et al., 2018) and on groundwater drought (e.g., Bloomfield and Marchant, 2013; Bloomfield et al., 2015). The variables and indices used to quantify human influence, including the low flow and hydrological drought characteristics, and the specific statistical techniques used to analyse the data at hand, depend on the research question being addressed and, on the availability, and quality of relevant large-sample datasets.

If meta-information (Section 4.2.4) is available that allows us to identify catchments with natural, or at least ‘near-natural’, conditions, then one option is to investigate systematic departures from those near-natural flow conditions in the set of catchments where human interventions are present. Tijdeman et al. (2018) applied this approach to hundreds of catchments with and without human interventions in

England and Wales, and Sadri et al. (2016) looked at the human influence on annual minimal flow (*AM*(*7*-day) and *AM*(*30*-day); Section 5.3.2) in more than 500 USA river flow records. These studies used large-sample screening to separate between near-natural and human-influenced catchments based on metadata (indicating human influence with labels or quality flags). Whether or not there are significant deviations between the sub-samples is explored through statistical analyses (e.g., correlation and trend analysis, Sections 7.3.2 and 7.4).

10.4.3 Catchment-scale scenario modelling

Process-based models were introduced in Chapter 9 and Section 10.4.1 as a tool to naturalise observed river flow data. Subsequently, the naturalised time series can be compared to observations to distinguish the effects of human interventions on low flow and hydrological drought from natural processes. Models can also be used for hypothesis testing, scenario analysis and attribution of individual drivers. Models have the advantage that they can simplify complex systems and that they can be altered – in contrast to large-scale experiments in the real world – to test the effect of different interventions, providing a valuable addition to observations supporting water management decisions. Models are well suited for these types of sensitivity analysis, especially in regions where observations are limited. Modelling tools have therefore become indispensable for analysis of low flow and hydrological drought under human influence. Observations are still needed as input data and for calibration and validation. Model results should always be validated against observations and uncertainties in the model simulations accounted for before concluding on the human influence on low flow and hydrological drought.

Models that do not include human interventions in their model structure can be used to naturalise disturbed time series (Section 10.4.1). However, there are also models that do include the effects of human interventions explicitly, including land use change, water management (reservoirs, water abstraction for irrigation, drinking water) and water allocation schemes (e.g., Section 9.4.3). These (water management) models can be used for scenario analysis of the human influence on hydrological drought. A variety of different scenarios can be simulated. For example, in the model, reservoirs can be added, abstractions can be added, increased or decreased, land use can be changed and return flows can be added or removed. Finally, low flow and drought characteristics can be compared between the scenarios and against a natural benchmark.

10.4.4 Large-scale scenario modelling

Section 10.4.2 introduced the approach of large-sample screening for observation-based analysis on large spatial scales. However, in large parts of the world, observational data are not available, or the dataset may not include all variables and information needed. In such cases, large-scale models that include the human influence provide a valuable tool (Section 9.4.2).

Similar to catchment-scale models, large-scale models need observations as input data (forcing data), and for validation, and they can be used for scenario (or sensitivity) analysis in which a scenario with human interventions is compared to one without. The availability of observations and metadata is more challenging on continental and global scales than on the catchment scale. Especially, information on human interventions, such as abstraction volumes or reservoir operation rules, are hard to obtain in a systematic way across nations. Due to the lack of data, large-scale models are rarely calibrated to observed river flow data with a few exceptions, in which case only a limited number of parameters are calibrated (Section 9.4.2.3).

An interesting aspect of large-scale models, compared to catchment-scale models (Section 9.3.3), is that the effects of different scenarios on low flow or hydrological drought can be evaluated spatially across the globe. This means that different regions can be compared and patterns identified that can assist the analysis of how the influence of human intervention on hydrological drought varies with climate, geology and socio-economic conditions. With the development of large-scale models, there has also been an increase in the application of these models to study the human influence on low flow and hydrological drought. Examples are Veldkamp et al. (2017, 2018), who found in a global study that hydrological drought is both alleviated and aggravated by human interventions resulting in a decrease of water shortage for some people and an increase for others (upstream and downstream communities).

Large-scale models have evolved over time (Bierkens et al., 2015; Telteu et al., 2021) and will evolve further in the future. Future versions of large-scale hydrological models are likely to include more human-water interactions and to operate on finer spatial and temporal resolutions, to bridge the gap to catchment-scale processes. For example, Wanders and Wada (2015) introduced abstraction and reservoirs in the PCR-GLOBWB model (Section 9.4.2), and later desalination and interbasin water transfers were included. Representation of reservoir operations is also expected to improve in large-scale models as well as estimates of agricultural withdrawal rates. However, it remains important to fully account for uncertainties in the process representations and to be aware of current limitations of using these models in attributing the human influence on low flow and hydrological drought across large spatial scales.

10.4.5 Analysis of qualitative data

Qualitative information is crucial for better understanding the interactions between hydrological drought and society. Even in the quantification of the human influence on hydrological drought, qualitative information is often used. For example, metadata indicating which observations are potentially affected by human interventions are important in large-sample screening (Section 10.4.2); observation-based methods rely on qualitative information on when and where the human interventions took place (Section 10.4.1) and estimates of water demand, abstraction, reservoir operation and land use change in both catchment-scale and large-scale models are often based on qualitative information.

Qualitative analysis of human-drought interactions can also be a goal in itself in cases where contextual information is important and diverse perspectives should be taken into account. Qualitative data can be collected via social science approaches, such as interviews with local water users or managers, participant diaries, oral recollections or narrative interviews, community histories, participant observation, photographs and other visual materials (Section 4.3.9).

Analysis of qualitative data may provide a useful and often detailed overview of, for example, human water use, water management measures, drought adaptation, and water use restrictions in a region. This information helps to understand the potential human influence of human interventions on low flow and hydrological drought, but it can also be used as input to the models described above and in Chapter 9. For example, socio-hydrological models (Section 10.4.6) need data to design the model structure and parameterise the human-water interactions. Additionally, both catchment-scale and large-scale models need information on which scenarios are most realistic to explore in a certain region.

10.4.6 Socio-hydrological modelling

Socio-hydrological models allow for dynamic changes and feedbacks between drought and society (Section 9.5) and can reveal unexpected behaviour. For example, subsequent droughts can make a society increasingly vulnerable; at a certain point a a tipping point is reached, beyond which it is impossible to recover. Different model types are available, including coupled-component models, system-dynamics models and agent-based models (Section 10.5.6). Kuil et al. (2016) used a socio-hydrological model (Section 9.5.3) to simulate the Maya collapse and showed that reservoirs can buffer small droughts so that society is not impacted, but they cannot buffer large droughts, making the impacts more severe when the reservoirs run dry.

Similar to large-scale models, socio-hydrological models are also rapidly developing. Blair and Buytaert (2016) reviewed the scientific literature and give an overview of socio-hydrological modelling approaches. They posit that the focus of socio-hydrological modelling is not on problem solving, but on creating new insight into human-water dynamics in a holistic way. Therefore, it is crucial that socio-hydrological models include interactions and feedbacks. They can do so in a bottom-up way, representing individual people and their heterogeneous interactions with the water system, or in a top-down way, setting general rules on a more abstract level. Both approaches are useful when studying human-drought interactions.

10.5 Examples of approaches of human interventions influencing hydrological drought

10.5.1 Catchment-scale, observation-based methods

10.5.1.1 Groundwater abstraction in the Upper-Guadiana catchment in Spain, using the observed-naturalised approach

In this example, we show an application of the observed-naturalised approach (Section 10.4.1.3) to quantify the influence of groundwater abstraction on hydrological drought. This example is based on the work by Van Loon and Van Lanen (2013) and uses data from the Upper-Guadiana catchment (Spain).

In the Upper-Guadiana, groundwater abstractions for irrigation substantially increased in the 1970s (Section 4.5.3.1), and the HBV model, a process-based lumped hydrological catchment model, is used to naturalise the observed hydrological time series in the period that followed the increase. The HBV model setup is described in detail in Section 9.3.2. Here, the model is used to quantify the effect of the groundwater abstraction on hydrological drought in Upper-Guadiana. The HBV model (calibrated and validated with observations from the pre-disturbed period) simulates the naturalised hydrological situation in the disturbed period based on meteorological forcing. The simulated river flow is used to calculate a daily variable threshold (Section 5.4.1). Then, the climate-induced droughts are derived by applying this threshold to the naturalised flow (Fig. 10.7a). By applying the same threshold to the observed flow (i.e., the human-influenced time series), human-modified and human-induced droughts are determined (Fig. 10.7b). Further details on this approach are given in Worked Example 10.1. Fig. 10.7c shows the observed flow, the naturalised flow and the threshold combined in one graph. The analysis reveals that the groundwater abstraction in the Upper-Guadiana increased hydrological

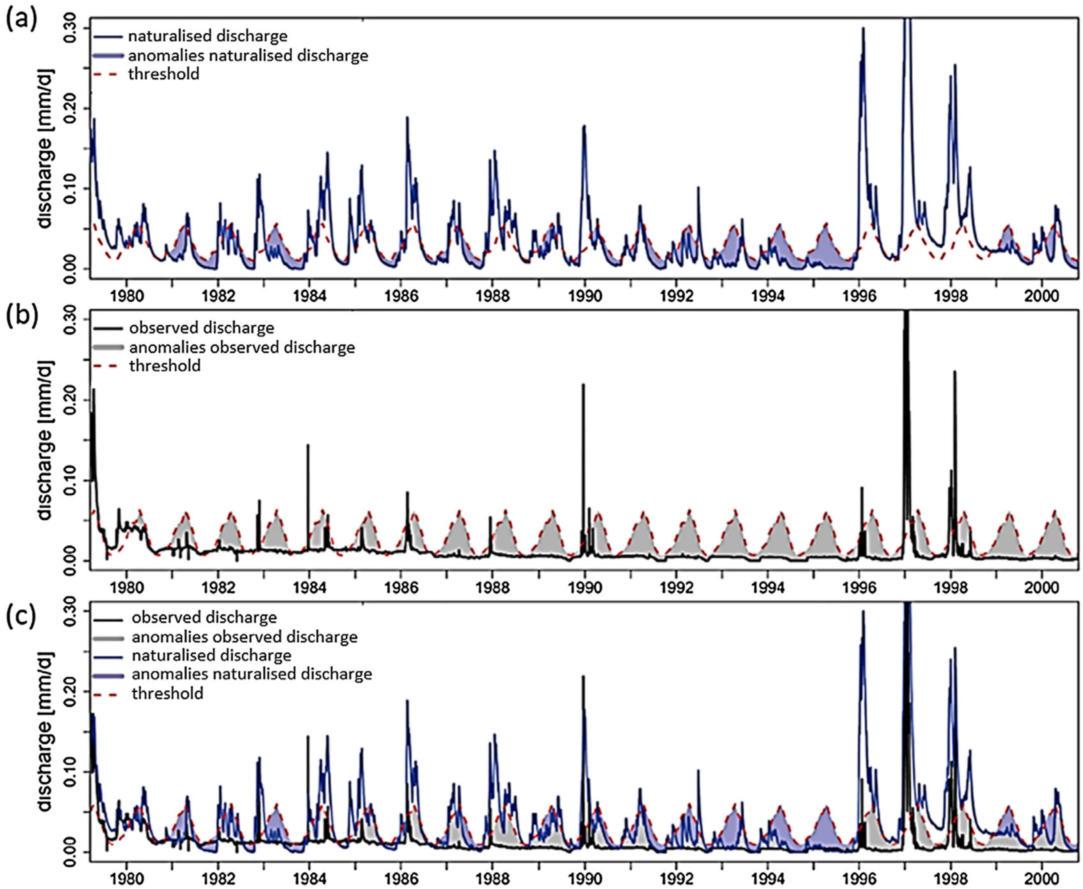

FIGURE 10.7

Observed (disturbed) and naturalised daily discharge in the Upper-Guadiana catchment during a period with substantial groundwater abstraction: (a) naturalised discharge (*blue areas* indicate climate-induced drought deficits), (b) observed discharge (*grey areas* indicate human-modified drought), and (c) comparison of observed and naturalised discharge (*blue areas* indicate climate-induced drought, *grey areas* indicate human-modified drought deficits).

Modified from Van Loon and Van Lanen (2013).

drought duration four times compared to the naturalised situation. The observed-naturalised approach was also applied to groundwater levels and showed that a permanent human-modified drought occurred in groundwater observations that was not present in the naturalised data (Van Loon and Van Lanen, 2013).

Worked Example 10.1 Quantifying the human influence on hydrological drought

https://github.com/HydroDrought/hydrodroughtBook

In this worked example, the catchment-scale, observation-based method is used to quantify human influence on hydrological drought, based on the threshold level method for drought calculation (Section 10.4.1; Fig. 10.5). We compare drought duration and deficit volume of two time series from the Upper-Guadiana catchment, one with and one without human influence. The time series without human influence can be calculated from a paired-catchment approach, an upstream-downstream comparison, observed-naturalised comparison or pre-post-disturbance approach (Section 10.4.1; Table 10.1). In this example, we use the observed-naturalised approach (Figs. 10.6 and 10.7).

1. ***Loading the data***
   We begin by loading the two time series from the Upper-Guadiana dataset: the benchmark (naturalised) time series and the human-influenced time series. The benchmark time series is simulated, as described in Section 9.3.3. In this case, the observed time series from the Upper-Guadiana catchment is the human-influenced time series (Section 4.5.3.1). The time series of discharge are converted into mm day^{-1}.
2. ***Threshold calculation***
   We use a daily varying threshold, the Q_{80}, calculated based on a smoothed 30-day moving average series over the reference period (1960–2000). The threshold is derived from the benchmark time series.
3. ***Calculate the benchmark drought characteristics (drought duration and deficit volume)***
   Hydrological drought events in the benchmark time series are identified with the threshold level method (Section 5.4.1) for a selected period. Note that this time period can differ from the reference period used to calculate the benchmark threshold. In this example, we derive hydrological drought events over the period 1981–2000, which equals the period with the main human intervention in the Upper-Guadiana catchment. To limit the problem of dependent droughts, consecutive drought events with an inter-event time less than or equal to 10 days are pooled into a single drought event (Worked Example 5.4). To remove minor droughts, only drought events with a duration of more than 10 days are kept (Section 5.4.1). Average drought duration and deficit volume are then calculated for the resulting series of events. We find for the naturalised benchmark time series a mean duration of 91 days and a mean deficit volume of 0.67 mm.
4. ***Calculate the human-influenced drought indices***
   Similarly, hydrological drought events in the human-influenced time series are identified. Note that we are using the same period (1981–2000) as was used to derive drought indices for the benchmark time series (Step 3). Furthermore, we are applying the same inter-event criterion and exclusion of minor drought events (Step 3). We find for the human-influenced time series a mean duration of 304 days and a mean deficit volume 3.59 mm.
5. ***Comparison of drought indices***
   In this final step, we compare the drought indices between the benchmark and human-influenced time series by calculating the percentage difference between the two series, ΔDI:

$$\Delta \mathrm{DI} = \frac{\mathrm{DI_{HI}} - \mathrm{DI_{BM}}}{\mathrm{DI_{BM}}} \cdot 100 \qquad \text{(WE10.1)}$$

where ΔDI is the percentage difference in drought index (DI) between the human-influenced ($\mathrm{DI_{HI}}$) and benchmark ($\mathrm{DI_{BM}}$) time series.

We find that the difference in mean duration is 236% and in mean deficit volume 434%. To conclude, streamflow drought in the Upper-Guadiana catchment have increased in duration and mean deficit, with on average 236% and 434%, respectively, in the human-influenced situation compared to the naturalised situation.

10.5.1.2 Reservoir in Chile, using the upstream-downstream approach

Here, we show an application of the upstream-downstream approach (Section 10.4.1.2) to quantify the influence of reservoir storage on hydrological drought downstream. This example is based on the work by Rangecroft et al. (2019) and uses data from the Huasco River (Chile).

The Huasco River is located in the semi-arid part of Chile, which means that downstream agricultural users are heavily dependent on water from rivers, such as Huasco, which are fed by glacier meltwater and snowmelt. There is a strong seasonality in river discharge, and water for irrigation is not always available at the right time. Therefore, a reservoir (the Santa Juana Dam, operational by 1998) was built to store water in the high-flow season and release it during the low flow season for downstream water use.

Hydrological drought characteristics of a downstream station (Fig. 10.8b) are compared to those of an upstream station (Fig. 10.8a), both derived using a monthly varying threshold (Section 5.4.1). The (benchmark) threshold is based on monthly time series of the upstream station. Results reveal an aggravation of hydrological drought downstream of the reservoir (Figs. 10.8a and 10.8b), with an increase in drought duration (+15% on average) and deficit volume (+158% on average). Because the reservoir completely changed the regime downstream, post-reservoir drought now occur in the previous high-flow season. If instead a fixed threshold would have been used, alleviation of hydrological drought downstream of the reservoir would have been found, because upstream low flow periods were completely removed by the reservoir. Finally, if the (variable) threshold would have been derived based on discharge data from the downstream station (instead of using the upstream threshold), the influence of the reservoir on hydrological drought would have been less. This demonstrates the potentially large influence the choices of threshold may have on the results.

10.5.1.3 Groundwater abstraction in the Neresnica Brook in Slovakia, using the pre-post-disturbance approach

In this example, we show an application of the pre-post-disturbance approach (Section 10.4.1.4) to quantify the influence of groundwater abstraction on hydrological drought. This example is based on the work by Fendekova et al. (2005) and uses data from the Neresnica Brook and the Podzamcok and Dobra Niva groundwater well fields (Slovakia).

The Podzamcok groundwater well field is located in the southern part of central Slovakia in the Neresnica Brook catchment, which has an area of about 140 km^2. The Neresnica Brook valley follows a deep tectonic zone between two mountain regions of volcanic rocks. The area has a mild climate with an average air temperature of 7.6°C and average annual precipitation of 670 mm (1963–2015). More details on the catchment location, geological and hydrogeological settings can be found in Fendekova et al. (2005). Abstractions from Podzamcok started in 1973 and peak abstractions occurred between 1981 and 1989. In the same period, groundwater levels decreased and the hydraulic connection between groundwater and surface water was broken. By analysing precipitation and discharge data using the double-mass curve, we can quantify potential in-homogeneities or shifts in the time series and, if

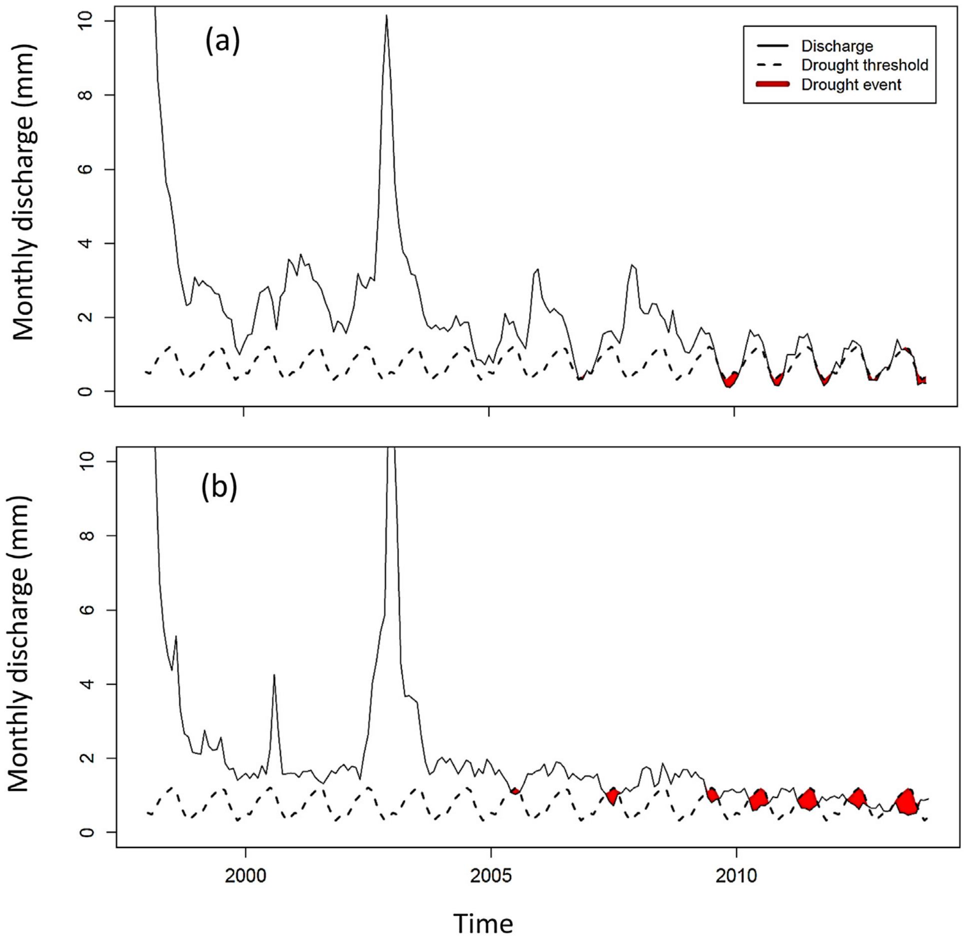

FIGURE 10.8

Hydrological drought analysis for the post-reservoir period (1998–2013) for: (a) upstream, and (b) downstream discharge stations in the Huasco River. Drought events are derived using a monthly variable threshold level and discharge data from the upstream station used to calculate the threshold.

Modified from Rangecroft et al. (2019).

possible, attribute these to groundwater abstraction. Data analysed include monthly precipitation totals at Dobra Niva meteorological station (since 1963), average daily minimum flow (*AM*(*1*-day)) of the Neresnica Brook at the Zvolen gauging station (since 1963) and groundwater abstraction from the Podzamcok and Dobra Niva groundwater stations (since 1973, although not complete).

The double-mass curve analysis is applied on *AM*(*1*-day) time series of the Neresnica Brook plotted against annual precipitation totals as the reference time series (Fig. 10.9). Three distinct shifts (or breakpoints) in the double-mass curve (DMC) are identified dividing the curve into four segments. The first segment mirrors the non-disturbed period (blue squares, 1963–73). The second segment (red squares, 1974–94) represents the period in which withdrawals were high, varying between 0.100 and 0.215 m^3 s^{-1}. During 1995–2007 (the third segment; green triangles), the abstraction decreased to

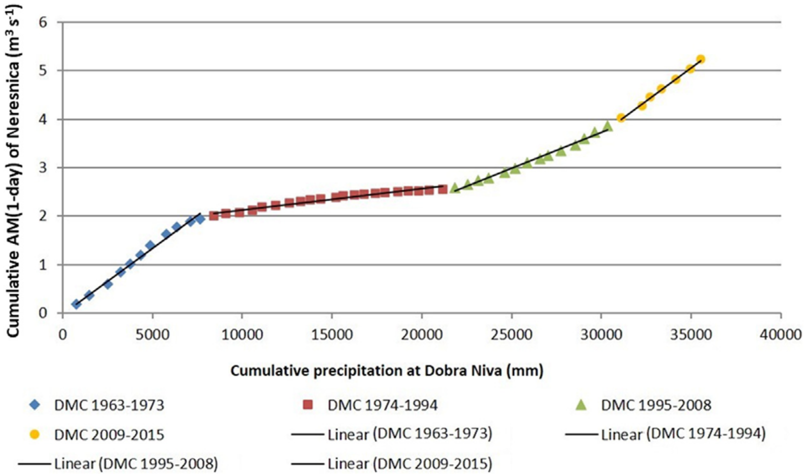

FIGURE 10.9

Double-mass curve (DMC) of the annual minimum flow (*AM*(*1*-day)) time series of the Neresnica Brook gauging station plotted against annual precipitation totals at the Dobra Niva meteorological station covering the period 1963–2015.

below 0.1 $m^3 s^{-1}$. The fourth segment represents the period 2009–15 (yellow circles) with limited withdrawals (not exceeding 0.03 $m^3 s^{-1}$) and has a slope similar to the first non-disturbed period.

Drought analysis using the threshold from the undisturbed period reveals that hydrological droughts in the period with high withdrawals (1974–94, Fig. 10.10b) were on average 120% longer and more severe than in the pre-disturbance period (1963–73, Fig. 10.10a) and 80% longer and more severe than in the post-disturbance period (1995–2007).

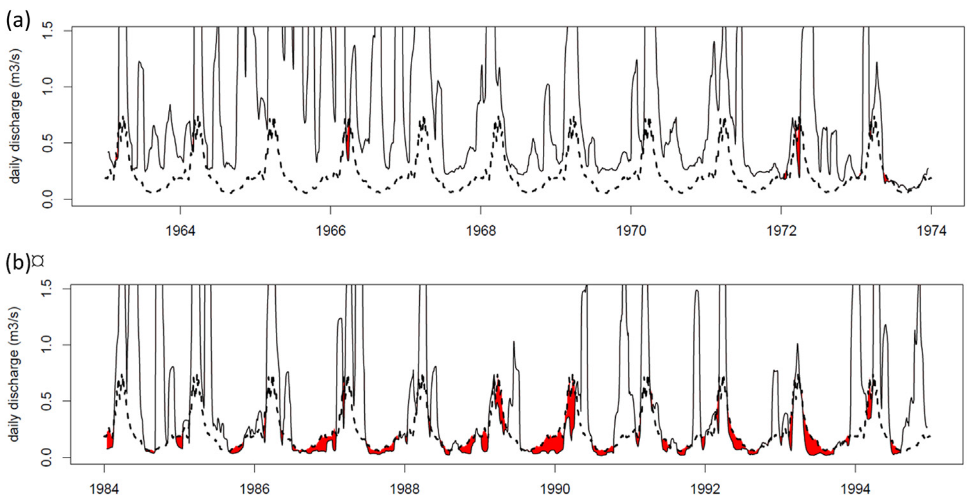

FIGURE 10.10

Hydrological droughts analysis for: (a) the pre-disturbance period (1963–73), and (b) a subset with intensive abstractions (1984–94) from the period with large abstractions (1974–94). The *dotted line* represents the variable threshold (Q_{80}) and the *area marked red* are the drought events.

10.5.2 Large-sample screening

In this example, we show an application of the large-sample screening approach (Section 10.4.2) to quantify the influence of groundwater abstraction on groundwater drought. This example is based on the work by Bloomfield et al. (2015) and Wendt et al. (2020) and uses data from the United Kingdom.

Bloomfield et al. (2015) analysed groundwater droughts using 74 standardised monthly groundwater water level hydrographs (Standardised Groundwater Index, SGI; Section 5.5.2) from three regional aquifers in Lincolnshire, UK, covering the common period 1983 to 2012. Climatic conditions are similar across the study area so it is assumed that any differences in observed groundwater droughts between sites can be explained either in terms of contrasting catchment and aquifer characteristics or human influences. To analyse this hypothesis individual standardised groundwater level time series are grouped using a k-means clustering algorithm, and the resulting mean cluster time series are then compared with corresponding mean standardised accumulated precipitation (Standardised Precipitation Index, SPI; Box 5.3) time series. The results show high correlations between SPI and SGI (0.86–0.74) for three of the six clusters. Sites in each of these clusters are spatially coherent and consist predominantly of sites from one of the three main aquifers representing near-natural groundwater drought histories for each aquifer system. The remaining ~20% of sites fall into three other clusters that all have much lower SPI-SGI correlations (0.53, 0.36 and 0.09). Sites in these clusters are from a range of hydrogeological settings and two of the clusters qualitatively exhibit declining trends in standardised groundwater levels. There is very limited or no spatial or temporal coherence in their groundwater drought behaviour. The conclusion of this study is that all three clusters were inferred to be affected by groundwater abstraction, including in some cases long-term overexploitation.

In a follow-on study, Wendt et al. (2020), used the SPI-SGI correlations of near-natural groundwater sites as a benchmark for a larger dataset of potentially human-influenced sites. The comparison revealed that groundwater abstraction led to an increase in shorter groundwater droughts in some areas and a lengthening and intensification of groundwater droughts in other areas.

10.5.3 Catchment-scale scenario modelling

In this example, we show an application of catchment-scale scenario modelling (Section 10.4.3) to quantify the influence of groundwater abstraction on groundwater drought. This example is based on the work by Van Lanen et al. (2004) and Van Loon and Van Lanen (2015) and uses data from two neighbouring catchments (Poelsbeek and Bolscherbeek) in The Netherlands.

Data comprise daily time series of groundwater level simulated with the distributed process-based model SIMGRO (Section 9.4.3) and daily meteorological data from 1951 to 1998. For more information, the reader is referred to Section 9.4.3, including Supporting Documents 9.1–9.4, and Van Loon and Van Lanen (2015). This example is available also online as a Self-guided tour (Section 9.4.3.4). Two groundwater abstraction scenarios are simulated using the SIMGRO model, with water being abstracted in the Poelsbeek catchment at a:

- **(a)** constant extraction rate of 2050 m^3 day^{-1} during the winter season (October–March) (scenario 05Y)
- **(b)** constant extraction rate of 2050 m^3 day^{-1} throughout the whole year (scenario 1Y).

Abstraction rates are modest, that is, the 05Y and 1Y scenarios amount to 4% and 8% of annual catchment discharge, respectively.

The model experiments show that groundwater abstraction leads to a pumping depression cone characterised by a large drawdown of the water table near the abstraction well. The depression cone enters into the adjacent Bolscherbeek catchment. The lowered groundwater levels cause a reduction in the discharge of the Poelsbeek catchment. This also happens in the Bolscherbeek catchment; however, this catchment receives part of the abstracted water as sewage water (return flow) leading to a net increase in discharge.

Based on these simulations, the effects of the groundwater abstraction on hydrological drought (river flow, groundwater) are quantified in both catchments. Groundwater drought is identified using a fixed threshold level (H_{70}, Box 5.1) derived based on daily groundwater level data from the natural (benchmark) situation.

Fig. 10.11 shows the deviation of the groundwater level from the threshold for the natural situation as compared to the two abstraction scenarios. Clearly, the drawdown at a location 500 m from the well field in the Poelsbeek gives relatively large deviations pointing at more prolonged and more severe groundwater drought, so an aggravation of drought, as compared to locations near the outer edge of the depression cone. For example, the cumulative frequency distribution (Fig. 10.11a) shows that a drought occurs 30% of the time for the natural situation (Ref), whereas this increases to 40% and 75% of the time for the abstraction scenarios 05Y and 1Y, respectively. Groundwater drought characteristics vary notably over time as the time series for the selected 16 years illustrates (Fig. 10.11b). In wet periods (e.g., second part of the 1960s), drought occurs less frequently and events are minor, whereas it is pronounced in the 1970s. When groundwater is abstracted (1Y), droughts are no longer interrupted as under natural conditions, and two multi-year droughts develop in the 1970s. Fig. 10.11b shows that the severe groundwater drought (deviation over 1 m from the threshold) can be observed in several

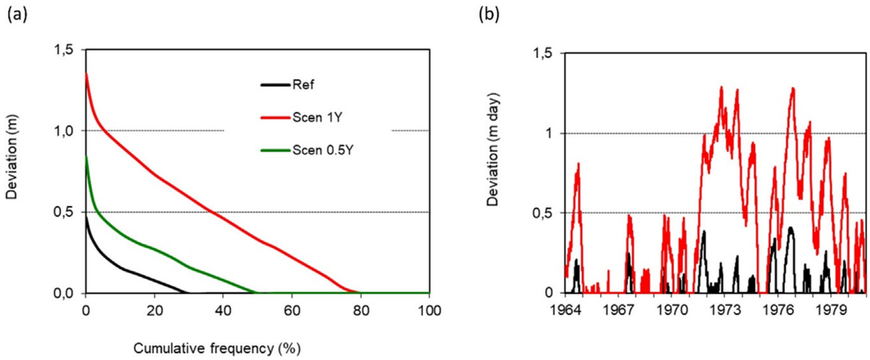

FIGURE 10.11

Groundwater drought (deviation in meter from the groundwater threshold) for the natural situation (Ref) and for the groundwater abstraction scenarios 05Y and 1Y for a location 500 m from the abstraction well in the Poelsbeek catchment: (a) cumulative frequency distribution of the deviation, and (b) time series of the deviation for the selected period 1964–80 (05Y scenario not shown).

periods (scenario 1Y). For example, in the 1970s, two such periods covering several years occurred. In these periods, the deviation remained high (in red), and significantly higher than for the natural situation (in black). This implies that groundwater levels did not recover in the wet season (multi-year drought) due to the continuous groundwater pumping. Groundwater drought for the 05Y scenario is less severe and did not significantly deviate from the reference situation at 500 m from the well field. The same holds for groundwater drought in the adjacent Bolscherbeek catchment because the abstraction takes place in the Poelsbeek catchment (not shown).

In addition, daily time series of simulated river flow for the Poelsbeek and Bolscherbeek catchments were analysed to assess the impact of groundwater pumping on streamflow drought. The annual average river flow of the Poelsbeek shows a decrease due to pumping by 2.5% and 5.9% for the two scenarios, whereas low flows are hardly affected. The effect of pumping on river flow of the Bolscherbeek is negligible. Accordingly, the impact of the abstractions on streamflow drought severity and duration is also limited.

10.5.4 Large-scale scenario modelling

In this example, we show an application of large-scale hydrological modelling (Section 10.4.4) to quantify the influence of human water use and management on hydrological drought. This example is based on the work by Wanders and Wada (2015) and He et al. (2017) and has a global and continental scope.

The large-scale hydrological model PCR-GLOBWB (Section 9.4.2) allows simulation of global hydrology with and without human interventions. Wanders and Wada (2015) analysed two global simulations of daily river discharge to assess the influence of reservoirs and water abstraction on streamflow drought. The natural discharge simulation, so without human interventions, was used to compute the benchmark threshold in the absence of human interventions. This threshold (90% daily varying threshold) was then used as a benchmark for the human intervention scenarios, similar to what is often done in observation-based approaches (Fig. 10.5), but now for different model scenarios. This allows to quantify differences in drought frequency and deficits between the natural and human intervention scenarios. We can also distinguish between the effect of different human interventions, such as reservoir construction and water abstraction.

A follow up study by He et al. (2017) used the same approach to look at the impact of irrigation and reservoirs on hydrological drought deficits over the continental United States. Four types of reservoirs were simulated (different purpose): water supply, including irrigation, flood control, hydropower and other, based on data of the Global Lakes and Wetlands Database. Irrigation water demand was estimated from a historic map of irrigated areas, cropping calendars and meteorological conditions. Livestock water demand was calculated from livestock densities and their water requirements. Water transfers were not considered. Irrigation resulted in short-term alleviation of soil moisture drought and increasing local runoff during drought (Fig. 10.12). This locally alleviated the drought deficit as can be seen from the large blue areas, which coincide with agricultural regions. However, in the following months, base flow is reduced as groundwater resources are depleted, leading to lower runoff (not shown in the figure). As for reservoirs, they have in general a negative impact on water availability in the downstream large rivers (see red areas in Fig. 10.12). Water is locally stored and often used to mitigate the drought, but overall this has a negative impact on downstream drought deficit. These two contrasting effects (from irrigation and reservoirs) add up to give a diverse total effect on hydrological

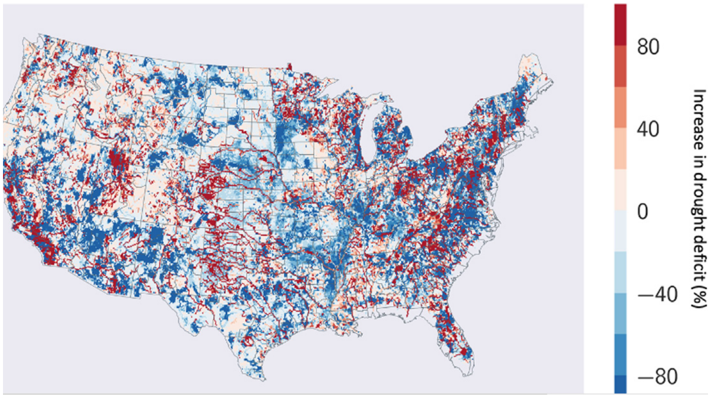

FIGURE 10.12

Changes in daily streamflow drought deficit in the USA as a result of the combined effect of reservoir construction and water abstraction for irrigation. Drought deficits were calculated using a 90% daily variable threshold approach on the simulated discharge, where the threshold was defined based on the naturalised simulation and applied to both the natural and human-impacted scenario. *Red areas* indicate an increase in hydrological drought, often due to upstream reservoirs. *Blue areas* indicate hydrological drought relief, often due to irrigation that enhanced local runoff.

drought, depending on the hydroclimatological regime and the degree and type of human interventions in the region. This is reflected in the high spatial variability in the (simulated) human influence on hydrological drought (Fig. 10.12), with some regions showing an overall increase in streamflow drought severity due to irrigation and reservoirs (e.g., California) and other regions showing an overall decrease (e.g., Great Plains).

10.5.5 Analysis of qualitative data

10.5.5.1 Drought changes in water uses in South Africa

In this example, we show an analysis of qualitative data (Section 10.4.5) to understand changes in water availability and use during drought. This example is based on the work by Rangecroft et al. (2018) and uses qualitative data from South Africa.

At-site field observations and metadata can be used to gather contextual information helping to understand the feedbacks between drought and society or to inform modelling. Rangecroft et al. (2018) made observations in the Nwanedi catchment in South Africa regarding catchment landscape, climate, geology, water resources and water management, which subsequently were included in a process-based hydrological model for scenario analysis. They also engaged in conversations with villagers at various water points and with a number of individuals (e.g., extension officer, commercial farmers, local government officials) to better understand the main water sources, its users and impacts when limited in supply.

With the help of the local community, they were able to observe and map key water sources in the catchment (Figs. 10.13 and 10.14). There are three main types of water sources in the village: (a) two reservoirs, (b) the river and (c) groundwater. The river runs through the village and is used for multiple

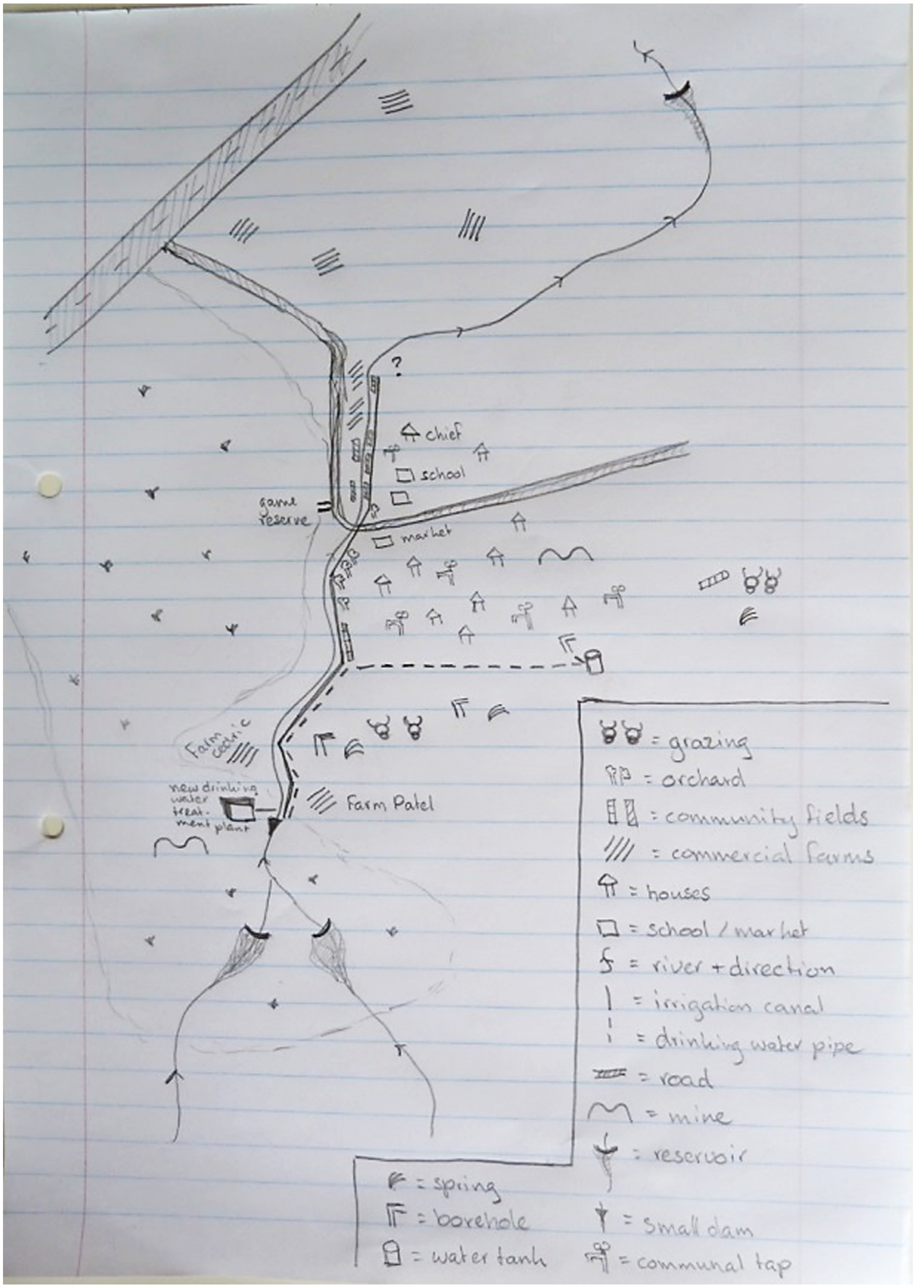

FIGURE 10.13

Field sketch of the water sources and its various uses in the Nwanedi catchment (South Africa).

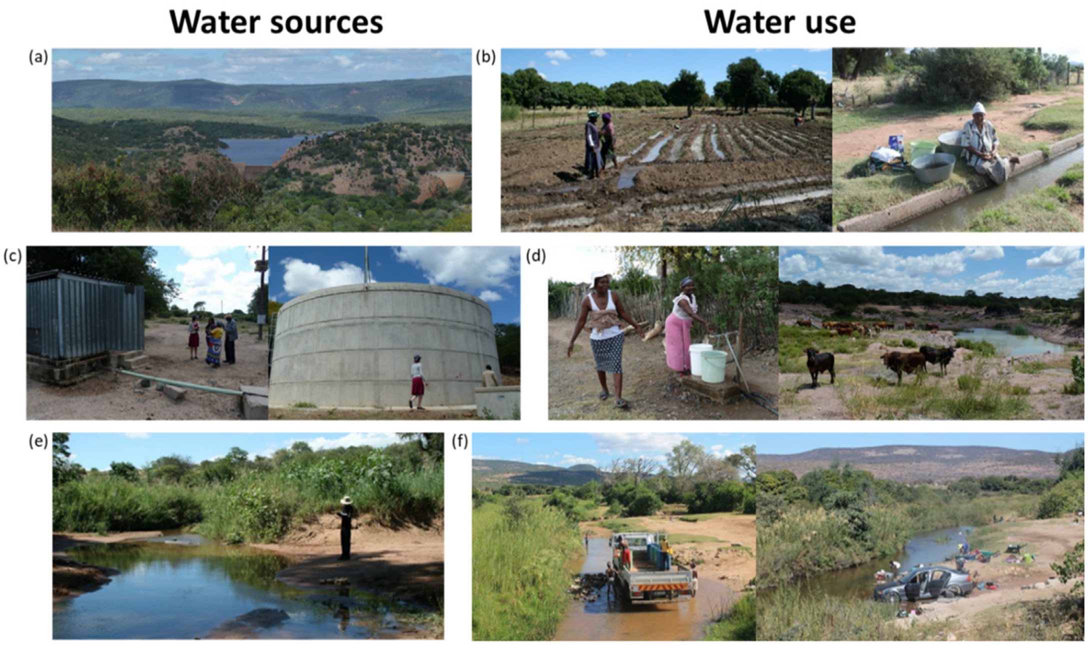

FIGURE 10.14

Water sources and water use in the Nwanedi catchment. Water from: (a) two reservoirs is used for (b) irrigation and washing, water from (c) groundwater is used for (d) drinking water supply (via a borehole and storage tank) and livestock (via natural springs), and water from (e) the river is used for several purposes, including (f) washing cars and brickmaking.

Photos by: Sally Rangecroft, Anne Van Loon, Mel Rohse; with permission of the Nwanedi community (South Africa).

purposes, such as laundry, car washing, but also for playing, fishing and bathing. The reservoirs are located upstream of the village. A 3 km-long irrigation canal is used to feed the irrigation scheme downstream of the village, with water taken from the river just below the reservoirs. The irrigation canal water is also used for other tasks, such as laundry. Groundwater from a well (near the storage tank in Fig. 10.13) is used for drinking water and water from groundwater springs is used for cattle, although these springs are known to dry up during drought. The current groundwater borehole for drinking water supply was installed in 1999 and is 99 m deep. It is connected to a water storage tank where the water is treated before being distributed in a system of water pipes and communal water taps in the village. Due to the imbalance between water supply and demand, taps in different parts of the village supply water only on specific days (typically twice a week). Only those who can afford it (3.5% of households) have a residential water tap.

Group narrative interviews were used to gain knowledge on how the community is impacted during drought, what measures are taken to mitigate the impacts and how these mitigation measures impact the drought itself (URL 10.2). Traditional methods to find water during a drought are to dig holes near the river and to look for springs further away from the village if the closer ones are dried up. However, during recent droughts all springs were dry and digging holes often did not yield enough water. Since no trends in precipitation were found, this may be a result of increased groundwater abstraction for drinking water following the installation of the borehole in 1999.

10.5.5.2 Irrigation and drying up of Lake Chilwa in Malawi

In this example, we show an analysis of qualitative data (Section 10.4.5) to understand human interventions influencing hydrological drought. This example is based on the work by Ngongondo et al. (2018) and uses qualitative data from Malawi.

Lake Chilwa lies in a drought-prone region in southern Malawi and is characterised as a shallow transboundary inland lake sustaining the socio-economic livelihoods of over 1.6 million people. Large parts of the catchment area draining to Lake Chilwa are located in relatively high rainfall areas of southern Malawi. The average annual rainfall in the Lake Chilwa catchment ranges from 1000 to 2000 mm in the highlands of Zomba, Mulanje and Chikala Hills, while the lowland plains around the lake receive between 900 and 1000 mm year^{-1} (McCartney, 2007). With a total lake area of about 2400 km^2 and depth ranging between 2 and 4 m, the lake has dried up and refilled more than 10 times in the last 100 years (Nagoli et al., 2018). Such wet and dry phases have considerable impacts on the livelihoods of the riparian communities that largely depend on the lake's resources for fishing and agriculture. In recent years, the frequency of dry episodes has increased. Between 2012 and 2013, the lake lost 80% of the surface area, but it recovered again in 2014–15 after prolonged heavy rainfall. As of November 2018, the lake completely dried up, despite the La Niña climatic conditions that persisted throughout the 2017–18 rainfall season and brought normal to above-normal rainfall to the region.

The fast lake recessions and dry-up periods have loosely been attributed to low rainfall periods and associated reduced discharge from the key perennial inflowing rivers. However, analyses of annual rainfall in Malawi have not found any significant trends in the region (e.g., Ngongondo et al., 2015). In the Lake Chilwa Basin, annual rainfall has shown a decrease, albeit not significant. Contrary to the rainfall trends, discharge from various key inflowing rivers shows statistically significant decreases (Fig. 10.15). In interviews, the local communities indicated that irrigation farming was their main source of socio-economic livelihood. Several surveys have shown that the major inflowing perennial rivers to the lake, including the Domasi and Sombani Rivers, have been dammed by the riparian

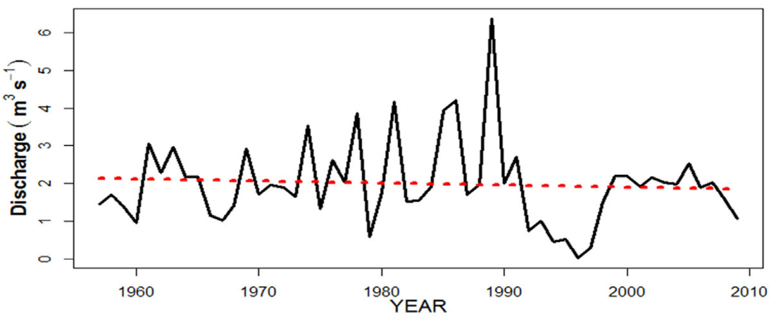

FIGURE 10.15

Mean annual discharge of the Domasi River at Domasi Teacher Training College (TTC) in Chilwa Basin, one of the seven perennial inflows into Lake Chilwa.

FIGURE 10.16

Irrigation dam along the Sombani River at Phaloni Hills. Sombani River is one of seven perennial rivers flowing into Lake Chilwa (Malawi).

Photo by: Cosmo Ngongondo.

communities to provide water for their irrigation needs (Fig. 10.16). Such damming does not only attenuate river flow downstream, but also increases evaporation losses, especially with higher temperatures as observed in the region. Thus, it is likely that the recent Lake Chilwa drying episodes to a large extent are due to human interventions, although global warming may have amplified evaporation losses.

10.5.6 Socio-hydrological modelling

10.5.6.1 Water management in the United Kingdom, using coupled-component modelling

In this example, we show an application of coupled-component modelling (Section 10.4.6) to quantify the influence of drought management strategies on hydrological drought. This example is based on the work by Wendt et al. (2021) and uses coupled-component model approach, described in Section 9.5.2. The model is designed to represent a typical situation in the United Kingdom, with different aquifer types and set of regulations and strategies in place to cope with drought impacts.

When a drought occurs, a number of supply-side measures are put in place, ranging from reducing leakage and surface water transfer into the region at certain low drought levels (based on return periods), increasing supply by increased groundwater abstraction, conjunctive use of water resources, reducing the ecological minimum flow at medium drought level, and taking in use new water sources, such as treated sewage and deeper groundwater boreholes at high drought level. Demand-side measures are also taken, increasing with drought severity, first with awareness campaigns and then with water use restrictions of increasing degree. In the coupled-component model approach (Section 9.5.2), these measures are classified into four drought management strategies:

(a) increased water use from both surface water and groundwater (1: Water supply)
(b) restricted water use (2: Restricted use)
(c) integrated use of surface water and groundwater (3: Conjunctive use)
(d) maintaining the ecological flow by reducing groundwater abstractions (4: Hands off flow).

Further details of the UK drought management strategies can be found in Wendt et al. (2021).

The coupled-component model is run for two types of aquifers: a high-storage aquifer and a low-storage aquifer. Fig. 10.17 shows for both these aquifer types the effect of the four drought management strategies on groundwater storage compared to the situation without management strategies (benchmark). Drought trigger levels (Section 13.2.5) – to activate drought strategies – are based on the value of SPI (Box 5.3) as shown in Fig. 10.17a. The benchmark groundwater storage (Figs. 10.17b and 10.17d) shows that the high and low storage aquifer types both have a strong seasonal cycle, but respond differently to meteorological droughts, with the high storage aquifer showing a more dampened response (Section 3.4.2). Figs. 10.17c and 10.17e show the relative effect of the (modelled) drought management strategies on the groundwater storage (mm) in both systems (benchmark minus scenario).

Groundwater and reservoir storage are used differently in the model to meet the human and natural water demand during drought periods. The results show that conjunctive use of surface water and groundwater has the largest (positive) influence on hydrological drought, as events are shorter and occasionally alleviated. Reducing the ecological minimum flow and increasing surface water and groundwater use aggravates droughts. A combined strategy shows mainly that the positive influence of conjunctive use (in alleviating hydrological drought) is amplified when the ecological minimum flow is maintained. Managing surface water and groundwater abstractions conjunctively and at the same time protecting ecological flows are key to effectively alleviate hydrological drought in this UK example, although according to the simulations these drought strategies sometimes increase the dependence on imported water.

10.5.6.2 Reservoir operation in three case studies, using system-dynamics modelling

In this example, we show an application of system-dynamics modelling (Section 10.4.6) to quantify the influence of reservoir operation rules on hydrological variability, including drought. This example is based on the work by Garcia et al. (2020) and uses the system-dynamics model described in Section 9.5.3.

In system-dynamics modelling, not only the hydrological system is influenced by human interventions, but also the social system is affected by changes in hydrological processes and especially extremes, such as drought. Garcia et al. (2020) simulate the reservoir storage, management and consumptive use and relate this to a growing population in three case study regions; two of which are discussed here, the Colorado River in the western United States (Fig. 10.18), and the Western Cape Water Supply System in South Africa (Fig. 10.19). The Colorado River drains a large catchment (630,000 km^3) located in a semi-arid (Bw and Cs) climate (Section 2.2.2) and supplying water to over 40 million people and 22,000 km^2 of irrigated agriculture. There are many reservoirs in the Colorado River (including Lake Mead and Lake Powell) providing water supply, flood control and hydropower by storing up to four times the average annual flow. The Western Cape Water Supply System includes

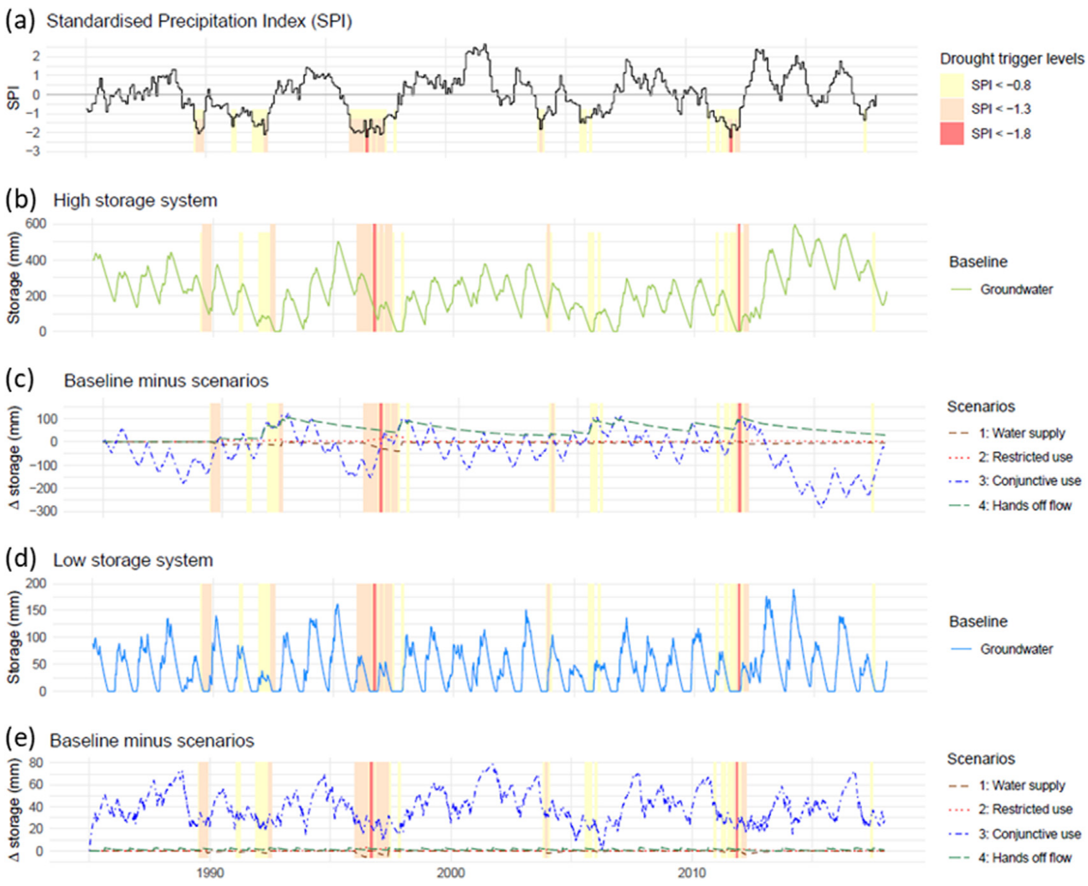

FIGURE 10.17

Effects of different drought management strategies (scenarios) on groundwater storage: (a) SPI time series, the colour bands represent three increasingly more extreme SPI values (used as trigger levels for implementing mitigation measures), (b) and (d) show the benchmark groundwater storage (or baseline) for high and low (groundwater) storage systems, respectively, and (c) and (e) show the relative effect of the four modelled drought management strategies (scenarios) in these two aquifer systems (benchmark minus scenario).

Modified from Wendt et al. (2021).

six major reservoirs with a total storage capacity of 898.10^6 m^3 and supplies a growing population in a region with a semi-arid (Cs) climate with drinking water. In both cases, the increase in water use over time due to population growth (Figs. 10.18d and 10.19d) is partly compensated by increased water use efficiency. Both regions experienced major droughts (Figs. 10.18a and 10.19a, shown in red) and related water use restrictions.

The effect of the drought periods on reservoir storage in the two cases is clearly visible (Figs. 10.18b and 10.19b). Interestingly, in both Colorado and Cape Town, water use initially increased

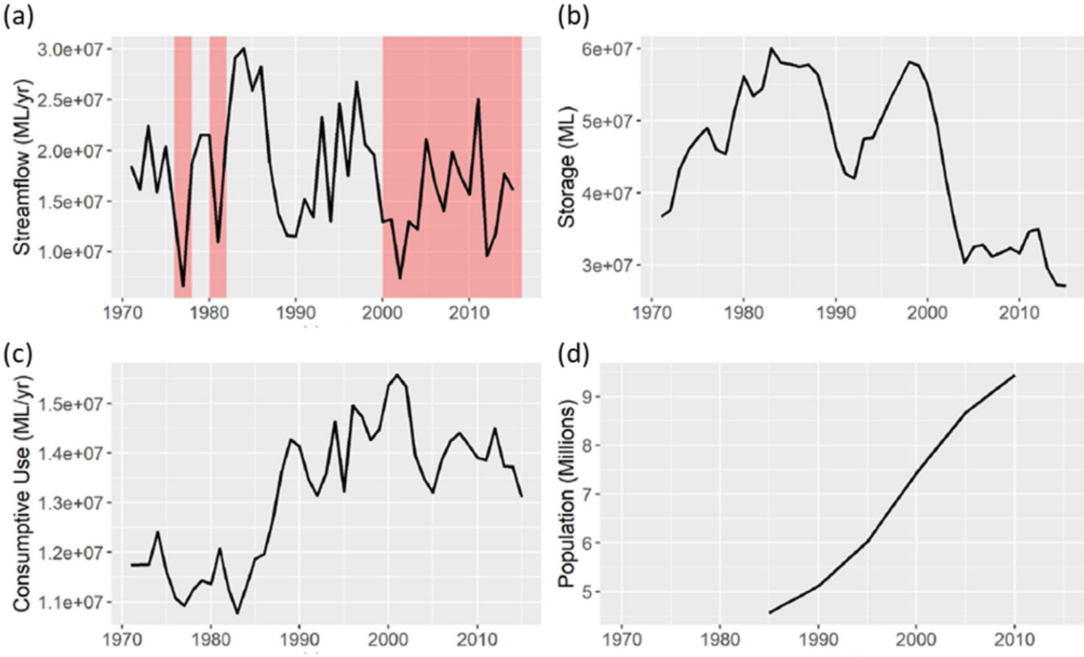

FIGURE 10.18

Colorado water supply system (1970–2015): (a) annual naturalised river flow with drought periods *highlighted in red*, (b) total volume of water stored in Lake Mead and Lake Powell, (c) annual water use (excludes Mexico), and (d) Colorado river basin population (excludes Mexico).

Modified from Garcia et al. (2020).

during the drought (Figs. 10.18c and 10.19c) until water use restrictions were put into place to prevent reservoirs running dry due to the combination of meteorological drought and abstraction (Colorado: early 2000s, Cape Town: 2016–18). In Colorado, water use remained relatively high throughout the drought period, whereas in Cape Town water use strongly decreased (Figs. 10.18c and 10.19c). The modelling study done by Garcia et al. (2020) shows that when reservoir storages are large, it takes longer before the shortage is recognised and adaptation strategies for reducing water use are put in place. However, if water use restrictions are triggered earlier, adaptation can lead to reduced total water abstraction.

10.5.6.3 Agricultural drought adaptation measures in Kenya, using agent-based modelling

In this example, we show an application of agent-based modelling (Section 10.4.6) to quantify the influence of drought adaptation measures on agricultural yields and poverty related to drought. This example is based on the work by Wens et al. (2020) and uses the agent-based model ADOPT (Section 9.5.4).

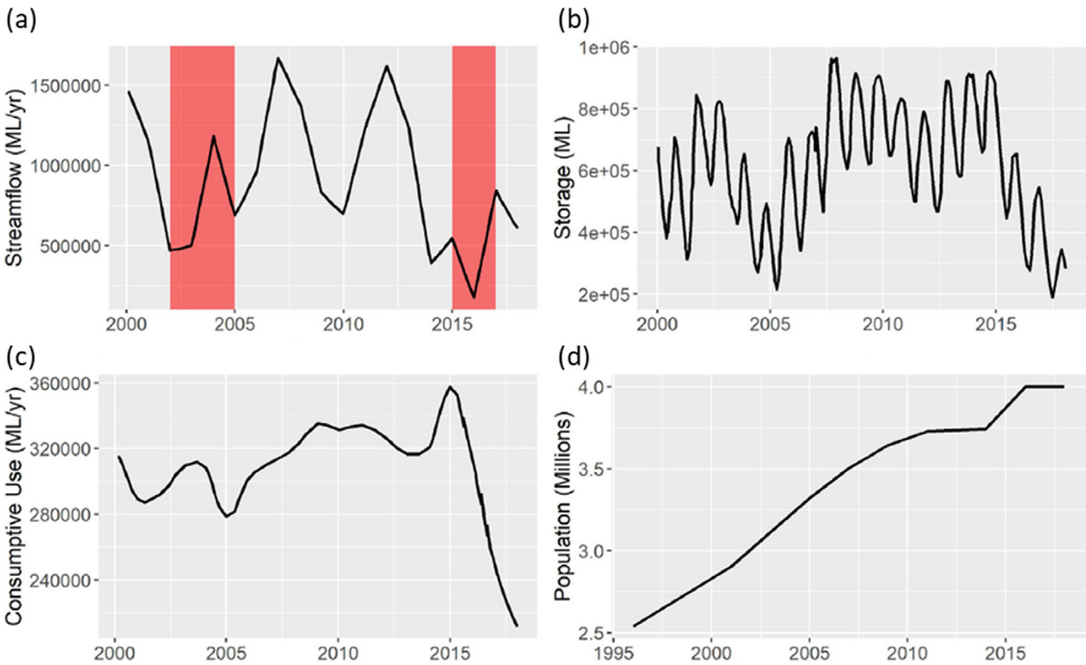

FIGURE 10.19

Cape Town water supply system (2000–18): (a) annual streamflow for all tributaries with drought periods *highlighted in red*, (b) total volume of water stored in reservoirs, (c) annual water use, and (d) Cape Town population.

Modified from Garcia et al. (2020).

The ADOPT model simulates the set of drought adaptation measures that individual farmers in Kenya have in their toolbox, such as soil water conservation with mulch cover, construction of terraces, digging of shallow wells and the installation of drip irrigation. Agent-based modelling is different from other socio-hydrological modelling approaches because instead of modelling the effect of drought policies in a top-down way, it simulates diverse individual decisions and their cumulative effect (bottom-up approach).

In this example, different economic theories for decision making are tested in three behaviour scenarios:

(a) a business-as-usual scenario where no adaptation is assumed
(b) an economic rational behaviour scenario where adaptation decisions follow the Expected Utility Theory (Von Neumann and Morgenstern, 1944; Schrieks et al., 2021)
(c) a bounded rational behaviour scenario based on the Protection Motivation Theory (Maddux and Rogers, 1983; Schrieks et al., 2021) with data from interviews and questionnaires with smallholder farmers and experts in the region.

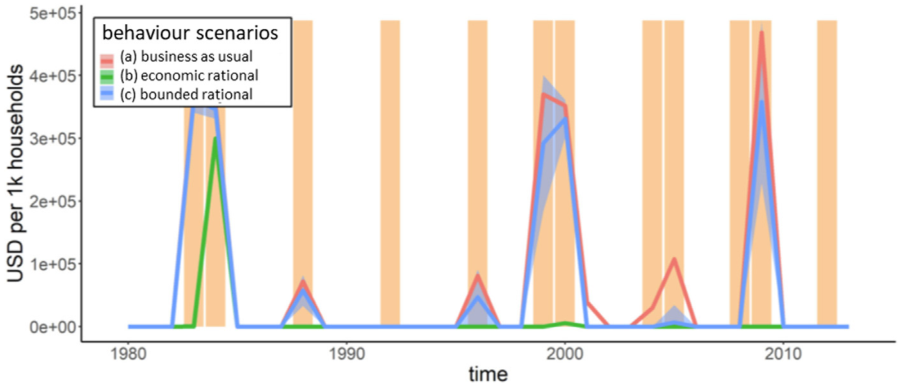

FIGURE 10.20

Food aid required per 1000 households for three behaviour scenarios. Food aid was calculated as the cumulative amount of food shortage of all individual households (in kg) multiplied by the maize price (in US$), accounting for a variable food price. Variability over time is visualised for each behaviour scenario: (a) business-as-usual (no adaptation), (b) economic rational, and (c) bounded rational. Drought years (SPEI value in crop season < -1) are *visualised as vertical orange bars*. The shaded blue area shows the variance among 50 bounded rational model runs (using different weights of the Protection Motivation Theory factors).

Modified from Wens et al. (2020).

The ADOPT model simulates the effect of different drought adaptation measures on crop yields and also food insecurity and food aid needed during a drought. The results show that there is a marked difference between the scenarios in terms of crop yield, food insecurity, poverty and food aid needed (ranging between 0 and 500 kUS$ between the bounded rational behaviour scenario (c) and business-as-usual scenario (a); Fig. 10.20). For example, during the meteorological drought of 2004–05 in Kenya, the scenarios including adaptation, so economic rational (b) and bounded rational (c) behaviour scenarios, do not lead to any agricultural impacts and no food aid is required, while the business-as-usual scenario without adaptation (a) results in a need of 100 US$ food aid per household. When adaptation decisions are assumed to be based on economic factors only (economic rational scenario (b)), even the impacts of the 2009 meteorological drought can be mitigated. The bounded rational adaptation scenario (c), however, does not fully mitigate drought impacts and food aid is still required, for example in 2000 and 2009 (Fig. 10.20). This shows that the decisions of individual farmers have a strong influence on drought impacts and that an agent-based model can provide a good approach to account for the effects of drought adaptation.

10.6 Choosing the most appropriate method

In the previous sections, different approaches to evaluate human-drought interactions and to quantify the human influence on low flow and hydrological drought have been introduced. The choice of approach is case study specific and depends on the aim of the study and data availability. This section provides guidance on what would be the most appropriate approach under different conditions.

In general, observation-based methods are recommended if the aim is to understand the current or historic situation of the influence of human interventions on low flow and hydrological drought. On the other hand, if the aim is to evaluate the effects of potential developments in human interventions or test out different management strategies, modelling is needed. Large-scale methods, such as large-sample screening and large-scale modelling, are suitable to understand the relation between human interventions and low flow or hydrological drought across a wide range of hydroclimatological and socio-economic settings. If on the other hand, detailed knowledge in a specific area is required, catchment-scale methods are recommended.

Several observation-based, catchment-scale methods were introduced (Section 10.4.1) and the choice depends on the characteristics of the human intervention, data availability and time aspects (time period and resolution). If the human intervention is located at a specific site and starts on a specific point in time, there are more options than if the human interventions are applied on a larger spatial scale and are changing gradually over time. For example, the upstream-downstream approach only works if the human intervention is located at a specific point in a river, and there are gauging stations upstream and downstream of this point, a pre-post-disturbance approach can only be used if the disturbance starts on a specific time. If the interventions are more gradual, moving windows can be used or an approach based on qualitative data can be applied.

A pre-disturbance dataset is needed when you want to calibrate and validate a hydrological model to naturalise your river flow observations. Naturalisation can be done, for example, by decomposition, which involves deriving the natural flow by adding all abstractions and subtracting all return flows and artificial additions or simulated using a hydrological model with no human interventions (Section 4.3.9). This method is dependent on the availability of good quality, complete time series for all artificial influences, which are often hard – if not impossible – to obtain.

Ideally, when doing paired-catchment (and upstream-downstream) analysis, you would have a pre-disturbance dataset as well to check the similarity of the catchments before the human disturbance started. However, if no pre-disturbance dataset is available, paired catchments can still be used, in which case the selection of the paired catchments is even more crucial (Section 8.2.1). The catchments need to be similar enough in climate and key catchment characteristics, such as area, land use and physiographic attributes. Adjacent catchments are preferable, except when analysing the influence of groundwater abstraction that crosses topographic catchment boundaries (Section 10.5.3).

When calculating hydrological drought using a threshold from a (natural) benchmark time series (Fig. 10.6, Section 10.4.1), the time series of the benchmark catchment or naturalised dataset need to be long enough to obtain a robust threshold (Section 5.4.1). The human-influenced time series can be shorter as long as they include enough drought events to get a reliable estimate on the average effects of the human influence on hydrological drought. However, the longer the time series, the more – and more robust – information can be obtained.

Socio-hydrological modelling and analysis of qualitative data can be used to get a better understanding of the complex interactions between hydrological drought and society and to add context. Socio-hydrological models allow for explicitly simulating and analysing feedbacks between drought and human responses and can be used to evaluate the cascading socio-economic effects of these feedbacks, for example, using different scenarios. Qualitative data approaches require fieldwork to collect the information and are especially useful when quantitative information is lacking, when several human influences have potentially opposite effects cancelling each other out, or when the effects of the human influence also may be felt outside the catchment. Qualitative data are also crucial for developing socio-hydrological models, for example, via surveys.

Often a combination of methods is preferable. This will increase the reliability of the analysis and results (Box 10.1). For example, some data may be available to look at trends and break points, but not enough for a full pre-post-disturbance analysis or modelling. Then, qualitative information from interviews or catchment observation can complement the quantitative data. Additionally, modelling-

Box 10.1 Uncertainty in assessment of human interventions due to process-based models and observations

It is important to consider the uncertainties and limitation of approaches for analysing human influences on low flow and hydrological drought. Model-based approaches are subject to the full range of model uncertainties discussed in Section 4.2.6 and Box 9.4, and in addition, an extra layer of uncertainty due to adding human interventions to process-based models. Human-water processes need to be parameterised, and data on human interventions are needed. However, details of abstraction rates and information on decision-making (e.g., reservoir operations, farmers' decisions) may be difficult to obtain (Section 4.3). Another large source of uncertainty is that people often make subjective decisions rather than follow pre-set deterministic rules.

There is high uncertainty in estimates from both large-scale and catchment-scale, observation-based methods. A significant disadvantage of the pre-post-disturbance approach is that the meteorological drivers of drought events occurring in the two periods can be considerably different because of climate variability and non-stationarity (Sections 2.4.2, 7.2.5 and 7.4.1). This means that any change in hydrological drought between the pre- and post-disturbance periods may not be solely caused by the human intervention. It is therefore important to select representative periods prior to and after the disturbance and to test the similarity in meteorological drivers between the two periods. Potential differences in the propagation from meteorological drought to hydrological drought among the two time periods may be the point of interest rather than directly comparing the hydrological droughts. In that way, differences in meteorological drought between the two periods can be taken into account.

The observed-naturalised approach does not have this problem because it compares hydrological droughts between the observed and simulated naturalised data over the same time period. However, model uncertainty (Box 9.1) may also here cause misinterpretation of the cause of the differences. An uncertainty analysis can be done to overcome this, both for the observed and modelled data, checking whether the difference between the time series is larger than the uncertainty range of each of them (e.g., Van Loon and Van Lanen, 2013).

Uncertainty in purely observation-based approaches, such as the upstream-downstream and paired-catchment approaches, mainly stems from uncertainty in observations and differences between the catchments that are not taken into account. For example, in case of the upstream-downstream approach, the upstream catchment may be considerably smaller and located at higher elevation, resulting in a natural difference between the upstream and downstream station (Rangecroft et al., 2019). For the paired-catchment approach, obtaining broadly hydrologically similar paired catchments is challenging. Especially subsurface properties, such as hydrogeology (e.g., aquifer characteristics, groundwater flow direction and boundaries), are crucial, and these are often poorly mapped and lack a quantitative assessment at the catchment scale. The best way to overcome this uncertainty is to have a pre-disturbance period to validate the catchment pairing, as was done in Rangecroft et al. (2019) using a pre-reservoir period. However, it can be difficult to obtain river flow data from a long enough period before the human influence, especially in regions where humans have been modifying the water system already for centuries.

Most of the observation-based approaches assume that groundwater and river flow are only altered due to one specific human intervention (e.g., groundwater abstraction) and other interventions are absent or constant over time. However, often more than one single intervention affect hydrological conditions and the relative effect of each of these may change over time. This is one of the reasons that Milly et al. (2008) postulated that "stationarity" (i.e., natural systems fluctuate within an unchanging envelope of variability) "is dead". Accordingly, observation-based approaches require a careful examination of which human interventions may have played a role. Only then a change in hydrological conditions can be attributed to a single human influence — or a combination — with confidence.

The success of large-sample analyses depends on, amongst other things, the quality of observational data, the spatial representativeness of the 'near-natural' catchments that are used as a reference, and the lack of unaccounted confounding factors, such as land use changes (Tijdeman et al., 2018). Comparing step-changes to trends can be problematic when the human influence is either gradual or is partly compensated by a climate signal with an opposite effect. Also, if catchments are large, changes in low flow and hydrological drought at the catchment outlet are the result of many local interventions and the effect of the individual interventions may be difficult to detect.

In summary, it is important to be aware of uncertainties, both in observations and simulated time series, when quantifying the human influence on low flow and hydrological drought.

based approaches can be validated on observation-based approaches and then used to extrapolate in time, naturalise the time series or to evaluate different scenarios.

10.7 Summary

Human actions are strongly linked to low flow and hydrological drought and human interventions influence drought propagation in a number of ways, direct and indirect, intended and unintended. Important interventions are: (a) surface and subsurface water abstractions lowering water levels in rivers and groundwater, (b) reservoirs and their management often reducing flow variability downstream, and (c) deforestation and urbanisation changing water pathways. This leads to hydrological drought being modified, either alleviated or aggravated, or even fully prevented or fully human-caused. To better understand the role of human interventions, also in the context of drought management and climate change, it is important to have tools at hand to be able to quantify the human influence and to predict the effects of human influence jointly with climate change. In addition, the system dynamics and human-drought interactions and feedbacks need to be better understood. This chapter presents several approaches using observations, modelling and analysis based on qualitative data and demonstrates their application for a range of special cases across the world. Observation-based approaches can be used to disentangle the human influence on hydrological drought from natural processes by comparing observed droughts with benchmark droughts derived from naturalised time series. Such naturalised series may either come from a benchmark catchment, from an undisturbed time period or from model simulation. Model-based approaches allow evaluation of the effect of applying different human interventions and climate change scenarios. Different model types and scales (catchment scale, global scale) are useful for various problems at hand and have to be weighted carefully before choosing among them. In situations where contextualised insight into complex human-drought interactions is needed, qualitative data analysis based on interviews and questionnaires can provide crucial information. These interactions can also be formalised in socio-hydrological models, which can be used to increase system understanding and explore feedbacks and cascading socio-economic effects. The examples provided in this chapter demonstrate that with the data and various approaches, methods available, human influences that both alleviate and aggravate hydrological drought can be quantified and human-drought feedbacks understood, albeit with some limitations and uncertainties.

10.8 Further reading

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