Assessing Drought Hazard and Risk

Principles and Implementation Guidance

GFDRR
Global Facility for Disaster Reduction and Recovery

Building Disaster Resilience in Sub-Saharan Africa

THE WORLD BANK
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Cover photo: Moldova's 2007 drought was the worst in a series of nine dry periods to settle over the country since 1990, and the World Food Program compared its severity to the drought of 1946 during which many Moldovans starved. Source: NASA.

Design: Miki Fernández/ULTRA Designs, Inc.

Table of Contents

Boxes

Figures

Tables

Foreword

From the Horn of Africa to Indonesia and from California to Cape Town, droughts are some of the most far-reaching hazards that affect communities around the world. Indeed, long periods of water shortage can have high socioeconomic impacts including crop failures, high food prices, increased levels of malnutrition, and a reduction in hydropower generation. Droughts also cause shocks to the budgets of governments as they struggle to support affected regions.

The Global Facility for Disaster Reduction and Recovery (GFDRR) has long been supporting countries around the world in strengthening their resilience to natural hazards. This guidance document, with its underlying technical reports, provides countries and partners a new toolbox to understand and manage drought risks.

The effective preparation and response to droughts require an accurate understanding of this phenomenon. Not only do we need to understand the causes and magnitude of droughts, we also need to have a grasp of the exposure and vulnerability of the population and economic sectors affected. Drought risk assessments that capture these elements can help in the design of social safety nets, risk financing strategies, and water management solutions, and are a cornerstone of climate adaptation strategies.

Despite the importance of drought risk assessments, we are often still struggling to get it right. Whereas floods, cyclones, and earthquakes can be easily pinpointed in time and space, droughts are more elusive hazards. They tend to develop slowly and can almost unnoticeably affect large regions over multiple months or even years. Furthermore, the impacts of droughts on communities are highly dependent on water infrastructure, access to markets, and social resilience. Forecasting and modeling droughts and their impacts has therefore been a complicated exercise.

In recent years, the toolbox available for assessing drought risk has expanded rapidly. New satellite observation techniques, hydrological datasets, and global drought models offer new opportunities to understand and forecast drought risk even in the most data-scarce countries. These tools can be used to forecast droughts, calculate their impacts, and design response mechanisms. For example, in Uganda, GFDRR and the World Bank are helping the government develop an online platform that automatically tracks vegetation coverage to inform rapid decisions about scaling up the disaster risk financing mechanism that provides early finance for drought response.

This guidance document provides direction to effective drought hazard and risk assessments. It is based on a new extensive inventory of drought models and tools, made available through www.droughtcatalogue.com, and a technical evaluation of these models on a set of case studies. The guidance note will hopefully provide the reader with a good overview of the tools and approaches to use for different applications.

I would like to personally thank the team that led the work on this, as well as the many colleagues and external collaborators who provided comments and suggestions.

We look forward to continuing to explore the challenging issue of drought risk with the broad community of experts and solution providers around the globe.

Julie Dana
Manager, GFDRR

The water crisis in Cape Town, South Africa has sent people to harvest water from natural springs daily. Photo: fivepointsix.

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Abbreviations

AAI	Aridity Anomaly Index
AAL	annual average losses
ADI	Aggregate Dryness Index
AED	annual expected damages
AI	Aridity Index
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
ARID	Agricultural Reference Index for Drought
ASI	Agricultural Stress Index
CAR	Corporación Autónoma Regional
CEE	Central and Eastern Europe
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMI	Crop Moisture Index
CSDI	Crop Specific Drought Index
CZI	China Z Index
DAI	Drought Area Index
DDV	drought deficit volume
DIE	German Development Institute
DRI	Drought Reconnaissance Index
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EDI	Effective Drought Index
EDII	European Drought Impact report Inventory
EM-DAT	International Disaster Database
EN	El Niño
ENSO	El Niño–Southern Oscillation
EPM	Empresas Públicas de Medellín
ESI	Evaporative Stress Index
ETDI	Evapotranspiration Deficit Index
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization of the United Nations
FEWS NET	Famine Early Warning Systems Network
GDP	gross domestic product
GFP	Global Flood Partnership
GFS	Global Forecast System
GIEWS	Global Information and Early Warning System on Food and Agriculture
GRI	Groundwater Resource Index
GWDT	Groundwater Table Declining Trend
GWI	Groundwater Drought Index
GWP	Global Water Partnership
IAM	Integrated Assessment Models
IAV	Impact, Adaptation, and Vulnerability
IDEAM	Colombian National Institute of Meteorology, Hydrology and Environmental Studies
IDR	Inflow-Demand Reliability
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
KBDI	Keetch-Byram Drought Index
LN	La Niña
MODIS	Moderate Resolution Imaging Spectroradiometer
MSDI	Multivariate Standardized Drought Index
MSRRI	Multivariate Standardized Reliability and Resilience Index
NGOs	nongovernmental organizations
NDI	NOAA Drought Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NMA	National Meteorology Agency
NOAA	National Oceanic and Atmospheric Administration
ONI	Oceanic Niño Index
PCA	Princeton Climate Analytics
PCR-GLOBWB	PCRaster Global Water Balance
PDSI	Palmer Drought Severity Index
PHDI	Palmer Hydrological Drought Index
PMAA	Planes de Manejo Ambiental de Acuíferos
PNP	percent of normal precipitation

POMA	Planes de Ordenación y Manejo de Cuencas Hidrográficas
RAI	Rainfall Anomaly Index
RDI	Reclamation Drought Index
RCPs	Representative Concentration Pathways
SAI	Standardized Anomaly Index
SAVI	Soil Adjusted Vegetation Index
sc-PDSI	Self-Calibrated Palmer Drought Severity Index
SDI	Streamflow Drought Index
SGI	Standardized Groundwater Index
SIAC	Sistema de Información Ambiental Colombia
SMA	Soil Moisture Anomaly
SMDI	Soil Moisture Deficit Index
SMRI	Standardized Snowmelt and Rain Index
SOPs	standard operating procedures
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SRI	Standardized Runoff Index
SRSI	Standardized Reservoir Supply Index
SSFI	Standardized Streamflow Index
SSPs	Shared Socioeconomic Pathways
SSP1	Shared Socioeconomic Pathway 1
SSP3	Shared Socioeconomic Pathway 3
SWI	Standardized Water-Level Index
SWSI	Surface Water Supply Index
TCI	Temperature Condition Index
UN	United Nations
UNHCR	United Nations Refugee Agency
UNISDR	United Nations Office for Disaster Risk Reduction
USAID	United States Agency for International Development
USGS/FEWS MODIS	U.S. Government Service Famine Early Warning Systems Moderate Resolution Imaging Spectroradiometer
VCI	Vegetation Condition Index
VegDRI	Vegetation Drought Response Index
VHI	Vegetation Health Index
WASP	Weighted Anomaly Standardized Precipitation Index
WaterGAP	Water - Global Analysis and Prognosis
WMO	World Meteorological Organization
WRI	World Resources Institute
WRSI	Water Requirement Satisfaction Index
WSI	Water Stress Index
WSR	Water Storage Resilience indicator

Executive Summary

Droughts are among the most far-reaching natural hazards in the world. They negatively affect all areas of the economy, including agricultural production, domestic water use, all other industries that use water, and the energy sector in large areas of the world. Besides short-term responses to droughts, such as food relief and increased groundwater pumping, the changing climate and socioeconomic conditions demand adaptive solutions and long-term decision making. A first and indispensable step toward solutions and adaptation to drought is a drought risk assessment and disclosure of knowledge gained from that assessment.

A wide range of models, datasets, methods, and tools are available for drought hazard and risk assessment for different applications. For nonexperts, however, it is very difficult to understand which model, dataset, method, and/or tool should be used in a specific situation. Moreover, the overall approach required to carry out a successful drought risk assessment under various conditions and to determine how the models, datasets, methods, and/or tools should be applied in a particular context is not straightforward. This guidance document is intended to provide support to nonexpert professionals on these issues.

This drought risk guidance gives support at various levels of detail. First, a foundation with **key** definitions and aspects of drought risk assessments is provided: drought hazard, exposure and vulnerability of sectors susceptible to drought, and drought risk. Next, **four guiding principles** of drought risk assessments that should be taken into account when designing the overall approach of the drought risk assessment are described:

1. Drought assessment should use a system scale perspective
2. Drought has to be defined and assessed in relation to its impacts
3. Drought risk changes over time
4. Effective drought management should increase resilience and enhance preparedness

Although this document does not provide detailed advice and guidance on drought management practices, the fourth principle is included because, in most cases, a drought risk assessment will be done to implement or improve existing drought management measures or plans. Just-in-time actions, for instance, require a different approach than setting up a drought forecasting system or implementing long-term drought risk reduction measures. Hence it is important that during a drought risk assessment the goal and outputs required for implementing drought risk management are kept in mind.

For professionals who require practical guidance while assessing droughts, an **implementation guide** is included. This part of the document provides practical guidance on how to set up and run a drought risk assessment and at which moments to involve experts. A schematic workflow is provided that leads users step by step through the four phases of a drought risk assessment (Figure 0.1): the scoping phase, the inception phase, the assessment phase, and the implementation phase. Links are provided to the available models, datasets, methods, and tools for which more detailed information that can be found in the online drought catalogue (www.droughtcatalogue.com; see also Deltares 2018a). While going through this workflow, guidance is provided for case-specific approaches. For instance, if the goal of the assessment is to gain initial insights into possible drought risks as part of a broad country-scale risk assessment, it might not be necessary to go through a very detailed assessment phase.

To translate the implementation guide into practice, it is illustrated with **examples of applications** of drought risk assessments. These examples cover various reasons and motivations for performing a drought risk assessment, each leading to a different (set of) implementation measures and actions. Hence, each of the examples requires a different approach, different outputs, and a different level of detail.

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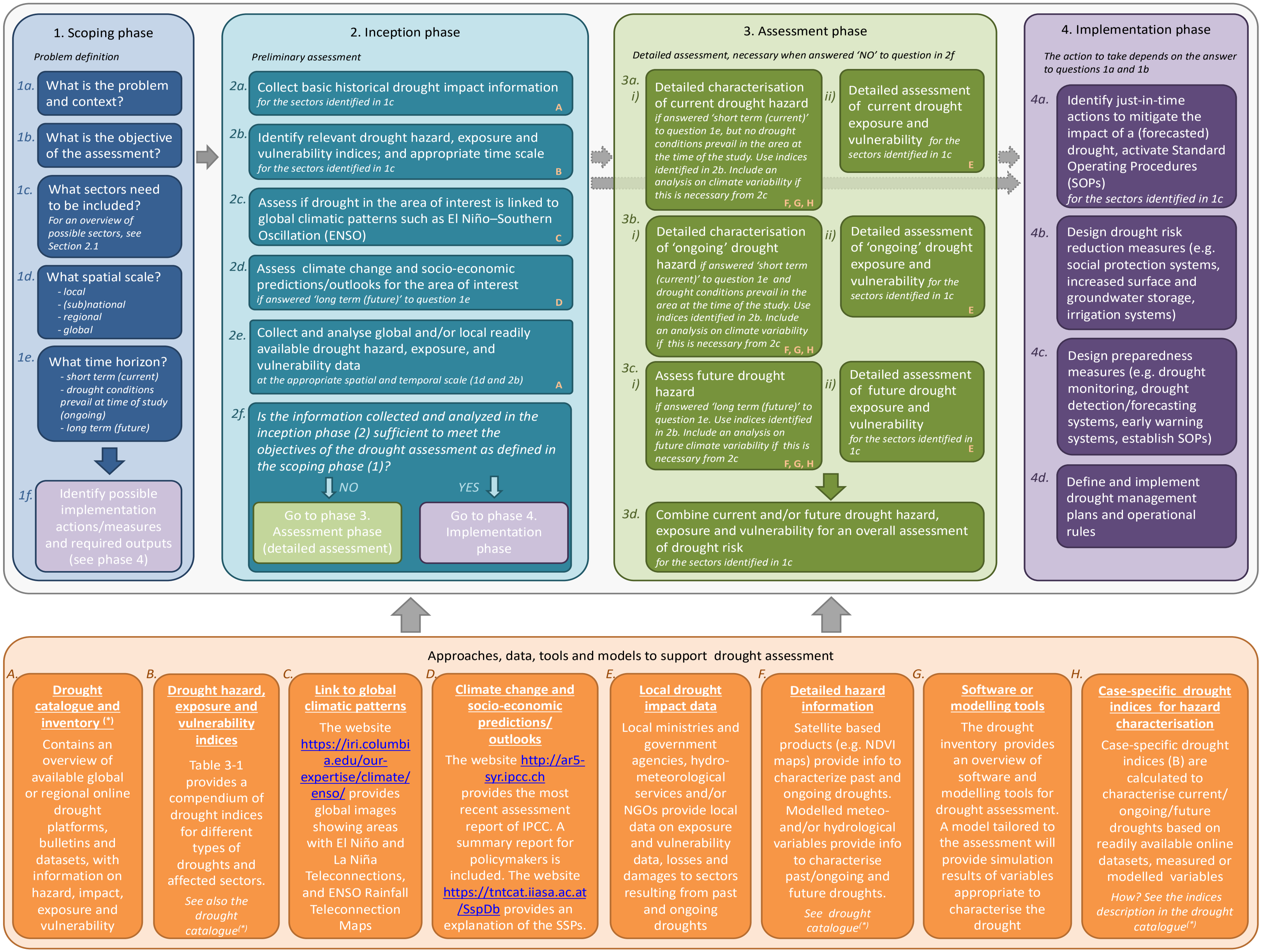
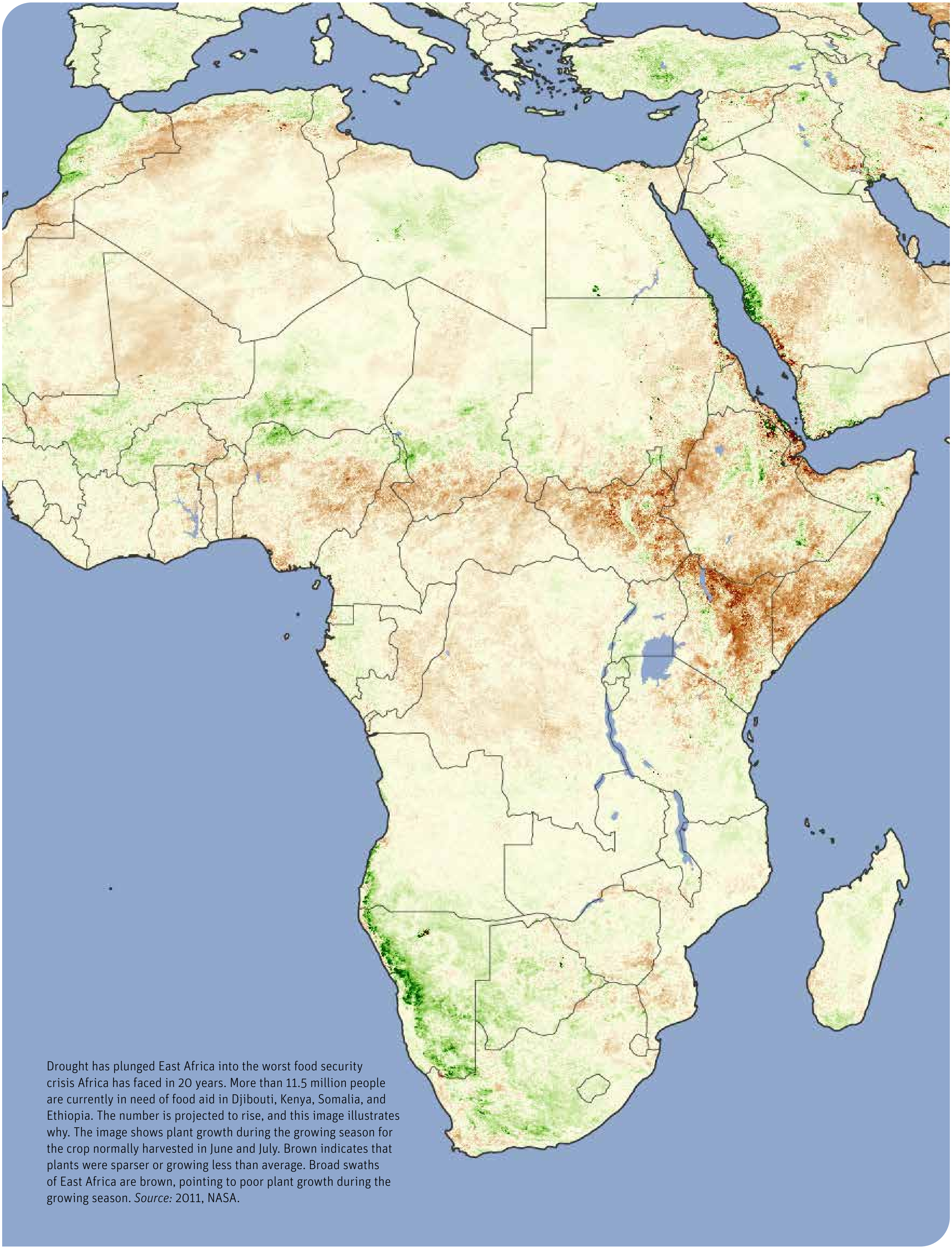
FIGURE 0.1 Overview of the Workflow to Perform a Drought Assessment (Phase 1 through 3) and Identify Potential Risk Reduction Measures (Phase 4)



* www.droughtcatalogue.com

Note: Letters at the bottom right of the phase boxes refer to the orange boxes at the bottom of the figure. ENSO = El Niño Southern Oscillation; IPCC = Intergovernmental Panel on Climate Change; NGO = nongovernmental organization; SSP = Shared Socioeconomic Pathways.



Drought has plunged East Africa into the worst food security crisis Africa has faced in 20 years. More than 11.5 million people are currently in need of food aid in Djibouti, Kenya, Somalia, and Ethiopia. The number is projected to rise, and this image illustrates why. The image shows plant growth during the growing season for the crop normally harvested in June and July. Brown indicates that plants were sparser or growing less than average. Broad swaths of East Africa are brown, pointing to poor plant growth during the growing season. *Source:* 2011, NASA.

1 Introduction

1.1 Introduction

Droughts are among the most far-reaching natural hazards that the world is facing today (WMO and GWP 2014). In recent years, countries around the world have been severely impacted by droughts that cause decreases in food supply, employment opportunities, and energy production. Recent examples of droughts with significant impacts are various. The 2015–18 drought over the Horn of Africa has put more than 15.6 million people in urgent need of food assistance, leading to a financial commitment from the European Commission of more than €300 million for humanitarian aid (Reliefweb 2018). In California, the prolonged 2011–16 drought caused more than US$5.5 billion in economic losses in the agriculture sector (Howitt et al. 2014; Medellin-Azuara, et al. 2016). The 2018 drought in northwestern Europe was one of the worst in recent history and led to severe losses, including €900 million to Danish farmers alone (Harris 2018).

Urban areas in drought-prone regions face serious water shortages affecting its citizens, businesses, and industries. The greater frequency of droughts and more erratic nature of rains in many countries, combined with underlying economic, social, and environmental vulnerabilities, result in increasing impacts to at-risk populations (FAO, no date; Hendriks 2018). Although developed countries are certainly affected by droughts (for example, by an increasing threat to energy security, water available for industry and services, an environment resistant to forest fires, and sustained natural habitats), the adverse impacts of drought are particularly devastating for the poorest and most vulnerable groups in the drylands of developing countries, where the economy relies on rainfed agriculture and pastoralism. The ways in which drought affects poor and vulnerable rural households are multifaceted and complex: they include lack of water for people, livestock, pasture, and crops; reduced energy production; decreased food availability and the consequent rise in food prices; and loss of lives, livelihoods, and assets (DIE 2017).

Poor people are generally disproportionately affected by climate-related shocks, not only because they are often more exposed and invariably more vulnerable to such shocks but also because they have fewer resources and receive less support from family, community, the financial system, and even social safety nets to prevent, cope, and adapt. Moreover, climate change will worsen these shocks and stresses, making it even harder to eradicate poverty in a sustainable manner (Hallegate et al. 2016).

Besides short-term responses to droughts, such as food relief and increased groundwater pumping, the changing climate and evolving socioeconomic conditions demand the development of adaptive solutions and long-term decision making. A first and indispensable step toward adapting to drought is to undertake a drought risk assessment and disclose knowledge that focuses both on specific sectors and users as well on the overall economy. A drought risk assessment is a formal step toward identifying vulnerabilities and taking mitigative and adaptive actions to reduce risk.

Drought assessments are (often) initiated to gain insight into existing and/or future drought hazard and/or risk. These drought assessments either can be carried out to get a better understanding of the overall drought risk a country is facing, based on a more general assessment of historic and future hazards and risks, or they can be initiated in response to a (forecasted) drought disaster that requires immediate action to reduce anticipated impacts. The goal can be to determine hotspots and distinguish the level of drought impact between areas and sectors in order to establish effective social protection systems or to increase the adaptive responsiveness to drought hazards—for instance, in the agriculture sector, by adjusting sowing and irrigation practices to the occurrence of dry spells. At longer time scales, drought risk assessments can provide the information necessary to develop a strategy to increase the resilience to drought of a country or an area, or of a specific sector.

Drought hazard and risk assessments are often established for the current climate situation; these assessments make use of historical datasets of drought hazards, drought impacts, and information about exposure and vulnerability to drought. However, when the objective is to develop adaptive solutions and long-term decision making related to drought, then projections of climate change and socioeconomic changes need to be included to extend the risk assessment to future periods. At shorter time scales, real-time drought assessments help increase immediate preparedness to droughts and can be crucial to mitigating the impacts of imminent events in drought-prone areas. Drought detection and forecasting systems are then used to provide information to water managers and the different sectors and user groups that rely on the availability of fresh water.

1.2 Drought management

In the past, drought management has often focused primarily on the (reactive) response to drought events. It is clear that a paradigm shift is required, reorienting the management of drought to focus on proactive drought management by improving resilience and preparedness. Examples of proactive drought management are drought detection and forecasting systems, policies on the regulation of water use, awareness raising among user groups that rely on the availability of fresh water, social protection frameworks to increase the resilience of vulnerable population, and so on. In the last several years governments have started to invest in having drought policies and management plans in place. A drought management plan is an administrative tool for the enforcement of preventive and mitigation measures in order to achieve the reduction of drought impacts on society, environment, and the economy (GWP CEE 2015). Several guidelines have been developed to assist in the development of national drought policies and drought management plans:

- *Guidelines for Preparation of Drought Management Plans: Development and Implementation in the Context of the EU Water Framework Directive* (GWP CEE 2015): This document provides guidance for the development and implementation of drought management policy based on the concept of reducing the risks associated with the occurrence of drought.
- *National Drought Management Policy Guidelines: A Template for Action* (WMO and GWP 2014): These guidelines provide a general approach toward developing national drought policies.
- *Drought Management Guidelines* developed for the Mediterranean countries within the MEDROPLAN project (EC, MEDA Water, and MEDROPLAN 2007): These guidelines provide an effective and systematic approach to develop drought management plans linking science and policy and that can be applied to other regions.

The basis for any good drought management plan or policy is a high-quality drought hazard and risk assessment. This document provides guidelines for drought hazard and risk assessments. These guidelines complement the guidelines for national drought policies and drought management plans above, and the reader is referred to the documents above for a complete understanding of the steps that need to be followed for the development of (sub-) national management drought plans.

1.3 Purpose and audience of this document

This document provides guidelines for assessing drought hazard as well as short- and long-term risks to specific sectors and a country's overall economy. The target audience of these guidelines are non-expert professionals, such as local policy makers, but they may also be of interest to water resources management practitioners, professionals in risk management and climate adaptation, nongovernmental organizations (NGOs), donors, and international organizations.

1.4 Reading guide

This document consists of two main sections. Chapter 3 describes the key principles of drought hazard and risk assessments; chapter 4 consists of an implementation guideline for drought risk assessment, providing a step-by-step overview of all activities that need to be done in order to carry out a thorough assessment of drought hazard and/or risk. The document also provides guidance on defining the approach of assessing drought risk; this depends on the characteristics of the area, the impacted and drought-prone sectors and users, and the available data and resources. Prior to these two key chapters, basic definitions of drought risk are introduced in chapter 2. Finally, chapter 5 presents three examples of the application of the guidelines. See also box 1.1 for details about two other documents that are also part of this project.

Box 1.1 Supporting Documents

This guidance document is supported by a comprehensive Global Inventory of Drought Hazard and Risk Modeling Tools and Resources that is available as an online catalogue (hereafter "model inventory report"; see Deltares 2018a) and a Quantitative and Qualitative Comparison of Drought Hazard and Risk Models (hereafter "comparative model assessment report"; see Deltares 2018b). The online drought catalogue and the reports delivered during the course of this project (the model inventory report and the comparative model assessment report), as well as this guidance, are available at www.droughtcatalogue.com**.**

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2. Basis for the Drought Guidance

2.1 Definitions

This report follows the widely accepted definitions related to disaster risk used in the Sendai Framework (UN General Assembly 2016), shown below:

Hazard is a process, phenomenon, or human activity that may cause loss of life, injury, or other health impacts, property damage, social and economic disruption, or environmental degradation. It is characterized by its location, intensity or magnitude, frequency, and probability.

Hazardous event is the manifestation of a hazard in a particular place during a particular period of time.

Exposure is defined as the situation of people, infrastructure, housing, production capacities, and other tangible human assets located in hazard-prone areas. Measures of exposure can include the number of people or types of assets in an area. These can be combined with the specific vulnerability and capacity of the exposed elements to any particular hazard to estimate the quantitative risks associated with that hazard in the area of interest.

Vulnerability is defined as the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.

Drought risk is defined as the potential loss of life, injury, or destroyed or damaged assets that could occur to a system, society, or community in a specific period of time, determined probabilistically as a function between drought hazard, exposure, and vulnerability.

Drought impact is the total effect, including negative effects (for example, economic losses) and positive effects (for example, economic gains) of a drought event. The term includes economic, human, and environmental impacts, and may include death, injuries, disease, and other negative effects on human physical, mental, and social well-being.

The subsections below consecutively describe the terms *drought hazard, exposure to drought, vulnerability to drought, and drought risk* in more detail.

2.1.1 Drought hazard

Drought is normally defined as a prolonged period of abnormally dry weather condition leading to a severe shortage of water. Drought is a natural temporary feature of the climate cycle that causes damage and can have severe impacts in most regions of the globe (AMS 2013).

Droughts are recurring and worldwide phenomena with spatial and temporal characteristics that vary significantly from one region to another. There are numerous definitions of drought, covering all parts of the hydrological cycle. The types of droughts commonly identified are *meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought* (Wilhite and Glantz 1985). The first three of these types of drought are based on physical phenomena, although anthropogenic influence on drought increases as drought propagates from meteorological to hydrological. Socioeconomic drought describes droughts in terms of the supply and demand of water. The length of time over which precipitation deficits accumulate becomes extremely important and functionally separates different types of drought. Agricultural (soil moisture) droughts, for example, typically have a much shorter time scale than hydrologic (groundwater, streamflow, and reservoir) droughts (McKee, Doesken, and Kleist 1993). A short description of each of these drought types is given below, based on Wilhite (1993).

Meteorological drought is usually defined based on the degree of dryness (that is, lack of precipitation) in comparison to some "normal" or average amount of precipitation and the duration of the dry period. Definitions of meteorological drought are region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region.

Hydrological drought is associated with the effects of periods of precipitation (including snowfall) deficit on surface or subsurface water supply (that is, streamflow, reservoir and lake levels, groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale. Although all droughts originate from a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system. Hydrological droughts are usually out of phase with or lag behind meteorological and agricultural droughts because it takes longer for precipitation deficiencies to show up in components of the hydrological system such as streamflow and groundwater and reservoir levels.

Agricultural drought (sometimes referred to as *soil moisture drought*) links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, and soil water deficits that can lead to crop failure. A few days or weeks of a lack of moisture in the root zone, especially during the growing season, may create stress on crops, resulting in reduced crop yields. Important in this context is the plant water demand, which depends on weather conditions, biological plant characteristics, growth stage, and soil properties.

Socioeconomic drought occurs when the demand of economic goods exceeds supply as a result of a weather-related shortfall in water supply. It is associated with the impacts of meteorological, hydrological, and agricultural droughts on social and economic aspects of the population affected.

Drought should not be confused with low flow, aridity, water scarcity, or desertification, or with related hazards such as heat waves and forest fires (Van Loon 2015). Whereas aridity is a permanent condition of some regional climates with very low annual precipitation, water shortage is a temporary water imbalance that can occur as a result of drought or human activities. Van Loon et al. (2015) define *water scarcity* as a water supply shortage or a situation in which anthropogenic influence on the water system plays an important role in the development of below-normal water availability. Water scarcity is caused at least in part by human activities and reflects conditions with long-term imbalances between available water resources and demands. The MEDROPLAN project nicely illustrates these concepts related to water availability (table 2.1; EC, MEDA Water, and MEDROPLAN 2007).

TABLE 2.1 Schematic Overview of Terms by Duration and Cause of Water Shortage

Duration of limited water availability	Cause of limited water availability	
	Natural	Anthropogenic
Temporary	Drought	Water shortage
Long-term / permanent	Aridity	Water scarcity Desertification

Source: Based on a figure from the MEDROPLAN project (EC, MEDA Water, and MEDROPLAN 2007, figure 4).

Drought hazard characterization

Droughts are often characterized by their severity, duration, timing, and geographical extent. To assess the intensity or severity of a drought, the use of different drought indices or indicators for the different types of droughts is accepted as best practice. For example, well-known indices for meteorological and hydrological droughts are the Standardized Precipitation Index (SPI; McKee, Doesken, and Kleist 1993) and the Standardized Runoff Index (SRI; Shukla and Wood 2008), respectively. A drought index is often a standardized numerical value based on anomalies of a selected parameter representing the availability of moisture or water (for example, precipitation, soil moisture, and streamflow) when compared with its long-term mean. A drought index can be used as an indicator when compared with an agreed categorization, thus allowing a conclusion to be drawn. As an example, a widely used classification considers an area to be in moderate drought conditions when the SPI index is at or below −1, in severe drought when the value is −1.5 or less, and in extreme drought when it is −2 or less.

When using maps of a distributed variable (for example, precipitation) to compute a drought index (for example, SPI), the resulting map will show the intensity of the drought for each grid cell (or area) as represented by the index value, thus allowing the spatial extent of the drought to be identified. This is also known as *drought mapping*. When using "point" variables, such as streamflow at a gauging station, to compute a drought index (such as SRI), the resulting index will also be a *point index*. Box 2.1 shows how a simple approach for drought hazard mapping can provide information about spatial and temporal variation of droughts in Africa at the continental, regional, and country levels. Box 2.2 provides an example of drought mapping in an operational platform, The North American Drought Monitor.

When assessing drought, it is recommended to work with multiple indices and data sources instead of with just one drought index calculated based on one dataset. Droughts are very complex in nature, and the use of a single index may result in not representing all aspects of the drought situation correctly, and could even result in missing an event in the assessment or forecast. Combining a number of indices will provide more insight in the range of possible levels of drought severity and the frequency and occurrence of drought hazards.

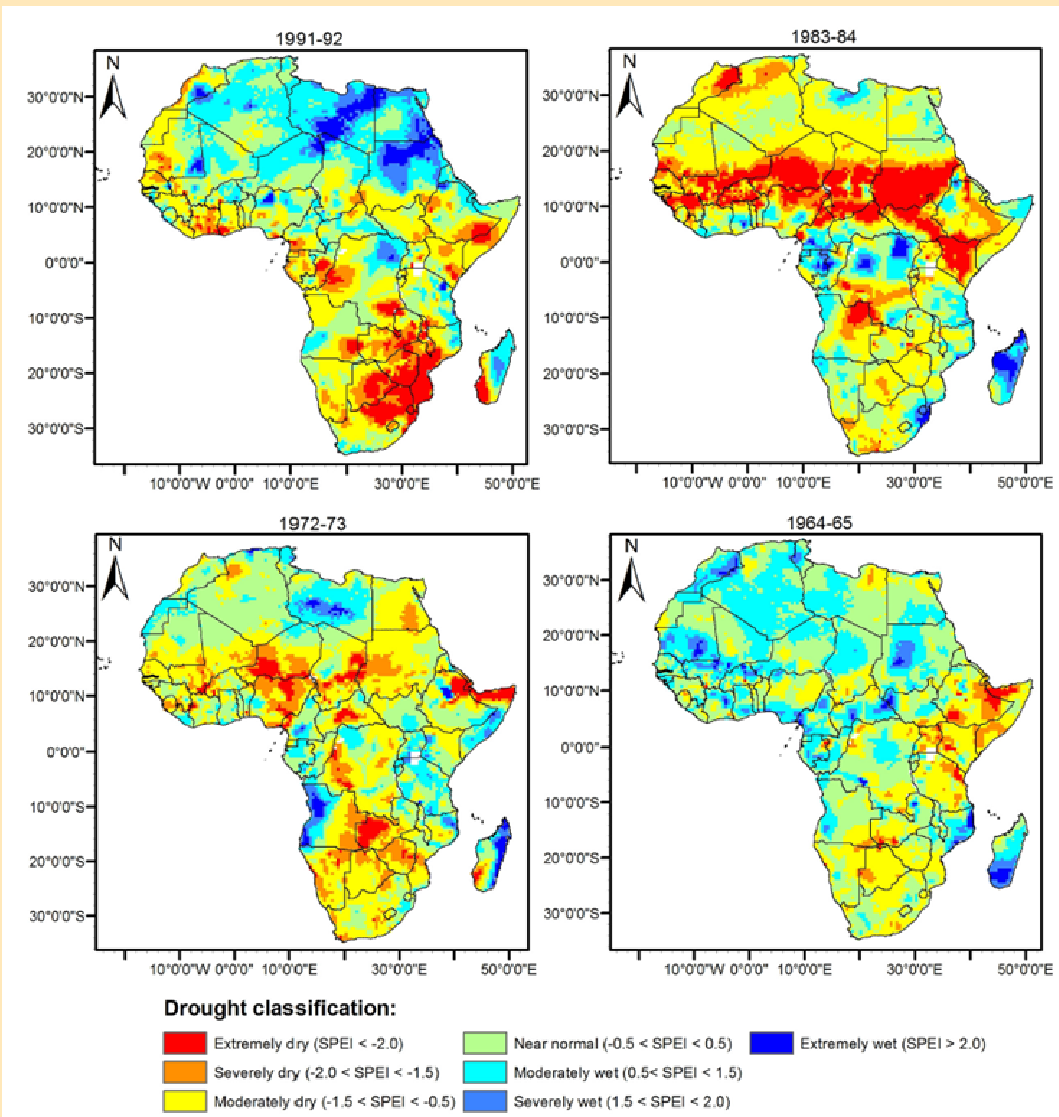
The *Handbook of Drought Indicators and Indices* (WMO and GWP 2016) covers some of the most commonly used drought indicators and indices (describing the hydro-meteorological characteristics of droughts) that are being applied across drought-prone regions. Moreover, the "Global inventory of drought hazard and risk modelling tools and resources" (Deltares 2018a) and the accompanying online catalogue provides a broad inventory of commonly used indices to characterize the different types of droughts. For each index, the online data catalogue provides a short description and reference literature, which gives an indication of the complexity of the index and the data and resources required to calculate the index.

BOX 2.1 Good Practice Example: A Simple Approach for Drought Hazard Mapping in Africa

The study by Masih et al. (2014) provides a continental, regional, and country-level perspective on geospatial and temporal variation of droughts in Africa. The analysis used a global dataset of the Standardized Precipitation Evapotranspiration Index (SPEI) (http://sac.csic.es/spei/home.html) to map meteorological droughts in the period 1901–2011 for Africa and thus substantiate the findings of their literature review.

The study presents a snapshot of the drought conditions in Africa (drought characterization as measured by the SPEI) for the four most extreme droughts from the previous 50 years according to their literature review (see figure B2.1.1). They indicate that three out of these four droughts (1972–1973, 1983–1984, and 1991–1992) could be regarded as continental in nature since they spanned many subregions and covered wide areas of the African continent. The study also computed the area of the African continent under different drought categories based on the SPEI dataset. The results of this analysis revealed a statistically significant increase in the area under all categories of drought for the continent during 1901–2011.

FIGURE B2.1.1 Geospatial Coverage of Four Extreme Droughts Indicated by 12 Months SPEI (October to September)



Source: Masih et al. 2014; data from Global SPEI database http://sac.csic.es/spei/home.html version 2.2, retrieved January 2014.

BOX 2.2 Good Practice Example: North American Drought Monitor

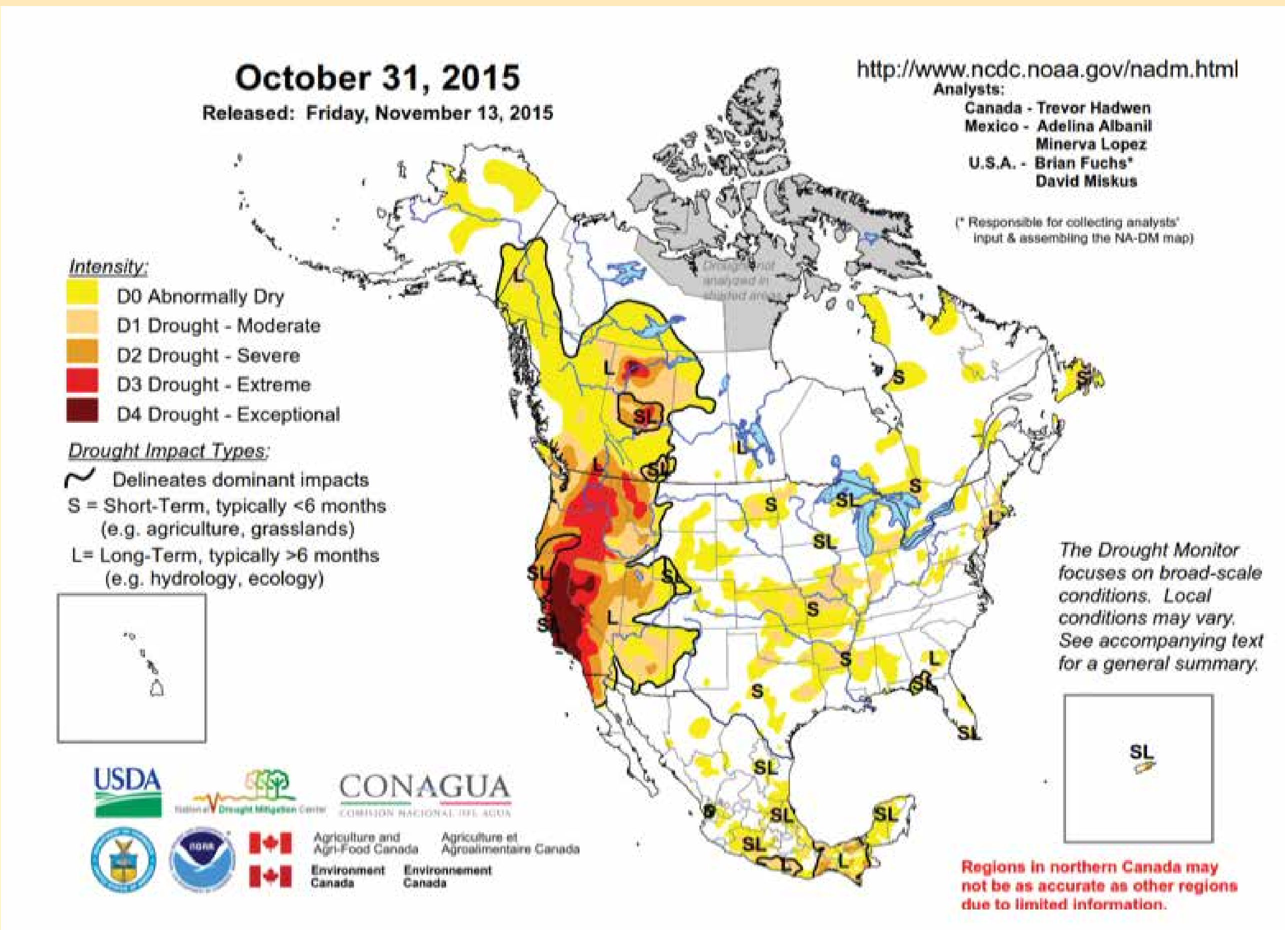
The North American Drought Monitor maps the intensity of ongoing droughts across Canada, Mexico, and the United States and presents information on different drought impact types.[a] For example, to illustrate the conditions during the 2011–2015 exceptional drought in California, figure B2.2.1 maps the intensity of the drought in California at the end of 2015 together with its impacts on the agriculture, hydrology, and ecology (agricultural and hydrological droughts). The four-year period between fall 2011 and fall 2015 was the driest in California since record keeping began in 1895.[b] The figure shows large variability in the drought conditions across the United States; while the western coast was suffering a very severe drought, conditions in the central and eastern United States were normal.

Note:

a. For more information, see https://www.drought.gov/nadm/content/welcome.

b. Hanak, Mount, and Chappelle 2015.

FIGURE B2.2.1 Snapshot of the North American Drought Monitor, October 31, 2015



Source: NOAA, https://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/maps/en/201510#map-selection.

2.1.2 Exposure to drought

Exposure to drought comprises all assets and sectors located in a drought-prone area. Examples of sectors that are susceptible to droughts and are relevant to include as exposure in a drought risk assessment include agriculture, energy and industry, drinking/domestic water supply, navigation, ecosystems, tourism, forestry, aquaculture and fisheries, and the financial sector (investors, insurances, asset owners).

In a drought risk assessment, it is important to collect data on exposure characteristics that will influence the magnitude of the potential impact of the drought. Populations relying on each sector (for income, food supply, water and electricity supply, and so on), along with the economic value of each sector, are relevant exposure characteristics and should be included in determining the impact of drought for all sectors. For example, the larger the share of exposed GDP (gross domestic product), the larger the potential impact of a drought on the economy of a country.

However, there are also many sector-specific characteristics that are relevant; these should be included in drought risk assessments. For example, certain crop types are more vulnerable to droughts than others. Therefore it is important to include the exposed crop types to determine the drought risk for the agriculture sector. A few of these sectors are highlighted here to illustrate the type of exposure characteristics that could be relevant when determining the magnitude of drought risk to a specific sector.

Variables that can be used to measure and/or express drought exposure for the **agriculture sector** are, among others:

- Agricultural land area
- Agricultural crop types
- Potential agricultural yield in volume or monetary value
- Livestock (for example, cattle, pigs, and poultry) density

Relevant spatial and temporal information has to be collected for these variables. For example, moving livestock to other, less-drought-prone pastures during the drought season will considerably lower the drought impact to the agriculture sector. Therefore, it is important to know when and where livestock are present.

Variables that can be used to measure and/or express drought exposure for the **energy and industry sector** are spatial and temporal information on industrial and energy producing activities, such as:

- Type of industry
- Specific location of industries
- Density of industrial activities
- Location and capacity (water, energy production) of dams and reservoirs used for hydropower production

Variables that can be used to measure and/or express drought exposure for the **drinking/domestic water supply sector** are, for example:

- Population density (distinguishing between rural and urban population)
- Domestic water consumption per capita
- Location, capacity, action radius, and economic value of drinking water utility firms

Variables that can be used to measure and/or express drought exposure for the **navigation sector** are, among others:

- Spatial information (following the river network) identifying the main navigation transportation routes or most important harbors
- Shipping density and specific shipping characteristics
- Economic value associated with navigation activities

Examples of variables that can be used to address the potential impacts of drought on **ecosystems** are, for example:

- Location and size of highly valued and/or protected nature areas (for example, RAMSAR)
- Location and density of existing species of flora and fauna, particularly when these are protected species
- Spatial information on highly valued rare ecosystems

Variables that can be used to measure and/or express drought exposure for the **financial sector** are, for example:

- Location of investments
- Value of investments
- Water use of companies in investment portfolio

2.1.3 Vulnerability to drought

The magnitude of the impact of a drought depends on the vulnerability of the exposed assets and sectors. *Vulnerability* can be defined as the predisposition of assets or sectors to suffer adverse effects when exposed to a drought event. The level of vulnerability to a drought (of a specific type) is determined by the intrinsic characteristics of the asset or sector. For example, certain crop types are more vulnerable to droughts than others; close proximity of a drinking water plant to the coast makes it more vulnerable to salt intrusion during a drought than a plant farther from the coast. Therefore it is important to collect the intrinsic exposure characteristics for the asset or sector as addressed in the exposure section above. Not all sectors are, however, vulnerable to all types of droughts. Below are descriptions of a few sectors that explain why they are susceptible to certain specific droughts.

Agriculture is affected by all drought hazard types. Rainfed agriculture is susceptible to meteorological and agricultural drought, while irrigated agriculture is susceptible to hydrological droughts. Box 2.3 provides examples of agricultural impact caused by droughts at different locations around the world.

BOX 2.3 Agricultural Drought Impacts

Over the past several years, droughts have impacted agricultural production in all continents of the world. "Drought is among the most devastating of natural hazards for agriculture—crippling food production, depleting pastures, disrupting markets, and, at its most extreme, causing widespread human and animal deaths. Droughts can also lead to increased migration from rural to urban areas, placing additional pressures on declining food production. Herders are often forced to seek alternative sources of food and water for their animals, which can create conflict between pastoral and farming communities."[a]

In recent years, agricultural droughts (see figure B2.3.1) "have resulted in some of the most high-profile humanitarian disasters—including the recent crises in the Horn of Africa (2011) and the Sahel (2012) regions, which threatened the lives and livelihoods of millions of people."[b] The 2017 droughts in India have led to serious problems and discontent from farmers across various states in the South Asian country. The discontent resulted in unrest and demonstrations, which have sometimes led to fatalities, pressing the government to offer the farmers more help.[c] And in South America, hundreds of municipalities and provinces in the agrarian regions of Bolivia, Brazil, Colombia, Paraguay, and Peru have declared a state of emergency over the past years as a result of the impacts of severe droughts.[d]

Conversely, California's agriculture sector has exceeded expectations during even the most severe drought in recorded history, but this was possibly only at the cost of massive and unsustainable groundwater pumping. Continued groundwater overdraft, while reducing the economic impacts of the drought for the agriculture sector now, has shifted the burden both in time and to other water users, including current and future generations, forcing them to dig deeper wells, find alternative drinking water sources, and repair infrastructure damaged by subsidence.[e]

Note:

a. FAO (Food and Agriculture Organization of the United Nations). FAO in Emergencies: Drought. http://www.fao.org/emergencies/emergency-types/drought/en/
b. FAO (Food and Agriculture Organization of the United Nations). FAO in Emergencies: Drought. http://www.fao.org/emergencies/emergency-types/drought/en/
c. Krishnan 2017.
d. See ReliefWeb. No date. Disasters: South America: Drought – 2015–2017. https://reliefweb.int/disaster/dr-2016-000002-col.
e. Cooley et al. 2015.

FIGURE B2.3.1 Agricultural Drought Impact

Source: Photograph taken by VirtualSteve. This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.

Energy and industry are often dependent on riverine water abstractions, and therefore on the volume and chemical quality and temperature of the river discharge water and groundwater. This means that the energy and industry sector is susceptible to hydrological droughts. In addition to streamflow, in specific regional cases (such as **hydropower** supply) reservoirs levels (absolute levels, deviations from normal, or relative to a critical threshold level) are also used to identify the hydrological drought hazard for this sector.

Drinking water/domestic water supply can be affected by hydrological droughts, because the drinking water supply utilities usually extract their resources from either riverine-fed reservoirs or groundwater resources.

Navigation is susceptible to hydrological droughts because it is the riverine streamflow that determines whether there is sufficient draft for ships to navigate or enter harbors.

Ecosystems can be affected by meteorological, hydrological, and agricultural droughts because of the varied nature of ecosystems. Terrestrial ecosystems are susceptible to meteorological and agricultural droughts, while aquatic ecosystems are susceptible to hydrological droughts.

Since different sectors are impacted in different ways by droughts, there is no single way to quantify vulnerability, so many different vulnerability indicators and variables are used to determine the potential impacts of droughts on specific sectors. To assess drought vulnerability in a more generic way—for instance, for large-scale or exploratory drought risk assessments—a distinction can be made between three vulnerability categories because vulnerability to droughts can be quantified by social, economic, and infrastructural factors. For each of these indicators, proxies have been identified to quantify the level of vulnerability (Naumann et al. 2014).

Economic vulnerability can be quantified by proxies such as energy consumption per capita, agricultural value added (as a percentage of GDP), GDP per capita, or poverty headcount.

Social vulnerability can be quantified by proxies such as the percentage of the population below the poverty line, the population's literacy rate, improved availability of water sources, life expectancy at birth, population ages 15–64, refugee population, government effectiveness, the country's rank in the Human Development Index, disaster prevention and preparedness finances, and presence and threat of conflicts.

Infrastructural vulnerability can be quantified by proxies such as the percentage of agricultural irrigated land, the percentage of renewable water that is retained, recycling ratios, irrigation efficiencies, road density, and age of the infrastructure.

2.1.4 Drought risk

In the classical approach to drought risk assessment, vulnerability factors are combined with information on hazard and exposure to assess drought risk (see figure 2.1). The magnitude of a drought event, along with the exposure and vulnerability information, together determine the impact of that specific drought event. In other words, the impact of a drought event is determined by hazard × exposure × vulnerability. Drought risk can then be expressed as annual average losses (AAL) or annual expected damages (AED) through a probabilistic analysis of either potential annual damages or potential damages for drought events for different return periods. However, determining the direct and indirect impacts of a drought on assets, economy, or population is often not a straightforward process because of the longevity and the diffuse nature of drought effects. As an alternative approach when a full probabilistic approach is not possible—for example, in large-scale or exploratory drought risk assessments—the levels of risk may be considered in broad categories (low risk to very high risk) or estimated using a combination of proxy values for exposure (for example, GDP, square kilometers of agricultural area) and vulnerability (for example, population below the poverty line, GDP per capita). Box 2.4 presents examples of cities facing drought risk.

FIGURE 2.1. Classical Approach to Drought Risk Assessment

BOX 2.4 Cities Facing Drought Risks

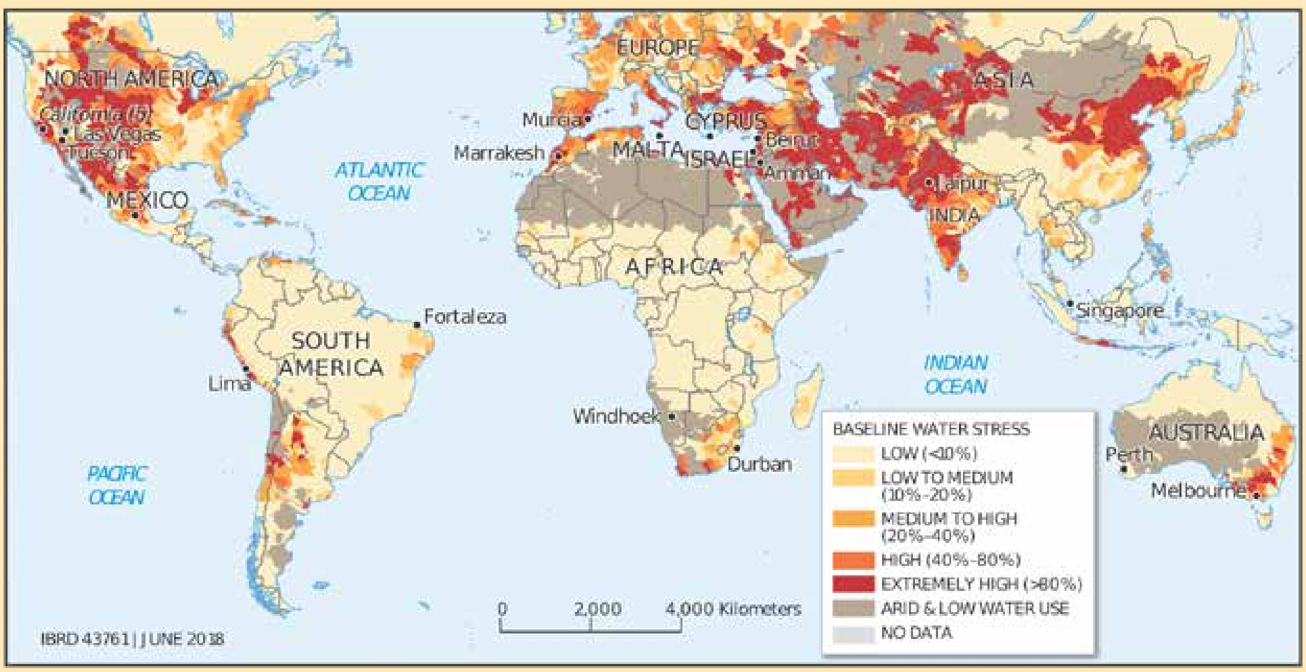
During the first months of 2018, the drought situation in Cape Town (South Africa) became world news. Local experts predicted that Cape Town could become the first major city in the world to run out of water. After years of droughts and water shortages in the area of Cape Town, the dam levels of the surface water reservoirs that Cape Town depends on for fresh water plummeted to dangerous lows. To prevent direct drought impacts, in addition to adaptive measures by the municipality (desalinization plants and stimulating "reuse-reduce-recycle"), many private groundwater boreholes were installed.[a] The year before, in 2017, over 850 cities in Brazil faced major water shortage issues; across Brazil, 872 cities were under a state of emergency by the federal government on account of a long period of drought.[b]

In a recent report, the World Bank shows an overview of major cities dealing with water stress, including Las Vegas (United States), Tuscon (United States), Mexico City (Mexico), Fortaleza (Brazil), Lima (Peru), Zaragoza (Spain), Murcia (Spain), Malta (Spain), multiple Israeli cities, Beirut (Lebanon), Amman, (Jordan) Jaipur (India), Singapore city, Durban (South Africa), Windhoek (Namibia), Perth (Australia), and Melbourne (Australia) (figure B2.4.1).[c] The World Bank has identified drastic changes in the hydrology of urban catchments as a result of climate change, leading to periods of drought. In addition, cities face large increases in urban water demand, progressive depletion and deterioration of water resources, and increasing vulnerability of user groups due to shifting priorities and competition for water resources. In combination, these developments lead to increased drought risks for water users and sectors in cities and urban areas. Impact-oriented mapping and assessing drought risk for current and future situations is needed as a basis for the development of adaptation strategies.

Note:

a. Dutch Consul-General Bonnie Horbach in Cape Town, personal communication with author Dimmie Hendriks,, June 21, 2018.
b. See ReliefWeb. No date. Disasters: South America: Drought – 2015–2017. https://reliefweb.int/disaster/dr-2016-000002-col.
c. World Bank 2018.

Figure B2.4.1 Major Cities Explored in the Report *Water Scarce Cities*



Source: World Bank 2018.

2.2 Modeling tools and resources for drought assessment

A wide range of models, methods, and tools are available for drought hazard and risk assessment for different applications. The *Global Inventory of Drought Hazard and Risk Modeling Tools and Resources* (Deltares 2018a) presents a global inventory of drought hazard and risk modeling tools and resources with global, regional, and national application scales. The global drought risk inventory focuses on a range of applications covering hazard mapping and monitoring and forecasting of hazards, impacts, and risks related to meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought. Almost 200 modeling tools and resources are included in the inventory. These consist of indices, datasets, platforms, newsletters/bulletins, modeling software packages, and other tools. The inventory provides an overview per region and concise descriptions in reports of all drought hazard and risk modeling tools and resources that are currently collected. Besides a general description of the overall tool and its main characteristics, for each drought modeling tool and resource, contact information, references, and online links are provided.

The content of the Model Inventory Report (Deltares 2018a) is available through an interactive, online drought catalogue that can be found at www.droughtcatalogue.com (see figure 2.2). This website contains all the information collected about the different drought platforms, datasets, indices, modeling software, bulletins, and tools. The online data provide links to online portals where indices are available as datasets or maps for the whole world and/or for specific regions. For many of the most common indices (the Standardized Precipitation Index, Standardized Precipitation Evapotranspiration Index, Vegetation Health Index, Standardized Streamflow Index, Groundwater Table Declining Trend, and Falkenmark Water Stress Indicator), such datasets are available and ready to use.

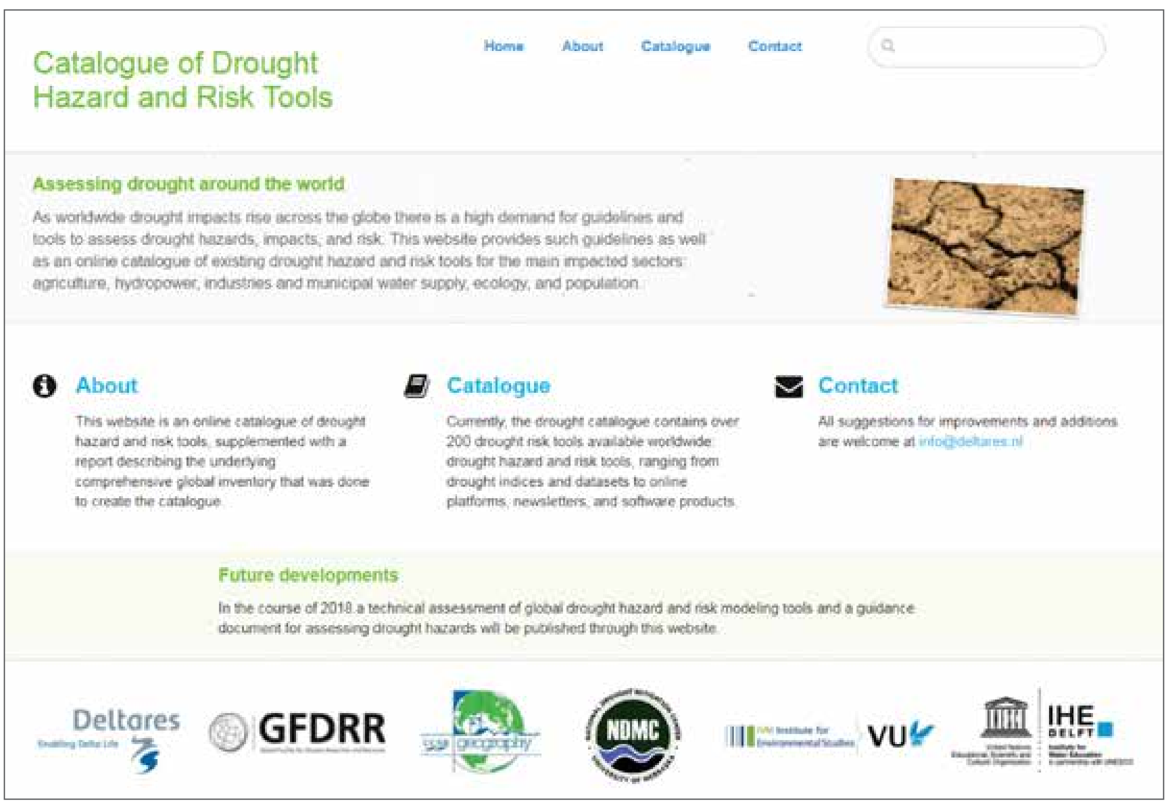
Notes:

1 The catalogue is available at www.droughtcatalogue.com.

2 For information about the Ramsar List see https://www.ramsar.org/about/wetlands-of-international-importance-ramsar-sites.

3 The United Nations Development Programme's Human Development Index is available at http://hdr.undp.org/en/content/human-development-index-hdi.

FIGURE 2.2 Homepage of the Interactive Online Drought Catalogue



Source: Deltares 2018a, www.droughtcatalogue.com.

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Photo: geogif..

3. Guiding Principles

This chapter describes four basic principles to guide the development of drought-related projects and applications, with a main focus on developing countries. The main purpose of these principles is to promote best practices and the use of optimal approaches for assessing drought hazard and risk in data-scarce environments. As such, these principles are meant to guide drought assessments and drought-related projects or programs. They are not intended to provide an exhaustive step-by-step handbook, which will be provided in chapters 4 and 5.

The following principles are presented:

- Principle 1: Drought assessments should use a system-scale perspective
- Principle 2: Drought has to be defined and assessed in relation to its impacts
- Principle 3: Drought risk changes over time
- Principle 4: Effective drought management should increase resilience and enhance preparedness

3.1 Principle 1: Drought assessments should use a system-scale perspective

A drought assessment should start with a system-scale analysis of the spatial and temporal scales at which the drought-prone sectors or at-risk user groups function. This analysis should include the relation of the sectors or user groups to the water system and the system's variability in time and space. Key stakeholders should be included in the assessment from the start of the analysis.

3.1.1 Defining the right scale

Spatial scale

Drought characteristics such as intensity, coverage, duration, and occurrence vary for different spatial scales. For example, Leelaruban and Padmanabhan (2017) present a case where, for smaller spatial scales, the drought persists for a shorter duration than for larger spatial scales. They suggest that drought management and resource allocation policies need to be developed for different spatial scales, not only at the country scale. Selecting the correct spatial and temporal scale is crucial for a proper drought assessment.

When defining the problem and the objective of a drought assessment, one of the first steps is to define the right spatial scale. Is this assessment needed at the community level (local)? Or is the assessment needed for a transboundary basin (regional)? Or anything in between? When the assessment is needed for decision making at a national or regional (transboundary) level, it is often not possible to carry the assessment out at a high-resolution spatial scale. This very quickly becomes too computation heavy. Therefore, these national or regional assessments at a coarser scale are often used to identify hotspots for drought risk in the region, for which more detailed local assessments can be carried out if needed.

The spatial scale of drought assessments is also related to the diversity of the area of interest as well as the spatial scale at which sectors and users are impacted. The level of diversity or heterogeneity in the area of interest needs to be reflected in the spatial resolution chosen for the drought assessment. The larger the diversity in the area, the higher the spatial resolution needs to be—otherwise you run the risk of missing important elements in the drought assessment. It is important to realize that the trade-off between the choice of a higher or lower resolution spatial scale is the computation time and data requirements.

Temporal scale

The temporal scale for drought events is determined by the complexity of the hazard and the time at which sectors and users are impacted. For example, rainfed agriculture—in particular, crops that are not resistant to dry conditions—will already suffer from dry spells (short periods of about two weeks of abnormally dry weather) or short droughts lasting for one or two months. Irrigated agriculture relying on reservoirs and groundwater, on the other hand, will most probably not suffer from a meteorological drought of only a few months but may be more affected by longer duration droughts that can have profound impacts on inflow volumes. The reason for this is that the reaction of surface water reservoirs and groundwater to climatic input is often delayed and smoothed (Van Loon 2015).

For instance, the temporal scale of a drought forecasting system will depend on the questions above. When considering rainfed crops with low resistance to droughts, the forecasting system would need to consider a high-resolution time scale (daily to dekadal). For irrigated agriculture, on the other hand, a monthly resolution time would be preferred. Selection of a too-coarse temporal scale for the type of crops and agriculture would probably result in a (significant) underestimation of the impact of the predicted drought.

The definition of the problem should also be linked to a time horizon. Is the problem (and solution) a short-term issue (for example, is it relevant for the next cropping season)? Or is it a future or long-term concern where possible climate and socioeconomic changes have to be analyzed? A correct understanding of the time horizon of interest is central to deciding on the appropriate type of analysis to conduct. For example, an assessment for a seasonal drought forecasting system for irrigated agriculture will consider only current climate conditions, and a forecast horizon of six months will suffice. On the other hand, the design of a hydropower dam that is resilient to changing climatic conditions needs to consider future climate and socioeconomic changes and a forecast horizon of at least 50–100 years needs to be considered.

3.1.2 Connecting with all stakeholders

Involving local stakeholders and citizens in the drought assessment has proven to be an effective method to grasp the system-scale perspective. Engaging relevant stakeholders and user groups in different ways makes a large contribution to the accurate definition of the comprehensive problem and to the determination of the main exposed and vulnerable sectors and users. Moreover, it provides relevant information needed to understand the main water sources and the drought impacts for these sectors and water users. For example, an effective way to involve stakeholders and citizens is by organizing local or (sub-) national stakeholder workshops on drought impacts and risks in relation to sectorial water use. Engaging stakeholders and citizens also brings about a process of organized and widely supported drought risk mitigation and adaptation. If the practical or political situation does not allow for the organization of workshops, interviews or questionnaires could provide a solution to connect to stakeholders.

Relevant stakeholders include, but are not limited to, water authorities, drinking water companies, municipalities, agricultural organizations or farmers associations, insurance companies, industries and multinationals, and national and local experts—depending on the main impacted sectors and user groups. Stakeholders can complement and specify the overview of impacted sectors and user groups based on their knowledge of the area. Also they may have valuable information on historical droughts and the specific sectors or users that were impacted in the past. Stakeholders can also be the key to accessing relevant local data on exposure and water use as well as vulnerability information. Box 3.1 provides an example of a project in which stakeholders in Colombian catchments were involved in early stages of a water-shortage risk assessment.

In this context, transparency and disclosure of information and data from all partners is essential. Without this it will be very difficult to build a shared data and knowledge base that is accepted and trusted by all stakeholders. It might be favorable to engage with an external interest-free party to collect, assemble, and evaluate all data information.

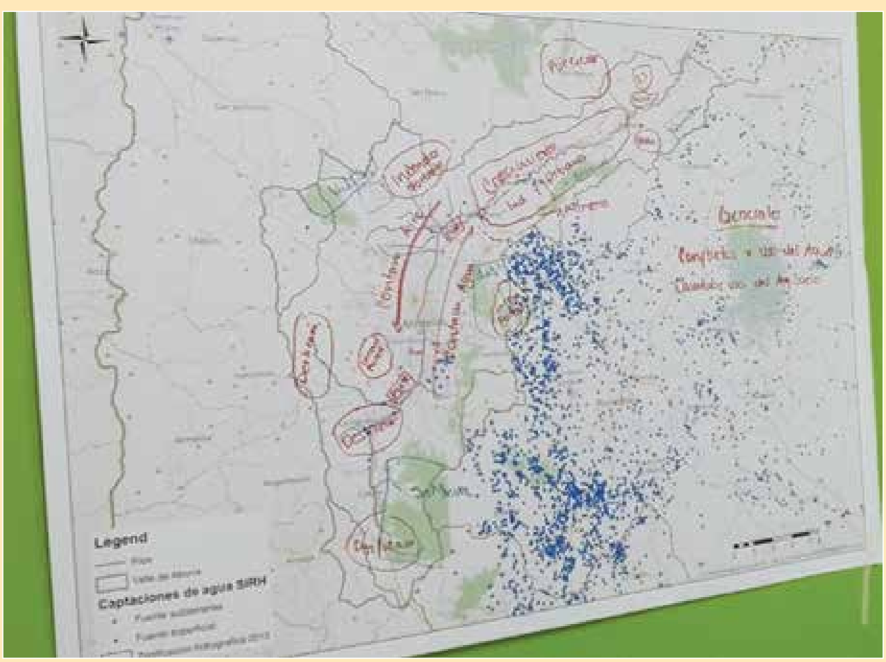
BOX 3.1 Good Practice Example: Assessing Water-Related Risks with Stakeholders in Colombia

In 2017 a detailed assessment was carried out of the water shortage–related risks in two basins in Colombia where paper mills are located.[a] To ensure sufficient water now and in the future requires the joint responsibility of all relevant stakeholders in the river basin at risk: municipalities; the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM); the Early Warning System of Medellín and the valley of Aburrá (SIATA); the Business Corporation Proaburrá North; the regional autonomous corporation of Antioquia (CORANTIOQUIA); universities; and the multinational corporationKimberly-Clark. Therefore two workshops were organized in Colombia in Barbosa (near Medellin) and Puerto Tejada (near Cali). The objective of the workshops was, with a participatory approach, (i) to evaluate the actual risks in the river basin connected to water management; (ii) to evaluate the future risks considering development scenarios (economic development in the river basin, changing climate, political and regulatory changes); and (iii) to obtain suggestions from the participants of the workshop about what information to include in a tailor-made dashboard to present the risks.

During the workshops, stakeholders provided useful information about historical water shortages, relevant databases, impact categories, regional and local hotspots, and future developments in the catchments (figure 3.1.1). Moreover, both workshops concluded that knowledge on water shortage risks at the catchment scale is a key factor in order to know how we can manage the water resources in the future, and that anticipating the possible changes and development scenarios is important in order to adapt water management in time.

Note:
a. Deltares 2017.

FIGURE B3.1.1 Water Shortage Risk Map Produced with Stakeholders during a Workshop in Colombia



Source: Deltares, from workshop on April 6, 2017, Cali, Colombia.

3.2 Principle 2: Drought has to be defined and assessed in relation to its impacts

*A thorough assessment of the sectors that are (potentially) impacted by droughts in the area should be conducted. This assessment should include an understanding of **how** these sectors are impacted (for example, economic losses) and **why** (for example, an empty reservoir).*

3.2.1 Focus on impacted sectors

Drought becomes a disaster if and when it impacts assets, the economy, people, or the environment, causing negative effects to the main sectors in a country. Sectors often identified as (potentially) vulnerable to droughts include agriculture, energy and industry, drinking/domestic water supply, navigation, ecosystems, tourism, forestry, aquaculture and fisheries, and the financial sector. A combination of impacts to different sectors undoubtedly has (negative) impacts on the overall economy and well-being of a geographical extent as established in Principle 1. Drought risk to a specific sector, or user, is determined by combining drought hazard characteristics with the level of exposure and vulnerability of that economic sector or water user. To improve the ability to cope with droughts, the impacts and risks associated with drought should be assessed and mapped for a country, region, sector, or user group.

3.2.2 The impact of different drought types on sectors and users

Sectors and users can be affected by some or all of the drought types defined in section 2.1. For example, although rainfed agriculture is mainly impacted by meteorological and agricultural drought, hydropower and inland navigation are impacted by hydrological drought (low river runoff). Likewise, water shortage risks of urban areas can best be analyzed by looking at socioeconomic droughts. Table 3.1 describes which sectors are mostly likely to be affected by which type of drought, together with the drought indices that are commonly used to characterize those drought types. Detailed information on the drought indices listed can be found on the *Global Inventory of Drought Hazard and Risk Modeling Tools and Resources (Deltares 2018a) and online catalogue* (www.droughtcatalogue.com).

3.3 Principle 3: Drought risk changes over time

Addressing future drought risk needs both a thorough analysis of expected changes in the drought hazard due to climate change as well as an analysis of expected changes in drought-related impacts due to socioeconomic changes.

Drought risk assessments for long-term time horizons are crucial for several drought applications. These assessments provide basic information for the development of a strategy to increase drought resilience of a country or an area. As climate changes and societies and economies develop, drought risk changes accordingly. To understand how drought risk may develop on short-, medium-, and long-term horizons, future developments of drought hazards as well as socioeconomic changes have to be assessed for the different sectors and water users.

3.3.1 Climate change will affect drought severity and scale

For an analysis of future drought hazard, climate change scenarios generated by the IPCC can be used (IPCC 2014). These scenarios, described in the most recent Assessment Report of the IPCC (AR5), focus on a parallel development of emissions and socioeconomic scenarios. The starting points of these scenarios are radiative forcing pathways that describe an emission trajectory and concentration by the year 2100. These radiative forcing trajectories are termed *Representative Concentration Pathways* (RCPs) and are broadly described as "climate scenarios." In a drought risk assessment, generally a combination of a dry climate scenario (worst case) and an intermediate scenario is used to capture the range of future drought conditions. Which RCP scenario is the worst case or intermediate scenario will differ from region to region and will have to be determined by an expert. Box 3.2 presents an example of the future assessment of Lesotho Water Security taking into account the effects of climate change.

The IPCC reports with medium confidence that in present-day dry regions, drought frequency will likely increase by the end of the 21st century under the RCP8.5 scenario, which corresponds to the pathway with the highest greenhouse gas emissions. In contrast, water resources are projected to increase at high latitudes under the same scenario (with high confidence). Regions where droughts

TABLE 3.1 Main Sectors Affected by the Different Types of Droughts, with Relevant Time Scales and Indices

Sectors affected (and relevant time scale)	Drought type	Time scales	Drought indices
• Rainfed agriculture • Domestic water supply (self-sufficient)	Meteorological	Dekade, month	SPI, PDSI, AAI, AI, CZI, DRI, Palmer Z Index, ADI, MSDI, Deficit Indices, Deciles, PNP, Weighted Anomaly, Palmer Z Index, WASP, EDI, RAI, sc-PDSI, SAI, SPEI, DAI
• Rainfed agriculture • Terrestrial ecosystems • Financial sector	Agricultural	Dekade, month	KBDI, CMI, NDI, ARID, CSDI, SMA, ETDI, SMDI, EVI, NDVI, TCI, VCI, VegDRI, VHI, WRSI, NDWI, SAVI, ESI, ADI, MSDI, Deficit Indices, Deciles, PNP, WASP, EDI, RAI, sc-PDSI, SPEI, SAI
• Irrigated agriculture • Hydropower (energy) • Energy and Industry (cooling) • Industry (water resource) • Domestic water supply • Navigation • Aquatic and terrestrial ecosystems • Recreation	Hydrological	Month, season, year	GWDT, SGI, GRI, GWI, DDV, RDI, PHDI, SRSI, SSFI, SRI, SWI, SDI, SWSI, SMRI, IDR, DAI, SPEI
• Energy and industry (cooling) • Industry (consumptive water use) • Domestic water supply (distribution) • Financial sector (water dependent businesses)	Socioeconomic	Season, year	MSRRI, WSI, WSR, Falkenmark Index, Watergap

Source: Extrapolated from Van Loon 2015.

Note: AAI = Aridity Anomaly Index; ADI = Aggregate Dryness Index; AI = Aridity Index; ARID = Agricultural Reference Index for Drought; CMI = Crop Moisture Index; CSDI = Crop Specific Drought Index; CZI = China Z Index; DAI = Drought Area Index; DDV = drought deficit volume; DRI = Drought Reconnaissance Index; EDI = Effective Drought Index; ESI = Evaporative Stress Index; ETDI = Evapotranspiration Deficit Index; EVI = Enhanced Vegetation Index; GRI = Groundwater Resource Index; GWDT = Groundwater Table Declining Trend; GWI = Groundwater Drought Index; IDR = Inflow-Demand Reliability; KBDI = Keetch-Bryam Drought Index; MSDI = Multivariate Standardized Drought Index; NDI = NOAA Drought Index; NDVI = Normalized Difference Vegetation Index; NDWI = Normalized Difference Water Index; PDSI = Palmer Drought Severity Index; PHDI = Palmer Hydrological Drought Index; PNP = Percent of Normal Precipitation; RAI = Rainfall Anomaly Index; RDI = Reclamation Drought Index; SAI = Standardized Anomaly Index; SAVI = Soil Adjusted Vegetation Index; sc-PDSI = Self-Calibrated Palmer Drought Severity Index; SDI = Streamflow Drought Index; SGI = Standardized Groundwater Index; SMA = Soil Moisture Anomaly; SMDI = Soil Moisture Deficit Index; SMRI = Standardized Snowmelt and Rain Index; SPEI = Standardized Precipitation Evapotranspiration Index; SPI = Standardized Precipitation Index; SRI = Standardized Runoff Index; SRSI = Standardized Reservoir Supply Index; SSFI = Standardized Streamflow Index; SWI = Standardized Water-Level Index; SWSI = Surface Water Supply Index; TCI = Temperature Condition Index; VCI = Vegetation Condition Index; VegDRI = Vegetation Drought Response Index; VHI = Vegetation Health Index; WASP = Weighted Anomaly Standardized Precipitation Index; WRSI = Water Requirement Satisfaction Index; WSR = Water Storage Resilience indicator.

are projected to become longer and more frequent include the Mediterranean, central Europe, central North America, and southern Africa (Jiménez Cisneros 2014). Moreover, the number of drought days could increase by more than 20 percent in most of the world by 2080, and the number of people exposed to droughts could increase by 9–17 percent in 2030 and 50–90 percent in 2080 (Hallegatte et al. 2016).

3.3.2 Socioeconomic developments affect drought impacts

Socioeconomic change will determine to what extent the sectors and user groups will be exposed to drought, and to what extent they will be able to cope with drought or even with a more permanent water scarcity situation. As the socioeconomic system develops, which sectors or users are affected most can also change.

Shared Socioeconomic Pathways (SSPs) are developed by the Impact, Adaptation, and Vulnerability (IAV) and Integrated Assessment Models (IAM) community (O'Neill et al. 2014; Riahi et al. 2017) to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. SSPs can be defined as possible future storylines. There are five SSPs that depict global narratives with distinctive combinations of drivers related to socioeconomic developments. Each SSP follows different quantitative assumptions in terms of economic growth, urbanization, and demographic developments and qualitatively describes differing storylines regarding the environment, international trade relations, economic growth, and geo-political context. The SSPs are often used in combination with the RCP climate scenarios of the IPCC to identify the major challenges with regard to mitigation and adaptation to climate change.

BOX 3.2 Good Practice Example: Lesotho Water Security and Climate Change Assessment

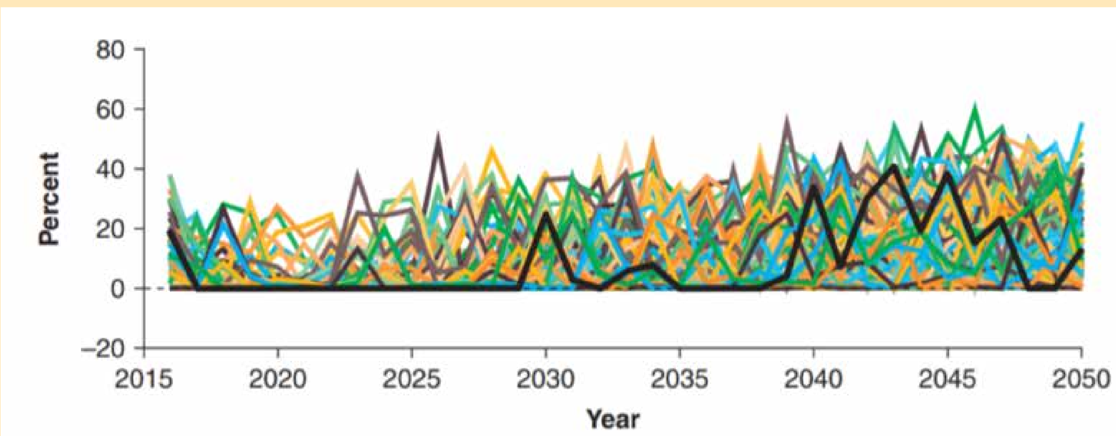
A recent study by the World Bank evaluated the possible impact of climate change scenarios on the domestic and industrial water availability in Lesotho.[a] The study indicates that demand in both sectors cannot be reliably met either by the historically available water resource or under the full range of climate futures. Without taking measures, unmet demand levels will reach 40 percent by 2050.

The study shows that although in a number of the future scenarios shortages already occur in all years, unmet demand is projected to grow significantly starting in 2025. Figure B3.2.1 shows the expected growth in unmet domestic demand to 2050 cross 122 climate scenarios.

Even for the baseline strategy, the study shows that unmet global domestic demand is anticipated to exceed 245 million cubic meters (37 percent) for many scenarios considered in the 2041–50 time period. As expected, unmet demand is greater for the high-demand scenarios as well as in drier climates. Even with average precipitation similar to that of the current climate, unmet demand could range between 32 and 110 million cubic meters for the average demand projection, and between 78 and 161 million cubic meters for the high-demand projection. Unmet demand in the industrial sector shows similar results, ranging from 0 percent to almost 60 percent for the last decade of the analysis.

Note:
a. World Bank Group 2016.

FIGURE B3.2.1 Unmet Domestic Demand for the Baseline Strategy for 122 Climate Scenarios, 2015–50



Source: World Bank Group 2016.

Some SSPs suggest water demand is set to increase, while others indicate a decrease. Likewise, there are SSPs that result in an increase in vulnerability of sectors and users, while other SSPs result in a decrease of vulnerability. For example, SSP1 represents a sustainable world with rapid development of low-income countries, reduced inequality, rapid technological development, and a high level of awareness regarding environmental degradation. Such developments probably lead to a reduction in water demand as a result of technological improvements as well as a reduction in vulnerability due to reduced inequality and increased awareness. In contrast, under SSP3, extreme poverty and a rapidly growing population are predicted as well as serious degradation of the environment and a low rate of technological change. Such conditions probably lead to a reduction of water demand as a result of hampered economic development. At the same time, the vulnerability of many sectors and users is high as a result of increased poverty, a rapidly growing population, and land degradation.

Finally, changes in policies and legislation for water management and water use should be considered, as this may affect water pricing and distribution and allocation of water. The SSP storylines take into account environmental regulation and enforcement. Tramberend et al. (2015) interpreted the SSP narratives to indicate direct or indirect consequences for key water dimensions, including those on regulations and enforcement.

3.3.3 The role of groundwater in assessments of future drought risk

Droughts do not always have an evident impact. Groundwater and/or surface water storage facilities may be available to compensate for the lack of rainwater and surface water. As a result, the detrimental effects of droughts are shifted in time—in some cases it can take years—even after the precipitation returns to normal. There may also be a shift to other water users that do not have access to these groundwater and surface water storage facilities. By overexploitation of renewable and nonrenewable groundwater, future generations will become more vulnerable to droughts and suffer larger drought impacts at a similar hazard level. Several studies have already shown that groundwater reserves in aquifers around the globe are diminishing as a result of overexploitation and the changing climate (Earth Security Group 2016; Gleeson et al. 2012; WWAP 2015), implying that groundwater may become unavailable as an alternative water source. As a result, future drought events may have an even bigger impact on agriculture, urban water supply, and the overall economy than current droughts of the same intensity. If these effects are not taken into account in the future drought assessments, the impacts of the future drought will be underestimated.

3.4 Principle 4: Effective drought management should increase resilience and enhance preparedness

Increased resilience and enhanced preparedness of a sector, country, water user, and so on for droughts includes a combination of both proactive and reactive approaches. Proactive measures such as the designing of preparedness and/or risk reduction measures, implementation of drought management plans, and identification of timely actions to mitigate the impact of a drought should be prioritized over reactive measures.

The last decade has seen an increasing awareness of droughts worldwide. During a high-level meeting on national drought policies hosted by the World Meteorological Organization (WMO) in Geneva in March 2013, several strategies were adopted on drought management (Trambauer 2015).

In countries or areas where droughts occur frequently, preparedness and responsiveness to drought needs to be increased. Action plans and measures need to be developed that improve the level at which the country or area can endure, adapt, and recover from droughts in the short and medium-long term—that is, improve its resilience. In the drought community there is a recognized need for a paradigm shift—moving from "crisis" to "risk" management (Wilhite 2002). A drought hazard and risk assessment is an indispensable starting point for developing drought management and action plans. In addition, an effective drought monitoring and early warning system, supported by established and suitable institutional frameworks and drought policies, is a key component of a successful drought preparedness plan.

3.4.1 Drought management plans in place

All countries, especially those that are drought prone, need to have drought management plans in place. Drought management plans normally identify both long- and short-term activities and actions that can be implemented to prevent and mitigate drought impacts. Such activities and actions are essential in the development of specific drought planning and response efforts. Examples include (EC, MEDA Water, and MEDROPLAN 2007):

- Establishing a well-organized governance mechanism that clarifies who is responsible for what
- Implementing preparedness, early warning, and monitoring systems
- Defining the conditions and thresholds to be met to declare the severity level of a drought
- Establishing priorities for water use for each drought severity level
- Establishing management objectives for each drought severity level
- Defining the actions (sector/area specific) that have to be taken at each drought severity level

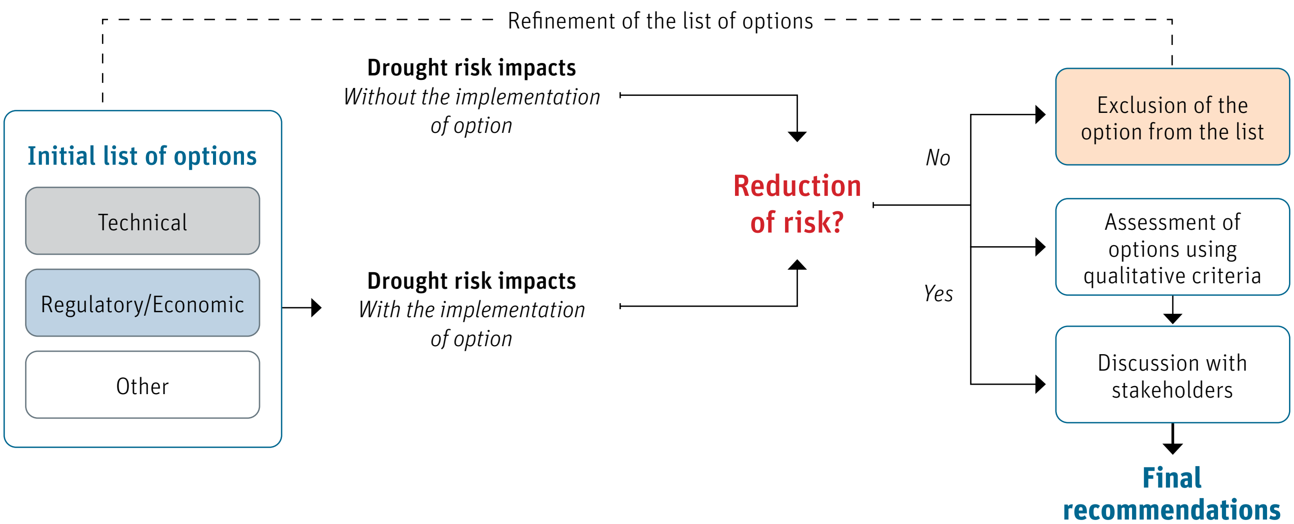
This guidance document does not provide a detailed description or implementation guide for the development of drought management plans. A number of guidelines to assist in the development of national drought policies and drought management plans and are available and presented in section 1.1 of this report. However, the drought hazard and risk assessment guidance provided in this report provides the knowledge base that is a required input for the development of drought management plans.

3.4.2 Investing in risk reduction measures

A wide range of actions or measures can be taken to reduce short- and long-term drought risks. Knutson, Hayes, and Phillips (1998) list a wide range of possible actions or measures that can be taken to reduce drought risk, and they present an effective matrix to choose which actions to take in the risk reduction planning based on issues such as feasibility, effectiveness, cost, and equity.

Similarly, the DROUGHT-R&SP (Assimacopoulos et al. 2015) project presents interesting recommendations for drought risk reduction and divides the different types of measures to address drought risk into two main categories (see figure 3.1): short-term actions that aim to alleviate the negative impacts of a drought episode (that is, actions to be taken during the course of a drought episode or as part of a drought recovery scheme; these are included in a drought management plan); and long-term actions that aim to reduce sensitivity to drought and build coping capacity (included in a river basin or water management plan). Figure 3.1 presents this approach toward developing recommendations for drought risk reduction and list of possible measures.

FIGURE 3.1 Approach toward Recommendations for Drought Risk Reduction and List of Possible Measures



	Technical	Regularoty/Economic	Other
Short-term (aimed at reducing drought impacts or at drought response and recovery)	• Emergency water transfers, water hauling	• Water restrictions/mandatory rationing • Emergency pricing • Re-allocation of available water resources • Recovery assistance & public aids for income losses	• Public information campaigns for water saving
Long-term (aimed at reducing sensitivity to drought and long-term coping capacity enhancement)	• Infrastructure rehabilitation to reduce losses • Sea or brackish water desalination • Construction of new reservoirs • Conjunctive use schemes and strategic reserves • Water recycling and reuse	• Water consumption metering and regulation • Mechanisms for tradable water use rights • Economic incentives for engaging in water saving • Insurance programs	• Education on water saving/ conservation • Change or coping patterns and agronomic techniques

Source: Assimacopoulos et al. 2015.

3.4.3 Toward efficient drought early warning systems

Drought early warning systems are widely recognized in the international agendas (see box 3.3). An efficient and people-centered early warning system comprises four elements: (i) disaster risk knowledge based on the systematic collection of data and disaster risk assessments; (ii) detection, monitoring, analysis, and forecasting of the hazards and possible consequences; (iii) dissemination and communication, by an official source, of authoritative, timely, accurate, and actionable warnings and associated information on likelihood and impact; and (iv) preparedness at all levels to respond to the warnings received (WMO 2018). Failure in any of these parts may result in failure of the whole early warning system. Moreover, people and communities at risk should be actively involved, public education and awareness of risks should be facilitated, and messages and warnings should be disseminated in an understandable way to those who will need to act upon them (WMO 2018).

To ensure a well-functioning, end-to-end people-centered drought forecasting system, it is essential to appoint one or several national and regional agencies to provide drought detection and forecasting information to authorities and the public. A trusted national or regional agency mandated to provide operational drought monitoring and warnings is vital to ensure that warnings are responded to. To enable these agencies to fulfil their mandate, they will need to be provided with the right tools, skills, and datasets needed so they can best utilize their local expertise on drought detection and early warning. These agencies cannot, however, work in isolation, and drought detection and forecasting products should be developed in close collaboration with the local/provincial agencies and key stakeholders to ensure these products meet specific needs. It is clear that this requires governments to commit to a multi-year long-term collaboration such that the operational potential of drought early warning systems can be realized, and to make sure that local agencies have the skill and infrastructure they need to keep such systems operating sustainably.

BOX 3.3 The Sendai Framework for Disaster Risk Reduction

The Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015) identifies the benefits of early warning systems. More specifically, one of its seven global targets, target (g) reads: "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030." Likewise, the 2030 Agenda for Sustainable Development (UN 2015) addresses early warning and gives it an important role across several of the goals defined, such as in food security, healthy lives, resilient cities, environmental management and climate change adaptation. The Paris Agreement stipulates early warning systems as one of the major focus areas in order to enhance adaptive capacity, strengthen resilience, reduce vulnerability, and minimize loss and damages associated with the adverse effects of climate change (WMO 2018).

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Water tower in Johannesburg, South Africa. Photo: THEGIFT777.

4. Implementation Guide

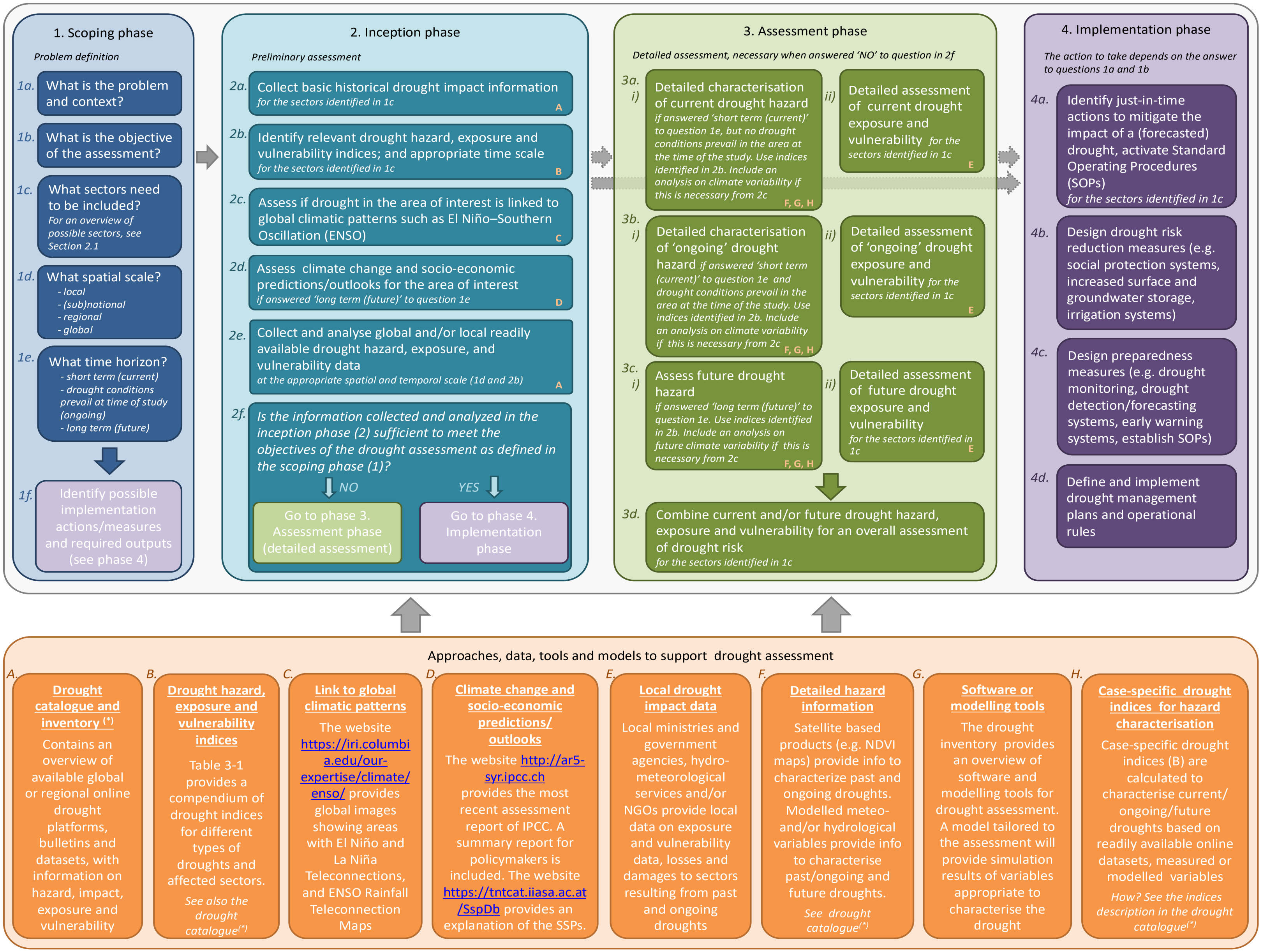
The previous chapter outlines the general principles for assessing and managing drought risk. This chapter presents an implementation guide for professionals in the field of water management and drought, outlining the steps that need to be carried out during a drought assessment (figure 4.1). These steps are incorporated into a workflow in four phases that can be used to guide the professional in developing the assessment. These include (i) a scoping phase in which the problem is defined and contextualized; (ii) an inception phase, when a preliminary assessment is made; (iii) a detailed assessment phase; and (iv) an implementation phase in which possible actions are identified.

The best route to navigate through the workflow will depend very much on the specific identified problem and the objectives of the assessment, the characteristics of the area, and the sectors and users potentially impacted, as well as on the availability of data and resources. In some cases, the detailed analysis phase may not need to be included, or even possible, given available data and resources. For example, the detailed analysis is not necessary when the objective of the assessment is to develop an overview of drought hazard and impacts at a large spatial scale (for example, continental or global). In this case the preliminary assessment made during the inception phase (phase 2), which is based on globally available drought information, would suffice.

To help establish which route to take, each phase comprises of a series of questions that need to be answered to decide on the next step(s) to be taken. The following paragraphs provide a comprehensive explanation for each phase. To illustrate how this workflow can be used, three examples of the application of the guidelines are provided in chapter 5. These examples cover a wide range of problems, analyses, and solutions, and provide a good overview of possible approaches for quite different applications. For each of these examples the step-by-step path through the four phases is explained, supported by a justification of choices made. These examples and the choices made to determine the appropriate path are intended to serve as an example when developing a drought assessment for a different application.

Numerous approaches, tools, data, and models are available to support the four phases of the assessment, particularly the inception phase (phase 2) and the assessment phase (phase 3). The orange boxes at the bottom of the workflow (figure 4.1) provide an overview of these, and also indicate where to find the data, models, indices, and other information that is needed at each step. The tools, data, and models listed are by no means exhaustive, and numerous other sources are also available. The (online) libraries listed in the workflow simply provide guidance to the professional carrying out the

FIGURE 4.1 Overview of the Workflow to Perform a Drought Assessment (Phase 1 through 3) and Identify Potential Risk Reduction Measures (Phase 4)



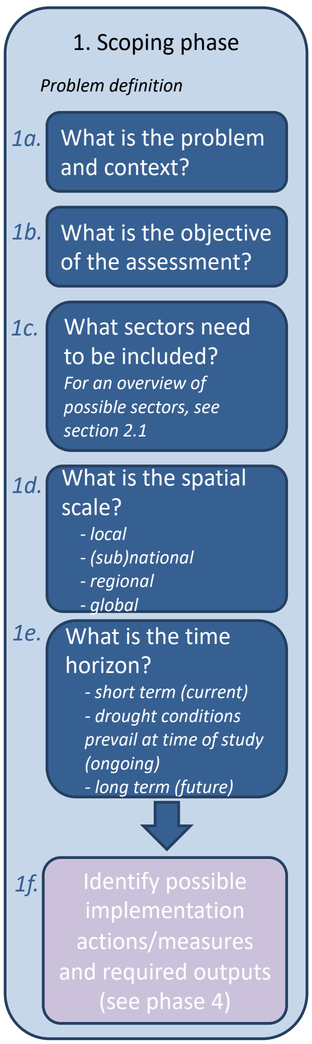
* www.droughtcatalogue.com

Note: Letters at the bottom right of the phase boxes refer to the orange boxes at the bottom of the figure. ENSO = El Niño Southern Oscillation; IPCC = Intergovernmental Panel on Climate Change; NGO = nongovernmental organization; SSP = Shared Socioeconomic Pathways.

assessment on where to search. As shown in the orange boxes, for several steps the necessary tools can be found in the *Catalogue of Drought Hazard and Risk Tools* (www.droughtcatalogue.com), which accompanies this document. However, depending on the context, additional links and contacts—in particular links to more local resources such as the national hydrometeorological services—are recommended.

4.1 Scoping phase

FIGURE 4.2 Phase 1: Scoping Phase



Every drought hazard and/or risk assessment should begin with a scoping phase in which issues that arise when droughts occur are broadly identified within the wider context (figure 4.2). The results of the scoping phase will largely determine how the solution to the identified problem is found. Several steps comprise the scoping phase, and while these are described sequentially, they mutually influence each other. During this phase it is important to use a system-scale perspective (see Principle 1). This phase serves to "set the scene" and does not result in any map or similar information. The output of this phase is a good understanding of the problem and its overall context in order to carry out a tailored but preliminary assessment during the following phase (inception phase). It also provides preliminary suggestions of possible implementation actions or measures as well as required outputs of the assessment to contribute to these actions/measures.

1a. Establish the problem and its context: In this step the problem at hand is clearly outlined and contextualized. Although this is normally defined by the problem owner, who will typically be a decision maker who has issued the drought-related project to limit adverse effects of droughts, it should be done in consultation with relevant identified stakeholders and the intended recipient audience of the drought risk assessment.

1b. Define the objective of the assessment: With the problem clearly outlined, the objectives of the assessment need to be defined and the scope established. While the objectives outline the goal of the assessment, the scope will define clearly what will be addressed within the assessment and what will not be considered. This may either be the result of limited relevance to the problem identified or of limitations in time and resources, which means priorities need to be set.

1c. Identify sectors that need to be included: It is important to determine the sectors or water users that may be affected by drought and thus need to be included in the assessment. Section 2.1 provides an overview of possible relevant sectors, such as agriculture, energy, navigation, and so on.

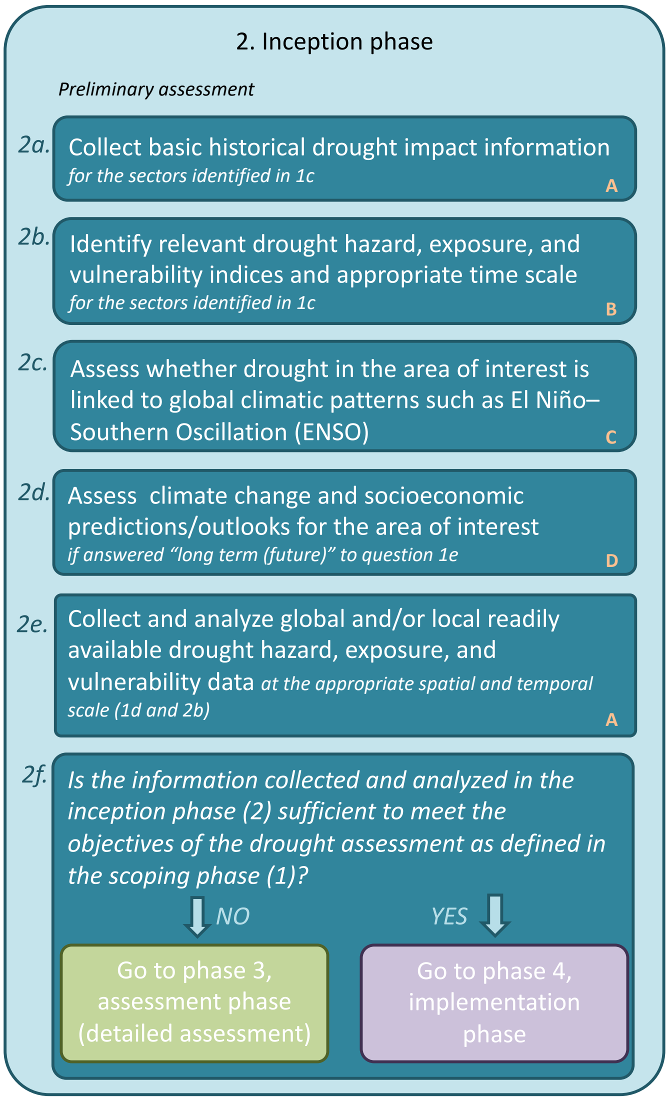
1d. Specify the spatial scale: Closely related to the objective of the assessment is the spatial scale. Does the drought problem relate to a community or to province? Or does it relate to a (large) transboundary river basin? Or is the assessment intended to consider the continental or even global scale? In phase 1 the issue of spatial scale is discussed, because the answer to this question will determine the scale of data and information that will be used during the inception phase.

1e. Stipulate the relevant time horizon: Again closely related to the problem and the identified scope is the time horizon that is relevant. Is the problem related to a short-term drought situation—for example, a response to an ongoing drought? Or is it related to a future drought (risk)? The answer to these questions will determine whether future climate and socioeconomic conditions would need to be considered in the inception phase. As explained in Principle 1, if the problem is related to a current drought, only current climate conditions would be considered; if the problem is related to future conditions, the analysis will require considering climate and socioeconomic changes.

1f. Identify possible implementation actions and/or measures and required output: Based on the problem and context of the risk assessment project (1a) and the answers to questions imposed in 1b–e, possible implementation actions and measures can be broadly identified. Furthermore, the required output that is needed to support these actions or measures can be described in phase 1f. Phases 2 and 3 of the risk assessment can be carried out with more focus if a general idea has been formed of the required implementation actions and/or measures required to mitigate or adapt to the drought issue under investigation. Phase 4 provides on overview of possible implementation actions and measures.

4.2 Inception phase

FIGURE 4.3 Phase 2: Inception Phase



Once the scope of the assessment has been clearly defined, a preliminary drought assessment should be carried out. This is part of the inception phase (figure 4.3) and will typically be carried out by a technical team of water resources and drought risk professionals. During this phase, a first estimate of the drought hazard and risk in the area of interest is made by collecting the available, relevant data from literature as well as from a variety of other, in many cases online, sources. The level of detail of the consulted data should be in line with the scope of the assessment as determined in phase 1d.

2a. Collect historical drought impacts: Available data of past drought impacts has to be collected in order to develop a good understanding of how sectors identified in the scoping phase have historically been impacted by droughts.

2b. Identify relevant indices and appropriate time scale: Relevant drought hazard, exposure, and vulnerability indices have to be identified for the selected sectors. Guiding Principle 2 provides "the rule" on how a drought has to be defined in relation to the sector it impacts; it also provides guidance on the type of drought that relates most to the different sectors and which indices should be considered (see table 3.1). In the same way, the time scale at which sectors and users are impacted determines the appropriate time scale to be used in the assessment (see guiding Principle 1 and table 3.1).

2c. Assess links to climatic patterns: In some regions of the world, droughts are linked to global climatic patterns such as the El Niño–Southern Oscillation (ENSO). For example, in Southern Africa droughts tend to occur during the onset of an El Niño event, while floods tend to occur during La Niña events. This teleconnection is a source of forecast predictability at the (sub)seasonal timescale. It is important to assess whether the region of interest could be influenced by these climatic patterns, in which case these patterns have to be taken into account in the assessment. Orange box C in figure 4.1 provides guidance on where this information can be found.

2d. Assess climate and socioeconomic change: When in the scoping phase the problem is defined to need a long-term solution, estimated future climate change and socioeconomic changes and their uncertainties have to be considered in the assessment. During the inception phase, a basic understanding of the estimated changes for the area of interest needs to be established. Section 3.3.1 refers to the relevant IPCC reports (climate change scenarios) and section 3.3.2 provides information about the SSPs (Shared Socioeconomic Pathways). Links to these can be found in orange box C in figure 4.1. If during the scoping phase it was determined that the problem concerns short-term drought impacts, climate change and socioeconomic changes do not have to be included in the assessment.

2e. Collect and analyze available data: Once this preliminary understanding (steps 2a–2d) provides a good overview of the type of data and information needed for the drought assessment to adequately address the problem defined (for example, what indices to use, and whether an ENSO analysis is necessary and climate change should be considered), available online data portals and databases should be consulted to obtain a first estimate of the level of drought risk in the area. The drought catalogue (orange box A in figure 4.1; www.droughtcatalogue.com) includes a compendium of online platforms, newsletters and bulletins, datasets, and indices. Models and tools required to transform the basic datasets (for example, precipitation) into derived parameters (such as runoff, groundwater levels) that are required for drought hazard and risk characterization are also included. An example of resources that can be used follows:

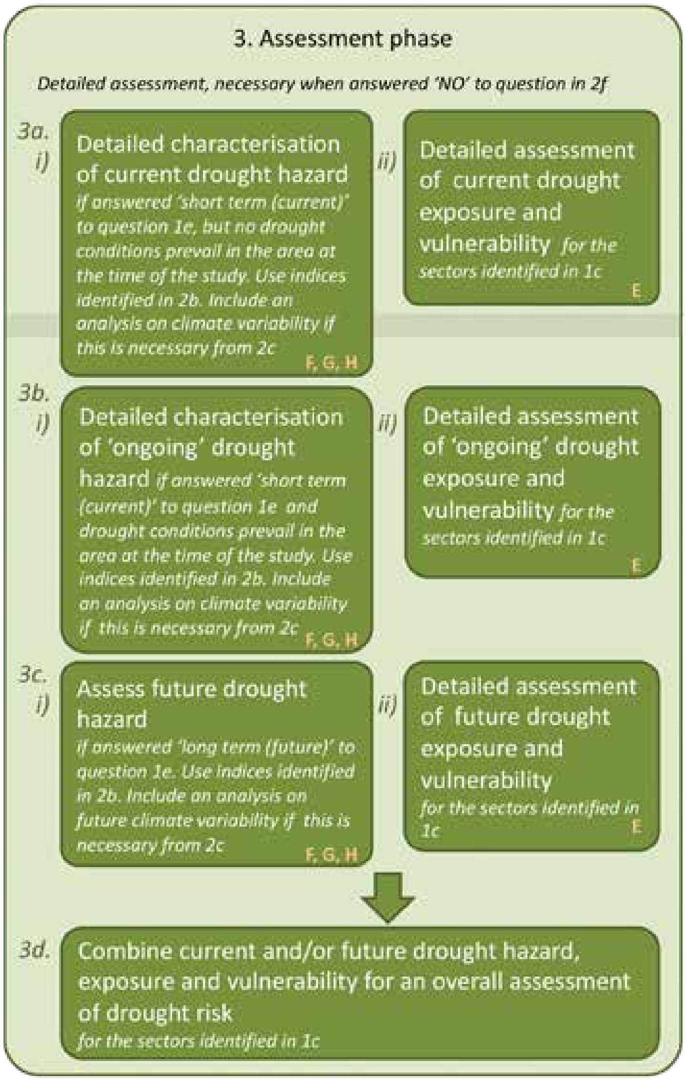
- Freely available global models and datasets generally provide meteorological, hydrological, and agricultural variables and drought indices with a time steps of dekades (10-days) or months. Generally, this is a good starting point for a drought hazard analysis. Global hydrological models (PCR-GLOBWB and WaterGAP) are relatively good at representing the relative variability of hydrological parameters, but less reliable in estimating absolute values correctly (Deltares 2018b). This indicates that global models can be safely applied in drought event detection and monitoring but should be handled with care when absolute values are important.
- A first estimate of the level of water stress and its changes over time can be obtained by calculating the Falkenmark Index or Water Stress Index (Falkenmark, Lundquist, and Widstrand 1989). This index consists of the sum of the total yearly local runoff per country compared to estimates of population density. For these calculations, time series of yearly local runoff can be obtained from global hydrological models such as WaterGap and PCR-GLOBWB through the web portal *Water Cycle Integrator*. Water availability of more than 1,700 cubic meters/capita/year is defined as the threshold above which water shortage occurs only irregularly or locally. Below this level, water scarcity is considered to arise.
- Information about (sub-) national levels of water stress for the current situation as well as the future can be obtained from the *Aqueduct Water Risk Atlas from the World Resources Institute (WRI)*. The tool can be very useful for obtaining a first estimate of possible water risks in a region or country. However, being based on global data, the *Aqueduct Water Risk Atlas* does not necessarily provide accurate representation of the drought situation at subnational scales.
- A first estimate on water scarcity at a provincial level can be obtained from the *Think Hazard!* portal. This portal provides classified hazard levels based on the Water Stress Index described above. As it based on the Water Stress Index from the *Aqueduct Water Risk Atlas*, again, it can be useful to obtain first estimates of water risk levels. However, it shares the same issues of accuracy or completeness at smaller scales.
- For historic drought events and their impacts on the population and overall economy, the International Disaster Database (EM-DAT) can be used as a starting point. It is, however, recommended to verify and supplement the information from EM-DAT with historical drought information reported by national or local official institutions (for example, national meteorological institutes). For Europe, the European Drought Impact report Inventory (EDII) contains close to 5,000 impact reports from 33 European countries (Stahl et al. 2016) (http://www.geo.uio.no/edc/droughtdb/index.php).

2f. Deciding on the next step in the assessment: As defined in the scope, the availability of resources (time, budget, data, and expertise) may condition the assessment to a basic, coarse-scaled assessment that can be carried out in limited time, making as much use as possible of readily available platforms and datasets for the region and sectors of interest. In this case, a readily available drought indicator time series might be chosen instead of doing a detailed assessment. Although a detailed assessment has a clear advantage in terms of flexibility, potential level of accuracy, and the ability to focus on the specific drought conditions, sectors, and output, it may not always be feasible. If the scoping phase has been carried out correctly, this will be reflected in the problem definition and scope of the assessment. In that case the preliminary assessment carried out in the inception phase will be sufficient to meet the objectives of the assessment and the detailed assessment phase can be skipped.

Therefore, after relevant available data on drought hazard, exposure, and vulnerability have been collected from readily available sources (for example, the drought catalogue), the following question needs to be answered: *Does the existing information provide an accurate estimate of drought hazard, exposure, and vulnerability that answers to the scope in terms of resolution and data input? In other words, is the information that has been collected and analyzed in the inception phase sufficient to meet the objectives of the drought assessment as* *defined in the scoping phase?* If the answer to this question is affirmative, then there is no need to do a detailed assessment, and phase 3 can be omitted. If, however, the answer to the previous question is negative, then the detailed assessment will need to be carried out (see section 4.3).

4.3 Assessment phase

FIGURE 4.4 Phase 3: Assessment Phase



In the assessment phase (figure 4.4), a detailed analysis of ongoing, current, and/or future drought hazard and risk should be carried out. The principal objective of this phase is to enhance the level of detail and build on the initial assessment undertaken in the inception phase to meet the objectives and scope of the assessment as identified in the scoping phase. This phase will be carried out only if a more detailed assessment has been ascertained to be relevant in the inception phase.

The steps to be undertaken in the assessment phase will depend to a large extent on the time horizon of the study, as identified in the inception phase (see step 1e in the workflow diagram of figure 4.1).

3a. Detailed characterization of current drought hazard: If the time horizon has been identified as short term (for example, relevant for the next cropping season), the detailed assessment considers current climate conditions (historical hydrometeorological data) and the same indices as identified in the inception phase (figure 4.1, step 2b), but at a higher temporal and/or spatial resolution. These indices are computed using local/regional datasets and models. These datasets and resulting indices will need to be available for a sufficient period of record (> 30 years) and properly represent relevant processes—including, for example, surface-groundwater interactions, which may be very important. In areas where climatic teleconnections are strong (see also figure 4.1, step 2c), a detailed analysis of climate variability and links to global climatic patterns are necessary. The characterization of drought conditions is to be complemented by a d*etailed assessment of the exposure and vulnerability* to drought (or alternative approach based on proxy values, see chapter 2), to elucidate how the sectors identified in the scoping phase are impacted by droughts. This should include a detailed analysis of how these sectors have been impacted by past (historical) droughts.

3b. Detailed characterization of "ongoing" drought: If the time horizon has been identified to be short-term and the drought conditions prevail in the area at the time of study, or drought conditions are imminent, the detailed analysis will focus on ongoing droughts. If available, developing drought conditions may have been predicted through a drought forecast. To place the ongoing or imminent drought conditions in perspective, historical drought events may be considered in the assessment, as well as a more detailed analysis of climate variability, building on the assessment of this from the inception phase. The characterization of drought conditions is to be complemented by a *detailed assessment of the exposure and vulnerability* to drought, to provide insight on how the sectors identified in the scoping phase are being affected by ongoing drought conditions or may be affected by imminent drought conditions. This will provide important information for designing just-in-time measures to mitigate the impact of the ongoing or imminent drought. As mentioned in section 2.1, variables or proxy values that can be used to measure and/or express drought exposure (for example, GDP, square kilometers of agricultural area; see section 2.1.2) and vulnerability (for example, population below poverty line, GDP per capita; see section 2.1.3) can be used as an alternative approach when detailed information on exposure and vulnerability is not available.

3c. Detailed assessment of future drought hazard: If the time horizon has been identified as long-term (for example, the next 50–100 years), then a more detailed assessment of the indices identified in the inception phase (figure 4.1, step 2b) is required in this step, and how these are projected to develop as a function of changing climate and, in particular, changing climatic variability. A detailed analysis of projected future climate variability will be required, possibly considering the results of one, or several, regional climate model(s). In areas where climatic teleconnections are strong (see also figure 4.1, step 2c), a detailed analysis of climate variability and links to global climatic patters is necessary. The characterization of future drought conditions is to be complemented by a *detailed assessment of future exposure and vulnerability* to drought (or alternative approach based on proxy values, see chapter 2), focusing on the sectors identified in the scoping phase and considering expected socioeconomic change in the area of interest.

In most cases, readily-available global or local datasets that were used to support the inception phase will have a relatively coarse spatial and/or temporal scale, or lack the variables required to compute specific drought indices related to (agro-) hydrological drought. Commonly surface water– groundwater interactions are very important for drought assessments, and these typically will not have a sufficient level of detail in these coarse datasets to support establishing drought indices related to these processes. These indices normally require sufficient spatial resolution and period of record of hydrological variables such as soil moisture, discharge, and groundwater levels (> 30 years).

If enough data are not available, a (geo)hydrological model can help simulate these variables. However, models that are available should be used with care because not every model is suited for this purpose. For example, a model that has been developed to simulate flooding will generally not be suitable for drought assessments (Trambauer et al. 2013). As a result, a detailed drought hazard assessment may require setting up (or using) a (geo)hydrological model that sufficiently represents the processes that are important for characterizing droughts in the area of interest (for example, surface water–groundwater interactions).

It may also be necessary to collect local data to validate/calibrate these (geo)hydrological models. We recommend consulting the online catalogue of drought hazard and risk modeling tools and resources (Deltares 2018a; www.droughtcatalogue.com). The online catalogue provides an overview of modelling software and a short description, reference literature, and the relevant URLs for each software type (see orange boxes E, F, G, and H in figure 4.1).

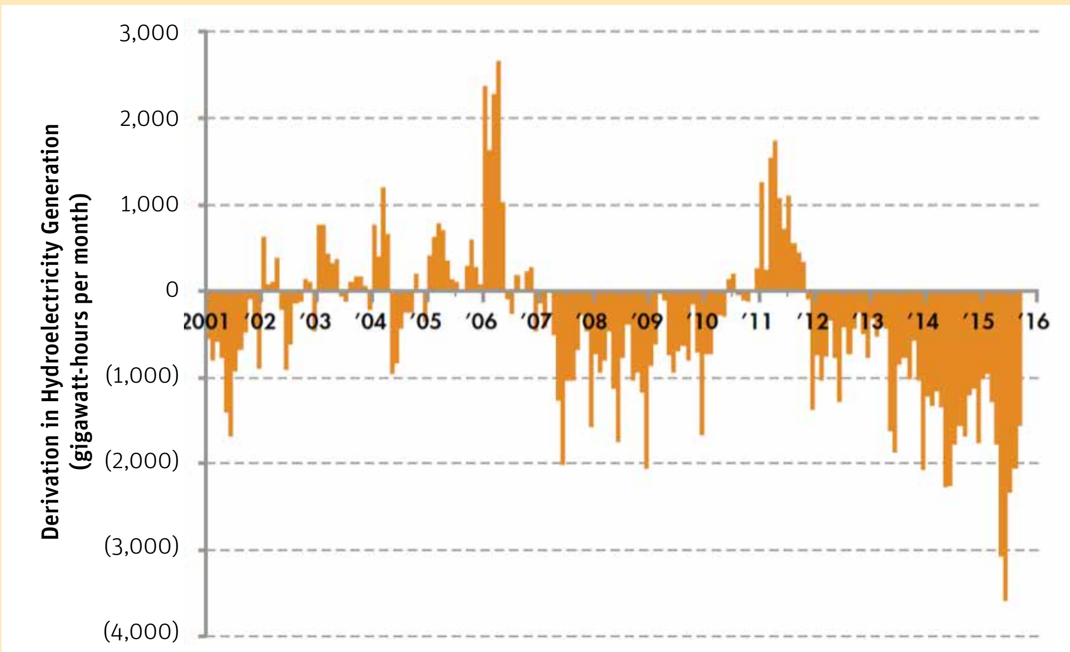
3d. Overall assessment of drought risk: In all three cases, to develop a full assessment of drought risk, drought hazard information needs to be combined with exposure and vulnerability data (or alternative approach based on proxy values; see chapter 2). Historic drought impacts should be quantified from (local) information on actual losses per sector and user group. Box 4.1 provides an example of the impacts of the 2012–15 California drought on hydropower. Several online platforms provide pre-calculated drought impact and risk indices, based on a combination of hazard, exposure, and vulnerability information. We recommend consulting the online catalogue of drought hazard and risk modeling tools and resources (Deltares 2018a; www.droughtcatalogue.com).

BOX 4.1 Good Practice Example: Impacts of California's Drought on Hydropower

The 2011–15 period is known as one of the worst droughts in the history of California. Gleick (2016) analyzed the impacts of this drought on hydroelectricity generation. In this study, Gleick shows that for the 2015 water year overall (the "water year" in California runs from October 1 to September 30 of the following year), hydropower production was especially low, providing less than 7 percent of total electricity generated in state, down from an average of 18 percent (see figure B4.1.1). The reductions in hydropower production were compensated for primarily by increasing production from natural gas–fired thermal power stations, increasing purchases from out-of-state sources, and expanding wind and solar generation.

The drought led to a direct increase in electricity costs to California, since hydropower is considerably cheaper than other forms of electricity. The study estimated that the total reduction in hydroelectricity generation during the 2012–15 drought increased statewide electricity costs by approximately US$2.0 billion.

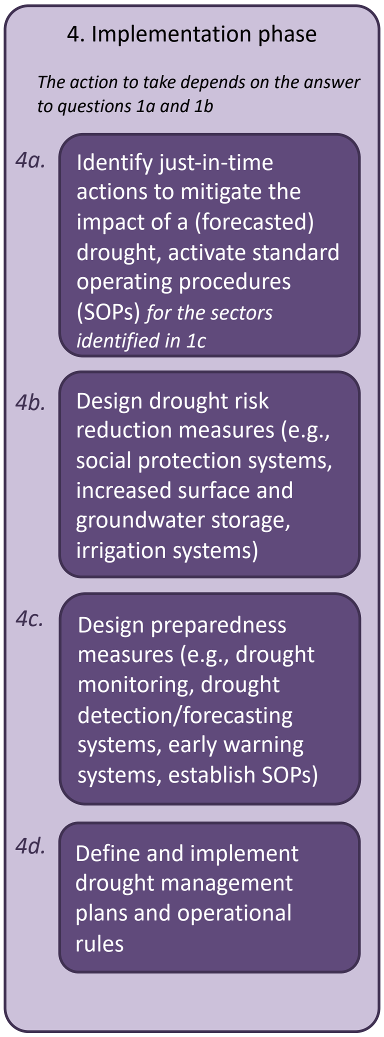
FIGURE B4.1.1 Deviations in Hydroelectricity Generation in Gigawatt-Hours per Month, 2001 through September 2015



Source: Gleick 2016.

4.4 Implementation phase

FIGURE 4.5 Phase 4: Implementation Phase



The fourth and final phase of the drought assessment is the implementation phase (figure 4.5). In this phase, actions that are most appropriate to solve the problem at hand are identified. The actions to be taken and implemented in this phase are largely guided by Principle 4. As with the detailed assessment phase, the actions that are established will be conditioned largely by the time horizon of the study, as identified in the inception phase (see 1e in the workflow diagram of figure 4.1). If the preliminary assessment in the inception phase is identified as sufficient to meet the objective of the assessment, this phase will be undertaken immediately following the inception phase. Otherwise, this phase will be preceded by the assessment phase.

4a. Identify actions to mitigate the impact of ongoing or forecasted drought: If the time horizon has been identified as short term, with a focus on ongoing droughts that may already prevail in the area of interested or that are imminent, then actions identified will necessarily focus on mitigating the impacts identified in the inception and/or assessment phase to the identified sectors. Impacts to be mitigated will depend largely on drought conditions that prevail in the area at the time of study, or drought conditions that are imminent as informed by a (seasonal) drought forecast. These actions may include putting into action standard operating procedures. If a drought management plan has been developed and is available, then this should include guidance on the actions to be taken. The outcomes of the (preliminary) assessment of the ongoing or imminent drought will inform which actions from the drought management plan are opportune to mitigate the impact of the drought.

4b. Design drought risk reduction measures: If the time horizon has been identified to be either short term or long term, the focus of the implementation phase will be to design actions and measures to reduce the impact of droughts in the area of interest. Some measures reduce drought risk for the limited period of one or some specific drought events (short term), such as social protection systems at the community level, water transport from other areas, or periodic water use restrictions. Other measures reduce drought risk in the short term while also increasing the overall resilience of an area to droughts (long term). Such measures are, for instance, increased surface and groundwater storage, the development of irrigation systems, operational rules for managing reservoirs during water shortages, and demand management strategies.

4c. Design drought preparedness measures: Additional measures to be considered that can help reduce drought risk include the establishing of drought preparedness measures. These include the development of drought monitoring, as well as drought forecasting and early warning. The technical report (Deltares 2018b) provides review and recommendations on drought forecasting systems. These will allow early detection of the onset of drought, even forecasting imminent droughts. When establishing such systems, a crucial step is to establish different warning levels and thresholds that are used to trigger the actions identified to mitigate (imminent) drought impacts. Another, or subsequent, measure to increase drought preparedness is the development of standard operating procedures. Box 4.2 presents an example of a FEWS-NET drought monitoring system for Afghanistan.

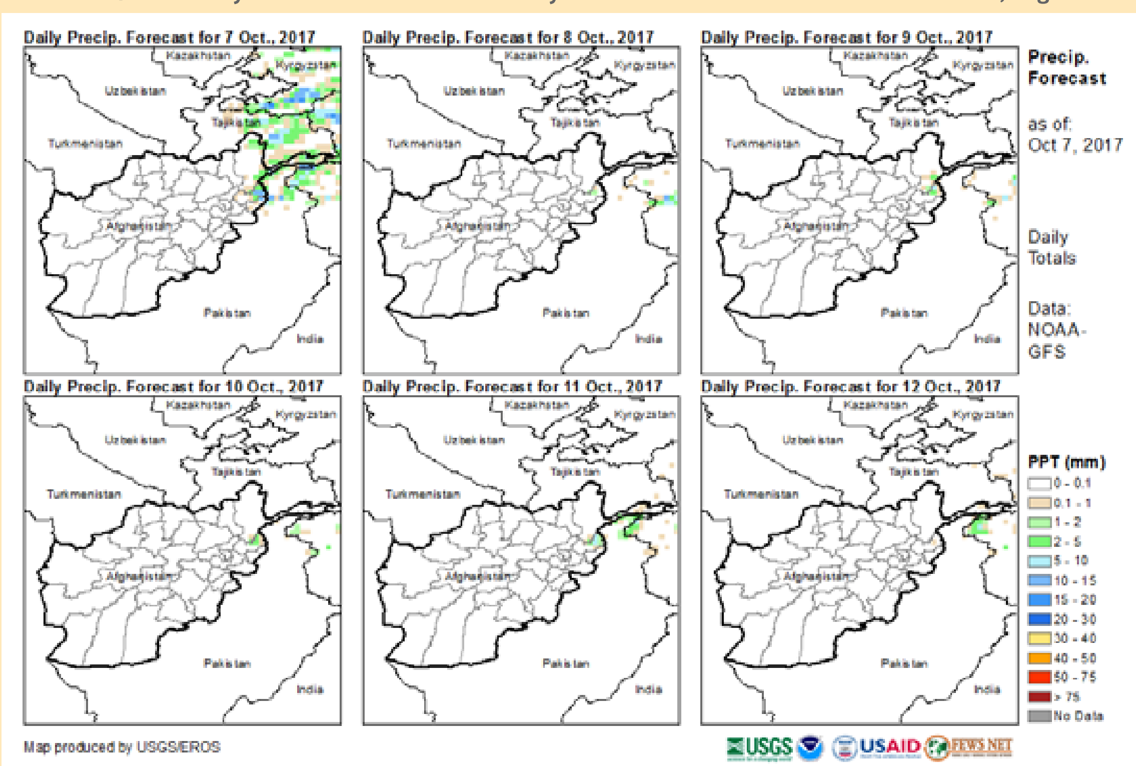
4d. Define and implement ***long-term*** *drought management plans and policies:* The actions (4a through 4c) designed either to be taken in response to a drought warning or identified to reduce current and/or future drought risk should be incorporated into a drought management plan. This plan should be developed in close consultation with the identified sectors, laying down rules on the operation of key water infrastructure and priorities in the allocation of water resources when water is in short supply, as well as longer-term drought reduction measures. Detailed guidance on the development of drought management plans can be found in the references provided in the introduction to this document (EC, MEDA Water, and MEDROPLAN 2007; GWP CEE 2015; Wilhite, Sivakumar, and Puwarty 2014), the process for creating a national drought management policy should begin with the establishment of a national commission to oversee and facilitate policy development. The purpose of this commission is to supervise and coordinate the policy development process and to be the authority responsible for the implementation of the policy at all levels of government (WMO and GWP 2014).

BOX 4.2 Good Practice Example: FEWS-NET Drought Monitoring System for Afghanistan

Despite records of frequent and devastating drought events and existing disaster risk management instruments, Afghanistan seriously lacks necessary infrastructure, resources, and well-developed drought preparedness and mitigation plans for the country. Only recently, the United States Agency for International Development (USAID) extended the coverage of the Famine Early Warning Systems Network (FEWS-NET) to Central Asian countries, including Afghanistan. Currently available FEWS-NET data products for Afghanistan include several drought-related products, such as the 6-day precipitation forecast (based on the National Oceanic and Atmospheric Administration (NOAA)'s Global Forecast System, GFS; see figure B4.2.1), dekadal (10-day) anomaly of precipitation, monthly anomaly of evapotranspiration, daily anomaly of snow depth, the Normalized Difference Vegetation Index (NDVI, based on MODIS), and so on. These data products have not yet been operationally used for decision making and providing early drought warnings in the country.

The rainfall product is the only forecast product currently available. It provides a daily rainfall forecast for up to the 6-day lead time (forecast horizon), and is updated on a daily basis. All other products are monitoring products, which are available up to the previous day, decade, month, or season (depending on the variable of interest), except for the agriculture products. For agriculture products, monitoring is based on 1993 and 2001 as there is little recent information available. Conventionally used drought indices, such as the Standardized Precipitation Index (SPI) and agricultural drought indices related to soil water are not available for Afghanistan yet. Currently these products are available only for Africa.

FIGURE B4.2.1 6-Day Rainfall Forecasts Currently Available from FEWS-NET: Central Asia, Afghanistan



Source: FEWS-NET: Central Asia, Afghanistan, http://fews.net/central-asia/afghanistan.

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Ethiopian village during the instalation of a drinking water pipeline. Photo: atlantic-kid.

5. Examples of Application

This chapter provides three examples of ways to apply the steps described in the implementation guide (chapter 4). The examples correspond to the different types of actions and measures described in the implementation phase (phase 4) of the implementation guide and consist of: (i) the placement of refugee camps in Uganda; (ii) the establishment of a social protection system in Ethiopia; and (iii) the drought-proof design of a hydropower dam in Colombia.

The described examples are relevant for the countries where they are situated. They are based on actual information about drought hazard, exposure, and vulnerability that was available to the authors of the guidance document (the model inventory report, Deltares 2018a and the comparative model assessment report, Deltares 2018b). However, no full risk assessments were available for these specific cases and no actual implementation plans could be consulted. The main purpose of the examples is to explain in a logical order how to apply the Guidelines to different drought application cases, with different environmental and socioeconomic realities.

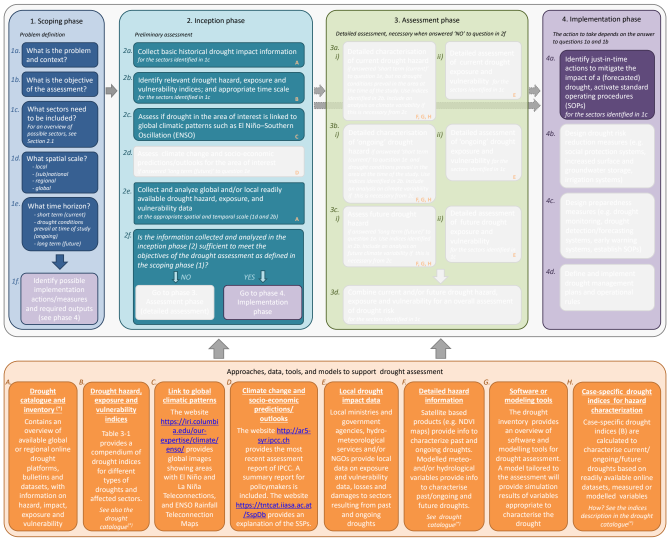
5.1 Placement of refugee camps in Uganda

This chapter presents an application of the workflow to a hypothetical example:

> *The Government of Uganda, a country that faces water shortages, would like to make a well-informed decision about where to accommodate newly arrived refugees preventing/limiting potential water gaps due to increased water demand.*

Figure 5.1 shows the workflow of figure 4.1; the steps that are not needed in this example are grayed out.

FIGURE 5.1 Workflow Steps that Apply to Hypothetical Refugee Camp Placement



* www.droughtcatalogue.com

Phase 1: Scoping phase

A decision maker contextualizes and frames the problem in consultation with relevant identified stakeholders and the intended recipient audience of the drought risk assessment by answering the following questions:

1a. What is the problem and context?

The Nakivale refugee settlement area in the Isingiro district in Southwestern Uganda (see figure 5.2) was selected as potential location for the accommodation of around 10,000 newly arrived refugees in response to a potential influx from the Democratic Republic of Congo. Water is a topic of extreme concern in the settlement since it is essential not only for supporting primary needs but also for ensuring livelihood through agriculture and livestock practices. Water standards have not yet been met in some settlement villages, which has led to the need to transport water by truck over the past five years. An increase in the population of the settlement can exacerbate the current water scarcity condition.

Currently, only one refugee settlement (the Nakivale settlement) is present in the catchment, specifically in the Isingiro district. This settlement hosts around 90,872 people from 12 different nations including Burundi, the Democratic Republic of Congo, Eritrea, Ethiopia, Rwanda, Somalia, South Sudan, and Sudan. During the Burundian crisis in 2015, the population of the settlement greatly increased (REACH 2018). The host community comprises 30 percent of the total population (Uganda Bureau of Statistics 2017).

An improved understanding of the drought risk in the Isingiro district and the River Rwizi catchment, in which the district is located, will support the decision makers in identifying suitable locations for the accommodation of newly arrived refugees and associated investment to prevent or limit potential water gaps.

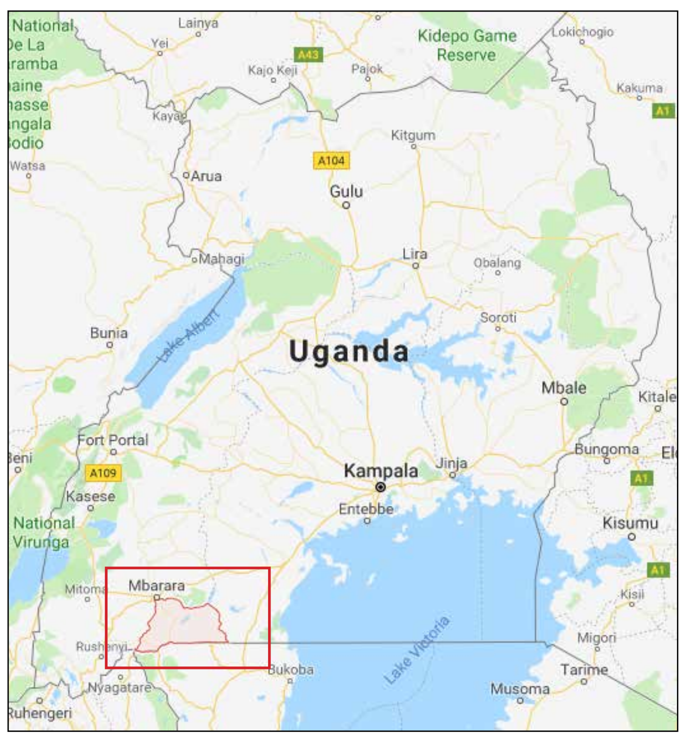
1b. What is the objective of the assessment?

The objective of the assessment is to determine the area in the Rwizi catchment with the lowest drought risk for the accommodation of newly arrived refugees.

1c. What sectors need to be included (are affected)?

Affected sectors are domestic water use (refugees and current inhabitants), agriculture, and livestock.

FIGURE 5.2 Map of Uganda



Source: Google Maps, October 20, 2018.

1d. What is the spatial scale of the problem?

The River Rwizi catchment covers an area of about 8,000 square kilometers in Southwestern Uganda. It comprises 10 districts, among which Isingiro, Mbarara, Rakai, and Sheema extend deep into the catchment area. Because severe water shortage has recently been reported in some towns and villages within the catchment, the Ugandan government and the UN Refugee Agency (UNHCR) are interested in having a better overview of the water situation in the area in order to support the decision makers in identifying suitable sites for newly arrived refugees.

1e. What is the time horizon?

The time horizon is short term (1 month), with an outlook to more detailed assessment.

1f. Identify possible implementation actions and/or measures and required outputs

The required output of the risk assessment is to detect spatial differences in drought hazard and the differences in exposure and vulnerability of the refugee and host community populations and the agriculture sector. Such information can help to accommodate newly arrived refugees.

Outputs to support this action are maps (or tables) with information of spatial differences of (historical) drought hazard, exposure, and vulnerability indices.

Phase 2: Inception phase

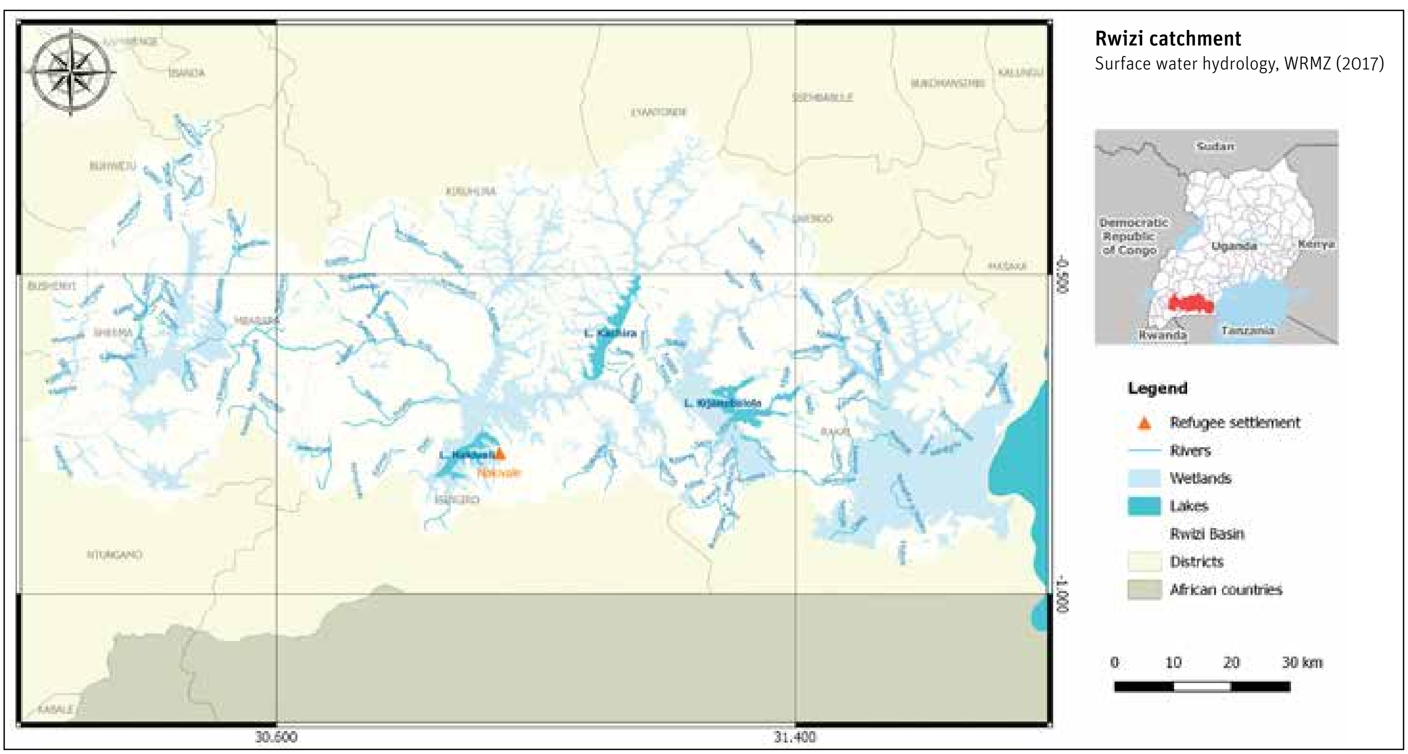
Preliminary assessment to be carried out by a technical team of water resources and drought risk professionals to have a better understanding of the problem.

A preliminary assessment for the Rwizi catchment, Southwestern Uganda, following the steps defined in the inception phase for the sectors identified in the scoping phase (phase 1) is hereby presented.

2a. Collect basic historical drought impact information for the sectors.

A literature review provided the following basic knowledge of the historic drought impact in the Rwizi catchment. In the last 10 years, severe water shortage has been reported in the whole catchment with serious consequences for commercial and agriculture activities especially in Mbarara and Isingiro. Figure 5.3 presents the Rwizi catchment and its surface water bodies as mapped in 2017.

FIGURE 5.3 Rwizi Catchment, 2017



Source: Matano 2018.

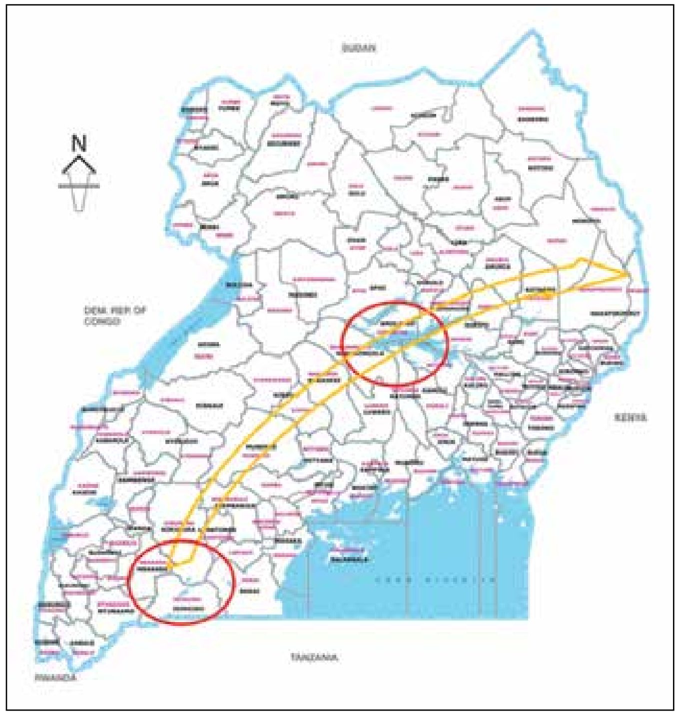
Part of the catchment lies in the cattle corridor (Nimusiima et al. 2013; see figure 5.4) and presents an ecosystem vulnerable to drought (District Planning Unit 2011). The cattle corridor has many semi-arid characteristics, including: (i) high rainfall variability; (ii) periodic late onset rains/droughts; and (iii) historical reliance on mobile pastoralism as an important strategy to cope with resource variability.

Wetlands and forests that used to hold water and release it slowly to the rivers have suffered encroachment (New Vision 2013). The River Rwizi, located in the north part of the district, is drying out in the dry season. This is one of the main water sources for Mbarara and the upstream districts. Lake Nakivale, the main water source for the Nakivale refugee settlement, is shrinking in size probably as a result of silting from soils eroded from the neighboring hills.

In 2016, the population in Isingiro, Mbarara, and Rakai experienced a protracted water crisis that led to severe famine and crop damage (Kushaba 2016). The water shortage is seen as one of the limiting factors for commercial economic activities and industrial growth in these districts. This is especially true for the agriculture sector, which is one of the main economic activities in the catchment.

The water shortages experienced in the past were probably driven by both drought and poor catchment management. However, how climate variations have impacted water availability with respect to inadequate water resource management is not well understood. An improved understanding is needed in order to efficiently and effectively allocate investments related to the refugee camp.

FIGURE 5.4 Cattle Corridor



Sources: Nimusiima et al. 2013 and McGahey and Visser. 2015.

Note: The cattle corridor is indicated with a yellow arrow; the Isingiro district is located in the lower red circle.

2b. Identify relevant drought hazard, exposure, and vulnerability indices for the sectors. Population and agriculture, see section 2.1.1 (hazard indices in table 3.1), section 2.1.2 (exposure indices), and section 2.1.3 (vulnerability indices). The drought catalogue (www.droughtcatalogue.com) provides descriptions and other relevant information for many drought indices. When analyzing drought hazard, it is preferable to combine multiple relevant drought indices and analyze differences occurring between the observed drought patterns.

The population and agriculture are mainly dependent on rainfall and water from Lake Nakivale. Hence, the relevant drought indices are the Standardized Precipitation Index (SPI), the Standardized Precipitation and Evapotranspiration Index (SPEI), and the Standardized Streamflow Index (SSFI). In addition, because the main land use and economic activity is agriculture, an agricultural drought index—such as the Agricultural Stress Index (ASI)—should be taken into account. In this area, the cause of the water shortage is probably a combination of droughts, increasing water demand, and mismanagement of water resources. Hence, including an index such as the Water Stress Index (WSI) or the WaterGAP index could provide important information (see also box 3.1).

For exposure, indices such as percentage areas of agricultural land use, water demand per sector, and population density can be gathered. Vulnerability data available could be GDP per capita for the different communities, the (extreme) poverty index, or the percentage of people below the age of 16 for the different communities.

2c. Assess whether climate variability (such as ENSO) needs to be included.

The report by Nimusiima et al. (2013) about the cattle corridor provides information about climate variability. However, no ENSO patterns are reported for the area.

2d. Assess whether climate change and socioeconomic changes need to be accounted for—Yes if answered "long term (future)" to question 1e.

Not relevant.

2e. Collect and analyze global and/or local readily available drought hazard, exposure, and vulnerability data at the appropriate spatial and temporal scale (1d).

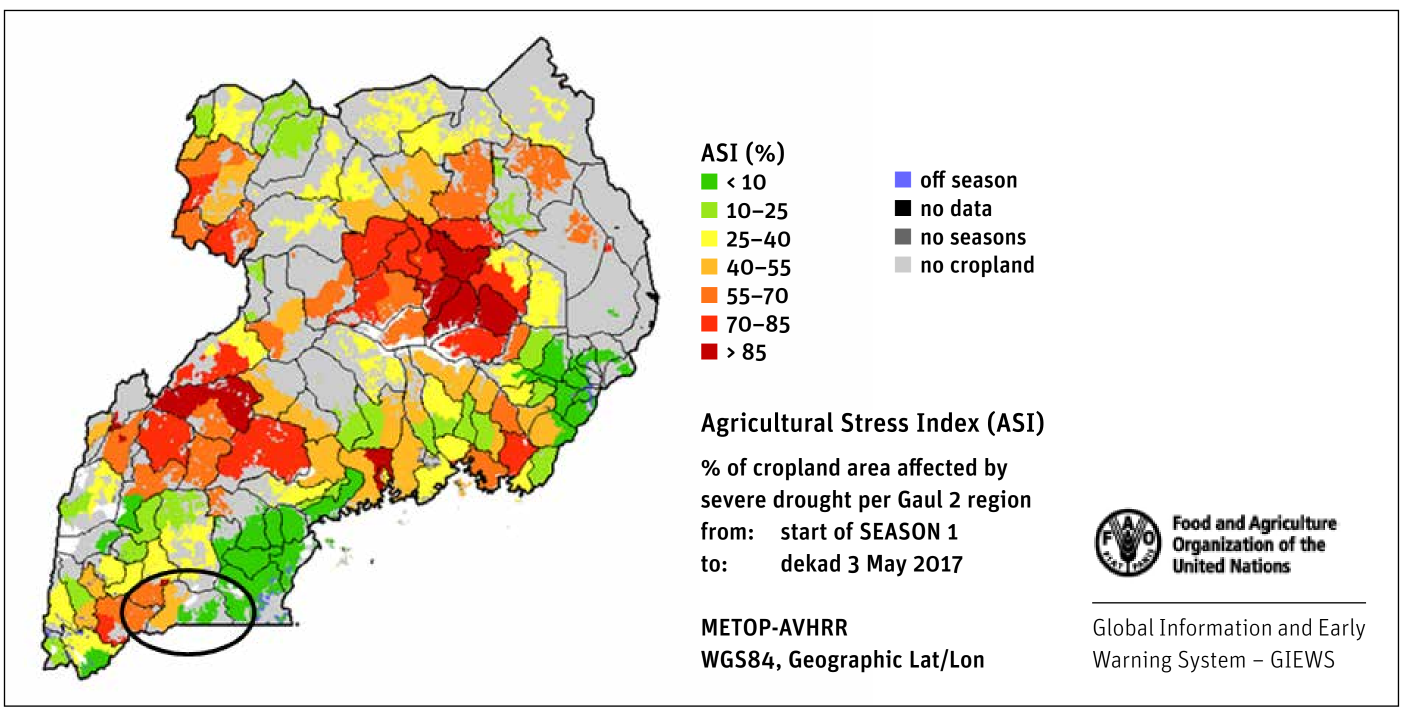
Few data from online platforms were available at the appropriate scale. Only the online Food and Agricultural Organization (FAO) platform Global Information and Early Warning System on Food and Agriculture (GIEWS) provides enough detail to see some spatial variation of the Agricultural Stress Index (ASI) within the Isingiro district (see figure 5.5). A difference in ASI between the eastern and the western part of the Isingiro district can be observed; the western part of the district shows a high percentage of areas affected by severe drought, while this is low in the eastern part. Within the Rwizi catchment, the following districts show relatively limited agricultural water stress during drought periods: Buhweju, Sheema, Bushenyi (the northern part), Isingiro (the eastern part), Kiruhura (the northern part), Lwengo, Lyantonde, and Rakai.

A literature review provided qualitative information of the exposure to drought and vulnerability in the area. The refugee community of Nakivale is spread over various livelihoods (figure 5.6) and relies heavily on rainwater and water extraction from the homonym lake to sustain the population's domestic water needs, agriculture activities, and livestock practices. The latter are the community's main means of subsistence. The main economic activities in the catchment are subsistence and commercial crop agriculture, livestock rearing, and fish farming. This is also represented in the water demand for these sectors (figure 5.7). The population and GDP per capita in the Isingiro district are somewhat above average compared with other districts in the Rwizi basin (figure 5.8 and table 5.1).

Summarized, the review provided the following relevant exposure information:

- The water demand is and remains (according to the 2035 projection) relatively low in the following districts: Buhweju, Bushenyi, Lwengo, Lyatonde, and Ntungamo.
- The current and future population is relatively low in the following districts: Buhweju, Bushenyi, Kiruhura, Lyantonde, and Ntungamo.

FIGURE 5.5 Agricultural Stress Index for the Districts of Uganda



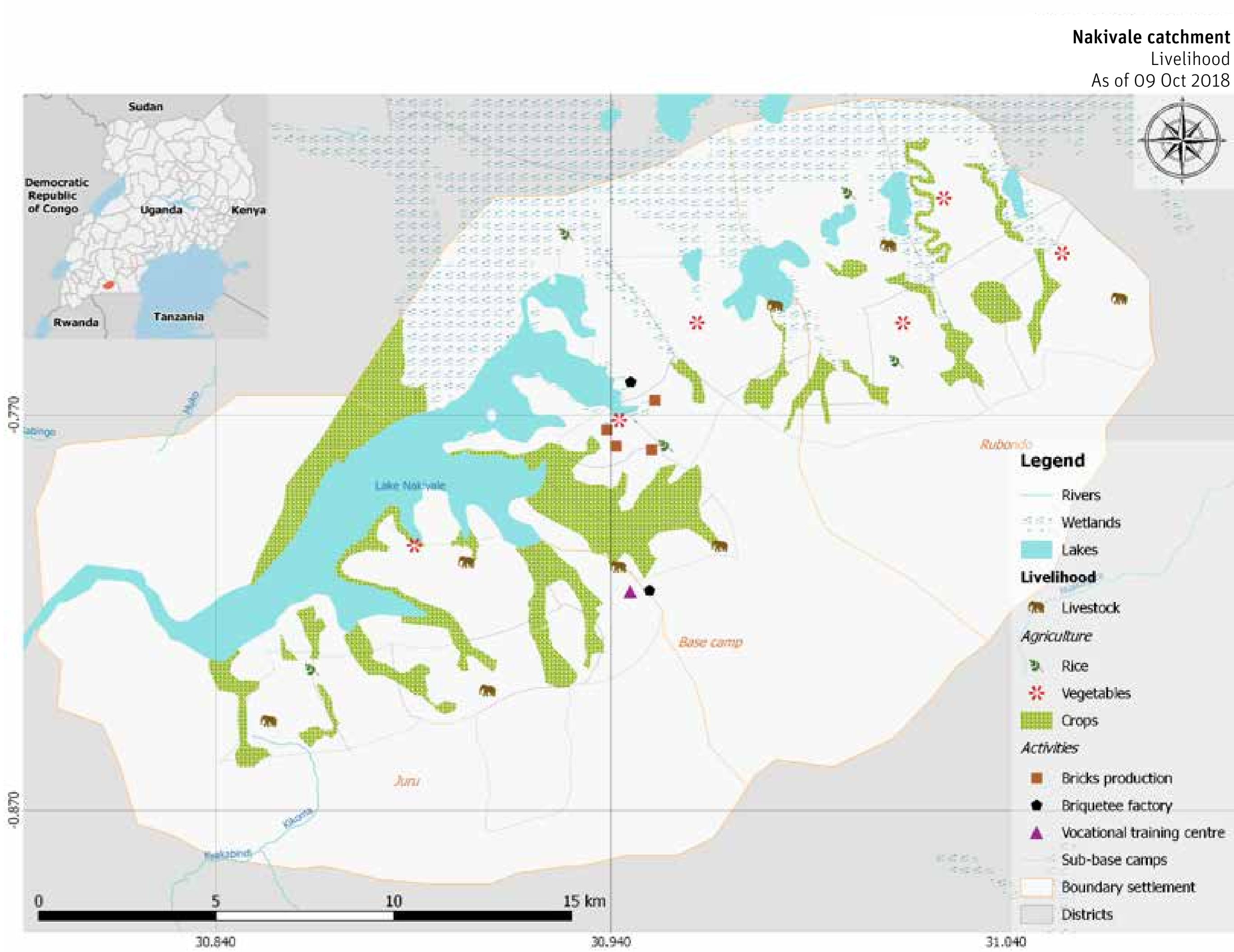
Source: FAO platform Global Information and Early Warning System on Food and Agriculture (GIEWS), http://www.fao.org/giews/earthobservation/country/.

Note: The Isingiro district is located in the black circle.

Summarized, the review provided the following relevant vulnerability information:

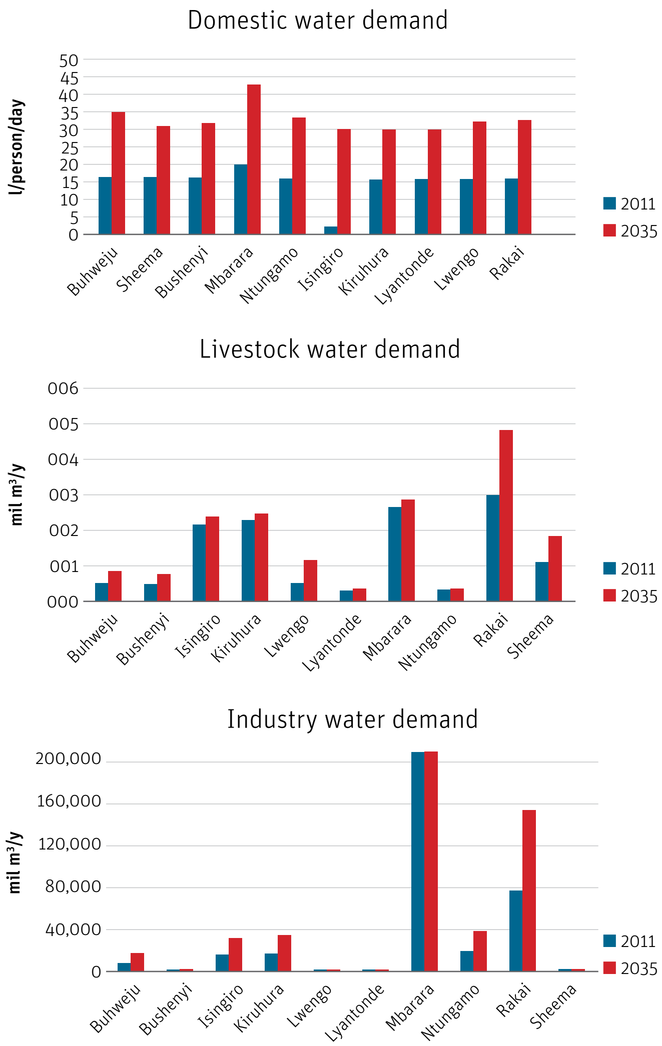
- The vulnerability indicator that is available is GDP per capita. Districts with relatively high GDP per capita (above US$500) in the Rwizi catchment, which are less vulnerable to drought, are Mbarara, Lyantonde, and Isingiro.

FIGURE 5.6 Livelihoods in the Nakivale Refugee Settlement



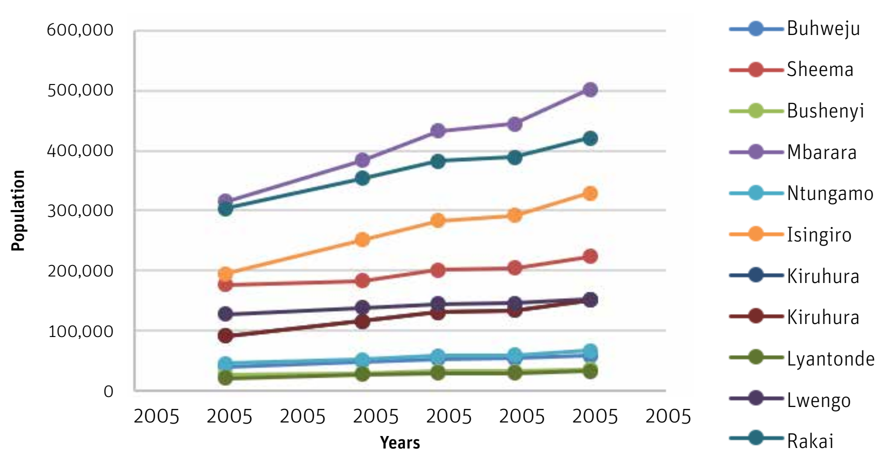
Source: Matano 2018.

FIGURE 5.7 Water Demand of the Main Sectors (Domestic, Agriculture, Livestock, Fisheries, and Industry) in the Districts of the Rwizi Basin, 2015 and 2035 (Projected)



Data source: Matano 2018.

FIGURE 5.8 Population Development in the Districts of the Rwizi Basin, 2005 to 2035 (Projected)



Data source: Matano 2018.

TABLE 5.1. GDP per Capita for the Districts in the Analysis

District	GDP per capita (US$)
Buhweju	241
Sheema	258
Bushenyi	457
Mbarara	1,013
Ntungamo	463
Isingiro	568
Kiruhura	289
Lyantonde	614
Lwengo	455
Rakai	325

Data source: Matano 2018.

2f. Decide on the next step: Does the information collected and analyzed in the inception phase (2) sufficiently meet the objectives of the drought assessment as defined in the scoping phase (1)?

Does the existing information provide accurate estimates of drought hazard, exposure, and vulnerability for your analysis regarding resolution and data input? If not, what kind of additional information is needed?

Yes, within the given time frame the available information is sufficient for a preliminary analysis to detect areas with relatively low drought risk in the Rwizi catchment for the accommodation of newly arrived refugees.

→ **Go to** Phase 4: Implementation phase

Phase 3: Assessment phase

Detailed assessment to be carried out by a technical team of water resources and drought risk professionals.

Phase 3 is not relevant if the answer to step 2f is "Yes."

Phase 4: Implementation phase

The action to take and/or measure(s) to implement depend on the answer to question 1f and the results from step 2 (and 3). The implementation phase needs to be carried out by the decision maker in close collaboration with technical experts and involved stakeholders.

4a. Identify just-in-time actions to mitigate the impact of a (forecasted) drought and/or activate standard operating procedures (SOPs) for the sectors identified in 1c.

In the case of this example, quick advice on the placement of newly arriving refugees is the required outcome from the drought risk assessment (just-in-time actions). The areas with relatively low hazard, low exposure, and/or low vulnerability have a relatively low drought risk and can be pointed out as preferred areas to accommodate newly arriving refugees with respect to water availability. Based on the information available from the inception phase, an overview of districts with relatively low hazard, low exposure, and low vulnerability could be listed (table 5.2). This overview points out that the Lyantonde district shows relative low numbers for drought hazard level, for exposure level, and for the level of vulnerability. It should be noted, however, that the Lyantonde district is a relatively small district and exposure data (water demand and population) are not scaled to the surface areas of the districts. Another area with a relatively low drought hazard level and low vulnerability is the eastern part of the Isingiro district. In addition, the Buhweju district and the northern part of the Bushenyi district have relatively low drought hazard levels as well as low exposure levels.

4b. Design short- and/or long-term drought risk reduction measures (for example, social protection systems, increased surface and groundwater storage, irrigation systems).

Not relevant.

Table 5.2 Overview of Districts with Low Drought Hazard, Low Exposure, and Low Vulnerability in the Rwizi Catchment

District	Low hazard (ASI)	Low exposure (water demand)	Low exposure (population)	Low vulnerability (GDP per capita)
Buhweju	x	x	x	n.a.
Sheema	x	n.a.	n.a.	n.a.
Bushenyi	(northern portion)	x	x	n.a.
Mbarara	n.a.	n.a.	n.a.	x
Ntungamo	n.a.	x	x	n.a.
Isingiro	(eastern portion)	n.a.	n.a.	x
Kiruhura	(northern portion)	n.a.	x	n.a.
Lyantonde	x	x	x	x
Lwengo	x	x	n.a.	n.a.
Rakai	x	n.a.	n.a.	n.a.

Note: ASI = Agricultural Stress Index; n.a. = not applicable.

4c. Design preparedness measures (for example, drought monitoring, drought detection/forecasting systems, early warning systems, establish SOPs).

Not relevant.

4d. Define and implement drought management plans and operational rules.

Not relevant.

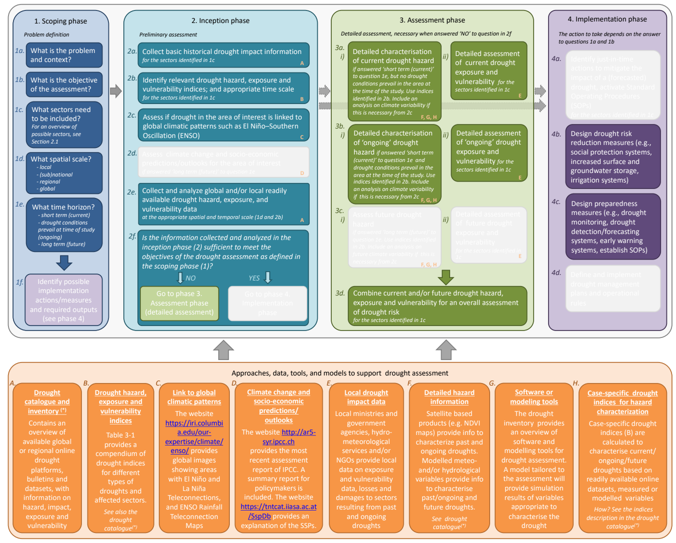
5.2 Establishment of a social protection system in Ethiopia

This section presents an application of the workflow for a hypothetical example:

The Government of Ethiopia, a country that faces occasional extreme droughts, would like to establish a social protection system at the district level to provide financial assistance to affected households during a drought event.

Figure 5.9 shows the workflow of this application; the steps that are not needed in this example are grayed out.

FIGURE 5.9 Workflow Steps that Apply to Hypothetical Social Protection System



* www.droughtcatalogue.com

Phase 1: Scoping phase

A decision maker contextualizes and frames the problem in consultation with relevant identified stakeholders and the intended recipient audience of the drought risk assessment by answering the following questions:

1a. What is the problem and context?

The country faces occasional extreme droughts across large parts of the country; these cause food shortage and famine. The government needs to understand the intensity, timing, and impact of drought for each district in order to estimate how many households require support through social protection and drought response mechanisms.

1b. What is the objective of the assessment?

The objective of the assessment is multifold: (i) to understand the timing, geographical scope, and impact (on food production) of droughts; (ii) to estimate, in a transparent and accurate way (limiting the number of false positives and false negatives), the number of beneficiaries who need food and financial support through the social protection system; (iii) to estimate the total yearly funding necessary for the social protection system; and (iv) to detect and predict extreme droughts to be able to provide focused and timely social protection.

1c. What sectors need to be included (are affected)?

Affected sectors are population and agriculture.

1d. What is the spatial scale of the problem?

The problem needs a district-level, high spatial resolution.

1e. What is the time horizon?

The time horizon is short term (months) with the need for regular updates. Drought conditions prevail at the time of the study.

1f. Identify possible implementation actions and/or measures and required outputs.

The required actions and measures closely relate to the objective of the assessment. In this case the following can be distinguished: (i) design or improve drought early warning system that enables focused and timely protection; (ii) establish standard operating procedures (SOPs) required for social protection in case an extreme drought is predicted or occurring; and (iii) design a social protection system, which is the overall goal of drought risk reduction.

Outputs required to support these measures include:

- Spatial information (preferably maps) of differences in exposure and vulnerability between districts
- An estimation of economic losses in case of drought (per district)
- An operational drought hazard monitoring and forecasting system

Phase 2: Inception phase

Preliminary assessment to be carried out by a technical team of water resources and drought risk professionals to have a better understanding of the problem.

A preliminary assessment for Ethiopia following the steps defined in the inception phase for a variety of sectors is presented in the comparative model assessment report (Deltares 2018b). The following paragraphs summarize the results of that analysis for the sectors identified in the scoping phase (phase 1) for this particular case.

2a. Collect basic historical drought impact information for the following sectors: Population and agriculture.

The following information on drought impact is collected for the population and agriculture sectors:

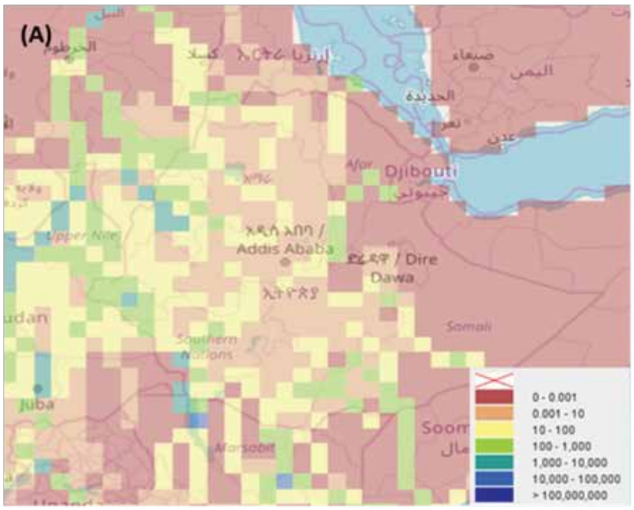
- Maps of drought impact data on the population from the International Water Management Institute (IWMI) data portal (figure 5.10)
- Maps on historical agricultural drought impacts by the online *Aqueduct Water Risk Atlas* (baseline water stress with respect to agriculture, https://www.wri.org/resources/maps/aqueduct-water-risk-atlas) and by the FAO platform Agricultural Stress Index and Precipitation Anomalies (http://www.fao.org/giews/earthobservation/asis/index_1.jsp?lang=en) (figure 5.11)
- Disaster data from the International Disaster Database (EM-DAT) provide information on affected population that results from past droughts (see 2e)

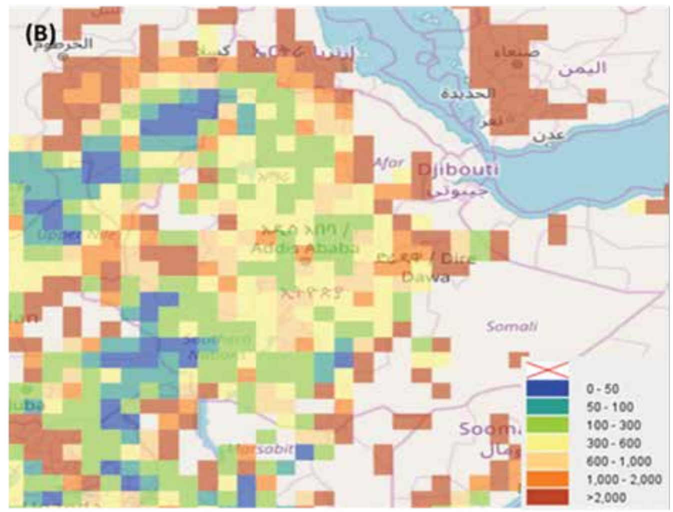
2b. Identify relevant drought hazard, exposure, and vulnerability indices for the sectors: population and agriculture, see section 2.1.1 (hazard indices in table 3.1), section 2.1.2 (exposure indices), and section 2.1.3 (vulnerability indices). The drought catalogue (www.droughtcatalogue.com) provides descriptions and other relevant information for many drought indices. When analyzing drought hazard, it is preferable to combine multiple relevant drought indices and analyze differences occurring between the observed drought patterns.

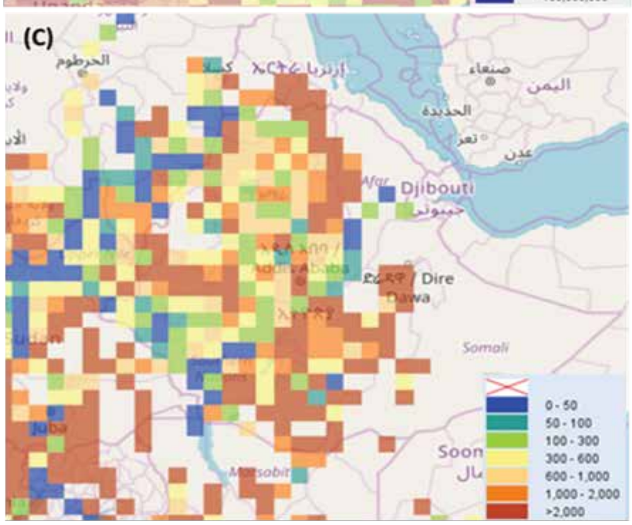
In the context of the establishment of as social protection system for Ethiopia, the following drought risk indices are relevant:

- Drought hazard indices for population comprised of meteorological drought indices and socioeconomic drought indices: the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), the Standardized Streamflow Index (SSFI), the Groundwater Table Declining Trend (GWDT), the Water Stress Index (WSI), and the WaterGAP index
- Drought hazard indices for agriculture comprised of meteorological drought indices and agricultural drought indices: the SPI, SPEI, the Normalized Difference Vegetation Index (NDVI), the Palmer Drought Severity Index (PDSI), and the Soil Moisture Deficit Index (SMDI)
- Exposure indices for the population: population density (distinguishing between rural and urban population) and location, capacity, action radius, and economic value of drinking water utility firms
- Exposure indices for agriculture: agricultural land area,

FIGURE 5.10 Maps Providing Impact (Exposure/Vulnerability) to Population







a. **Per Capita Mean Annual River Discharge (m³ per person)**

b. **Agricultural Water Crowding with Respect to Mean Annual Precipitation (population per m³)**

c. **Agricultural Water Crowding with Respect to Mean Annual River Discharge (population per m³)**

Source: IWMI Water Data Portal, http://www.iwmi.cgiar.org/.

Note: Indices were designed to measure population numbers per one volumetric unit of precipitation falling on croplands. Thus these measure the number of people who share 1 cubic meter of agricultural water in a grid cell. See Sullivan and Meigh 2007. IWMI = International Water Management Institute.

agricultural crop types, potential agricultural yield in volume or monetary value, and livestock density (for example, density of cattle, pigs, and poultry)

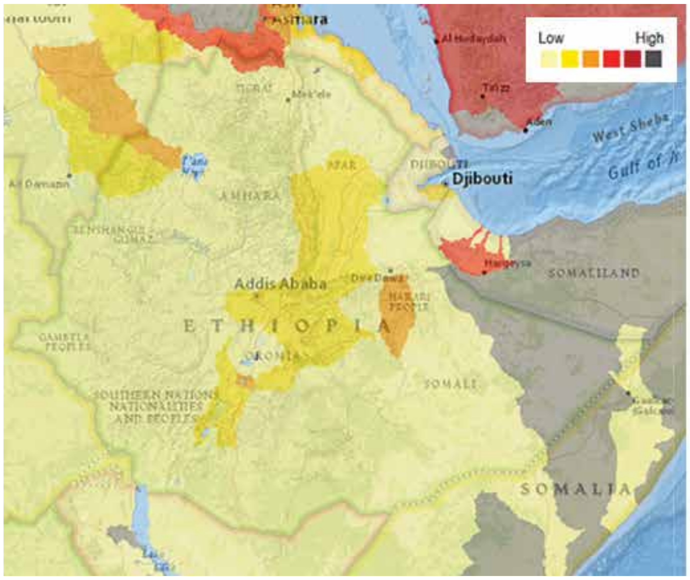
- Vulnerability indices for the population: economic vulnerability proxies (GDP per capita, poverty headcount), social vulnerability proxies (percentage of the population below the poverty line, literacy rate, life expectancy at birth, population ages 15–64), and infrastructural vulnerability proxies (percentage of retained renewable water, road density)
- Vulnerability indices for agriculture: economic vulnerability proxies (GDP per capita in urban areas, agricultural value added) and infrastructural vulnerability proxies (agricultural irrigated land, irrigation efficiencies, road density)

2c. Assess whether climate variability (for example, ENSO) needs to be included

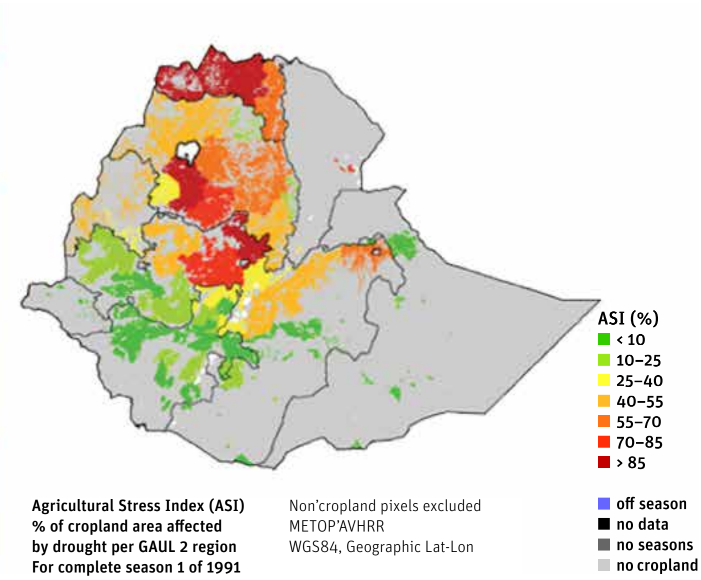
A preliminary assessment indicates that for this region it is important to consider ENSO-related information. The analysis presented in the comparative model assessment report (Deltares 2018b) based on two global models (PCR-GLOBWB and WaterGap) shows that, for a vast majority of the land area, the frequency of drought months significantly decreases during La Niña (LN) years when compared to non–La Niña years (see figure 5.12). Only in the southeastern parts of the country did we find isolated areas having significant increases in drought frequency during La Niña years. For El Niño (EN) years the opposite signal is shown. Most of the land area shows a significant increase in drought frequency, while a few spots indicate areas with a significant decrease.

FIGURE 5.11 Maps on Historical Agricultural Drought Impacts

a. Baseline Water Stress with Respect to Agriculture



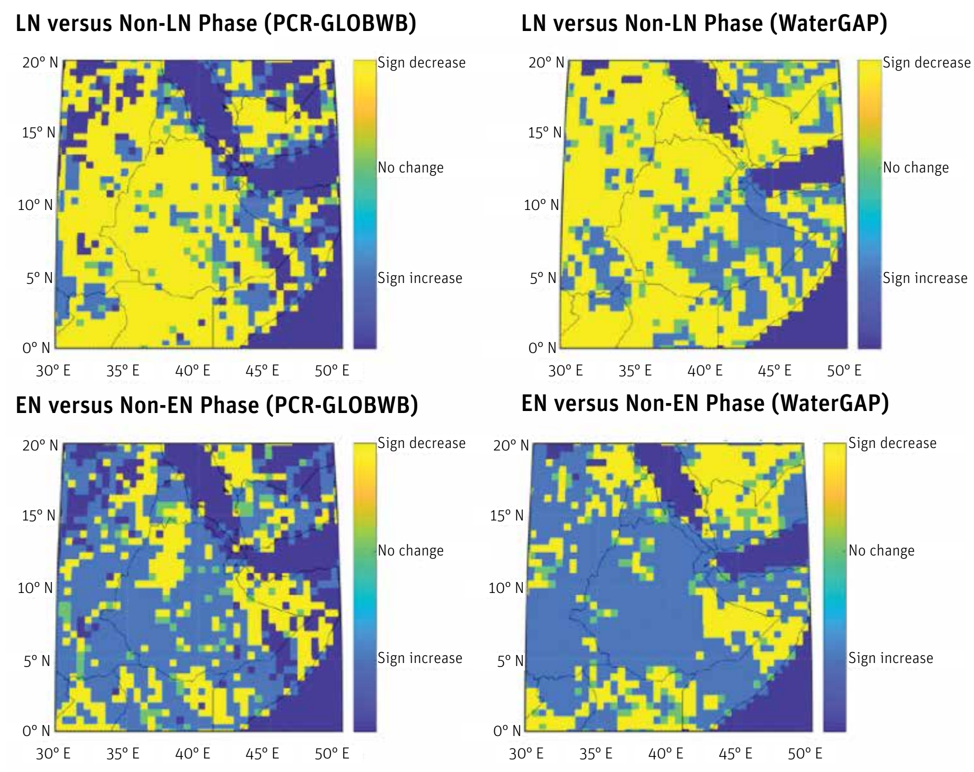
b. Stress Index and Precipitation Anomalies for a Relatively Dry Year



Sources: (a) Aqueduct Water Risk Atlas, https://www.wri.org/resources/maps/aqueduct-water-risk-atlas; (b) FAO Agricultural Stress Index, http://www.fao.org/giews/earthobservation/asis/index_1.jsp?lang=en.

Note: According to the Aqueduct Water Risk Atlas, "baseline water stress measures the ratio of total annual water withdrawals to total available annual renewable supply, accounting for upstream consumptive use. Higher values indicate more competition among users."

FIGURE 5.12 Spatial Distribution of Area with a Significant Increase, Decrease, or No Change in Frequency of Drought Months: El Niño Years Compared with Non–El Niño Years and La Niña Years Compared with Non–La Niña Years



Note: Left: Sub-plots show the results for PCR-GLOBWB; Right: Sub-plots show the results for WaterGAP.

2d. Assess whether climate change and socioeconomic changes need to be accounted for—Yes if answered "long-term (future)" to question 1e.

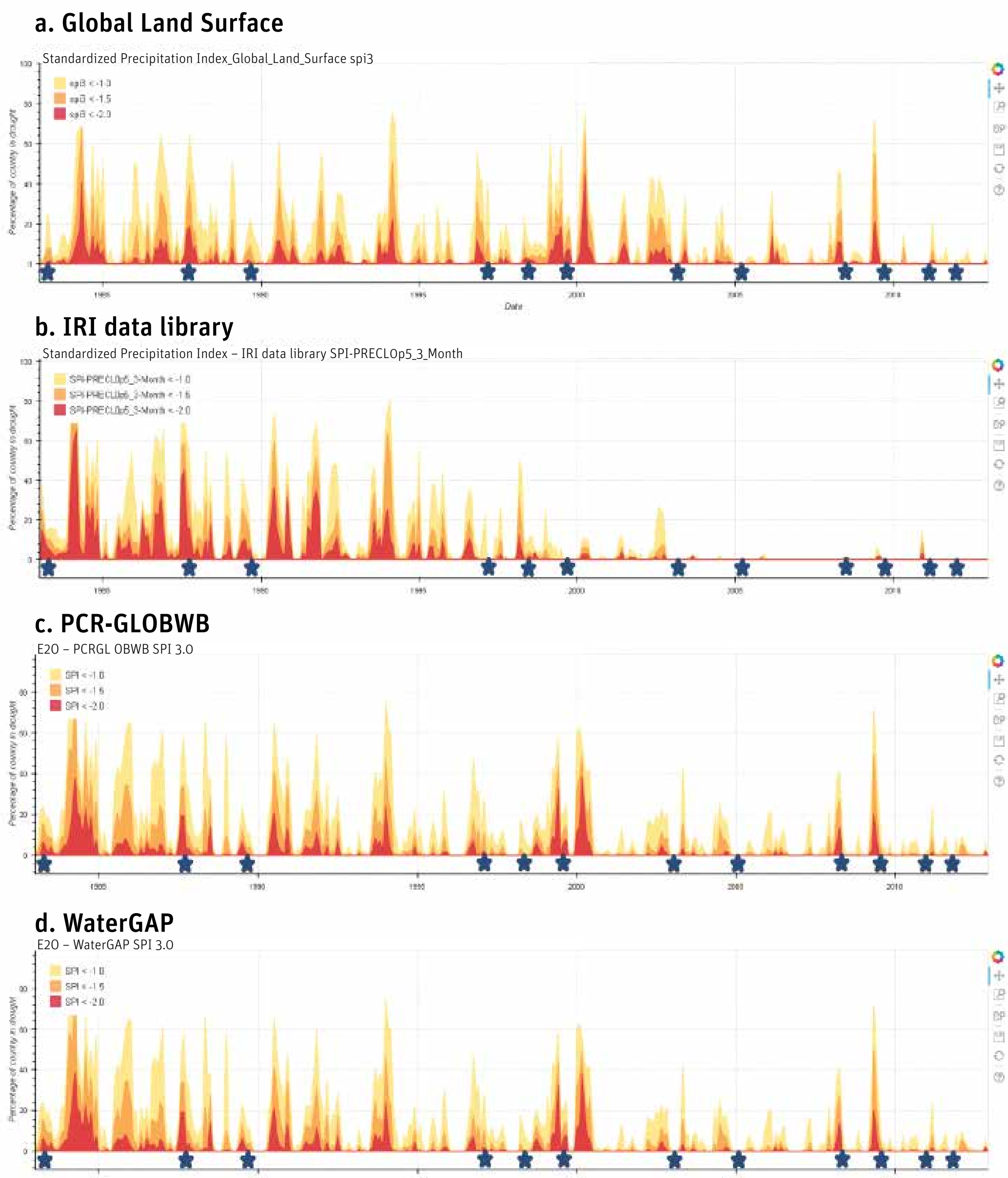
There is no need to account for climate and socioeconomic changes in this instance because the answer to question 1e is "short term (months) with the need for regular updates."

2e. Collect and analyze global and/or local readily available drought hazard, exposure, and vulnerability data at the appropriate spatial and temporal scale (1d).

- Assessment of available drought hazard models

  For the relevant drought hazard indices available from the global datasets (see the comparative model assessment report, Deltares 2018b), graphs were produced for the percentage area of the country experiencing drought conditions at three drought levels: moderately dry (index value below −1), severely dry (index value below −1.5), and extremely dry (index value below −2). In these graphs (an example is presented in figure 5.13), the registered droughts from EM-DAT are plotted as well. Based on the graphs, the overlap of global drought hazard with reported

FIGURE 5.13 Meteorological Drought Index SPI3 based for Ethiopia



Note: Blue stars indicate drought events recorded by EM-DAT.

droughts was assessed as well as the comparability of datasets and indices. For Ethiopia, the reported droughts are not always well predicted by the drought hazard indices from the global datasets. The SPI3 index based on the WaterGAP database shows a relatively good overlap with registered drought events.

- Evaluation of available drought monitoring and forecasting systems

A qualitative assessment of the currently available operational systems that support decision processes on the management of drought conditions in Ethiopia is performed (see details in the comparative model assessment report, Deltares 2018b). A summary of the analysis of the operational system by the National Meteorology Agency (NMA) and Climate Prediction and Applications Centre (ICPAC) is presented in table 5.3.

TABLE 5.3 Characteristics of Seasonal Drought Monitoring and Forecasting Systems Available in Ethiopia

Characteristic	NMA monitoring and forecasting system
Monitoring	Yes
Forecasting	Yes
Region/countries/areas	Ethiopia, Greater Horn of Africa region
Spatial resolution	Various including national and regional scale
Datasets used	Climate and satellite derived climate data (e.g., precipitation estimate) and regional and global climate products including stations (ground) observations, ECMWF products, NOAA GFS, and USGS/FEWS MODIS.
Software and tools used	—
Indices presented	Climate and satellite-derived indices such as SPI and NDVI
Reflective of impacts	Yes
Forecast horizon	Seasonal
Update frequency	Ten-daily and monthly
Accessibility of forecast	Freely accessible
Method of access	Radio, TV, and forecast bulletins through NMA website
Procedure / steps	Final climate products can be downloaded directly.
Resources required	Internet, TV, and radio access
Post-processing	Weather assessment information periodically provided
Hit rate (estimation)	—

Note: NDVI = Normalized Difference Vegetation Index; NMA = National Meteorology Agency; NOAA GFS = National Oceanic and Atmospheric Administration Global Forecast System; SPI = Standardized Precipitation Index; USGS/FEWS MODIS = U.S. Government Service Famine Early Warning Systems Moderate Resolution Imaging Spectroradiometer; — = not available.

- Readily available information from (famine) early warning systems from http://fews.net/east-africa/ethiopia (figure 5.14).
- Readily available early warning and situational awareness information on meteorological and agricultural indices (such as SPI and NDVI) from the Princeton Climate Analytics (PCA) platform (https://platform.princetonclimate.com/PCA_Platform/; figure 5.15).

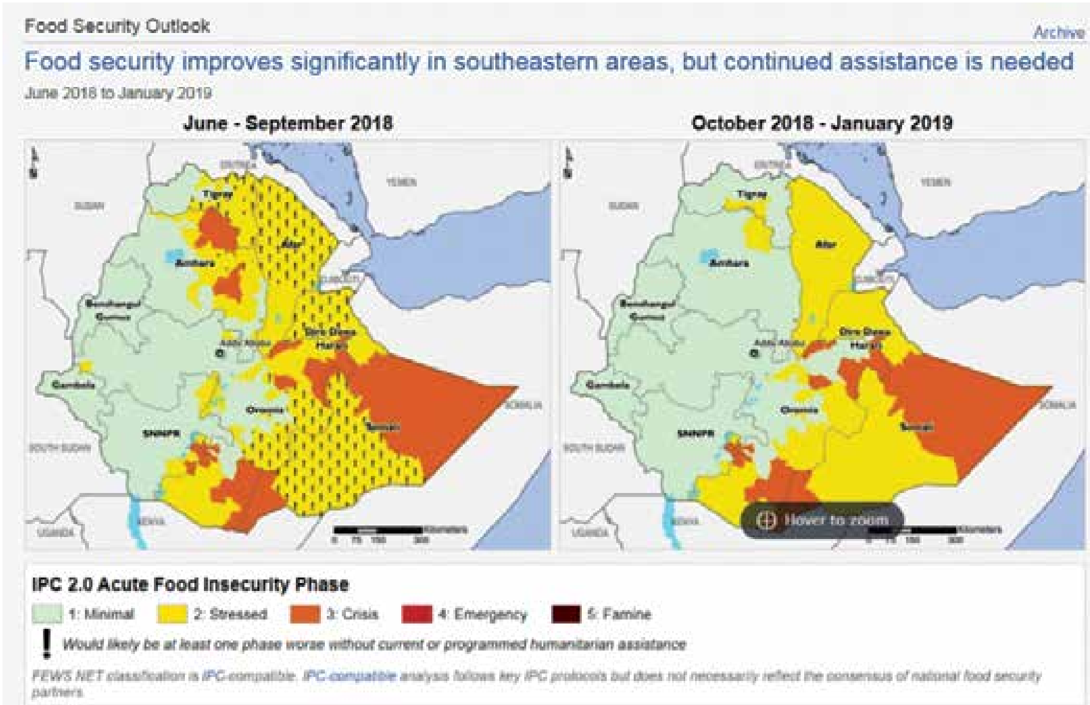
2f. Decide on the next step: Does the information collected and analyzed in the inception phase (2) sufficiently meet the objectives of the drought assessment as defined in the scoping phase (1)?

Does the existing information provide accurate estimates of drought hazard, exposure, and vulnerability for your analysis regarding resolution and data input? If not, what kind of additional information is needed?

No, the available information is sufficient for a preliminary analysis but more detailed local information is needed for the social protection system at the community level.

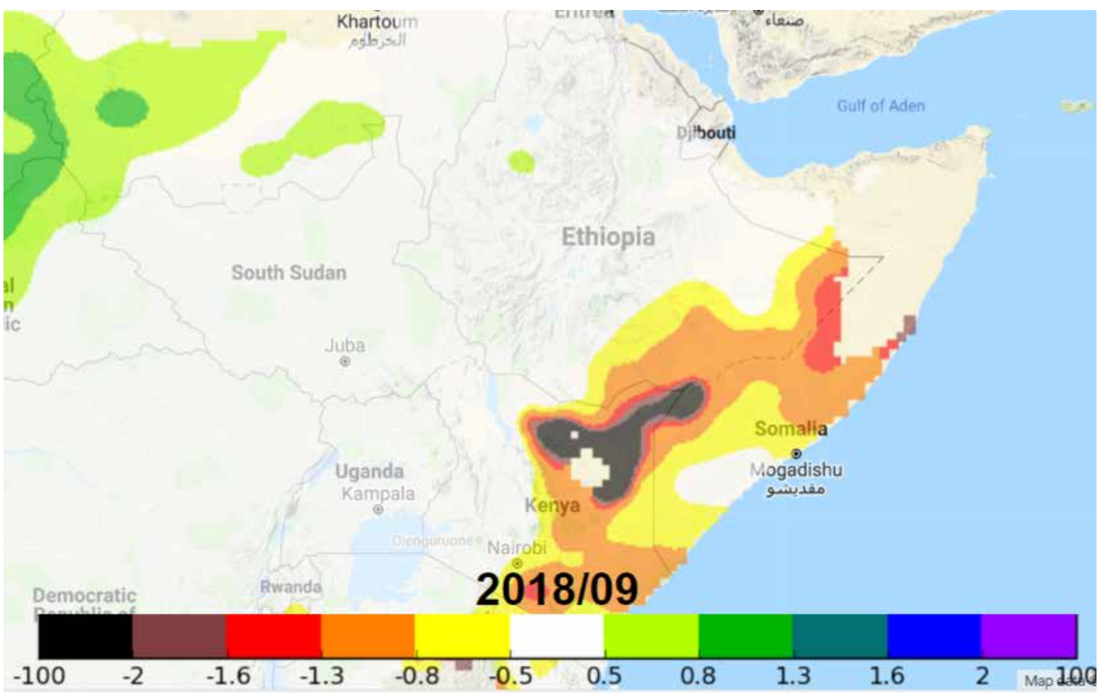
→ **Go to** Phase 3: Assessment phase **(detailed assessment)**

FIGURE 5.14 Food Security Outlook from FEWS-NET



Source: FEWS-NET, June 2018, http://fews.net/east-africa/ethiopia.

FIGURE 5.15 Forecast SPI3 for September 2018 from the African Flood and Drought Monitor



Source: African Flood and Drought Monitor, July 2018, http://stream.princeton.edu/AWCM/WEBPAGE/interface.php.

To be able to provide focused and timely social protection, more detailed information is required at the level of local communities about the exposure and vulnerability of the sectors included (population and agriculture) in the drought-prone areas as well as more detailed drought hazard information.

Additionally, this phase determined that the drought detection and forecasting system should be improved to provide more localized (community-level) information and should provide more specific information about local drought impacts of drought-prone areas.

Phase 3: Assessment phase

Detailed assessment to be carried out by a technical team of water resources and drought risk professionals. This is necessary when the answer to question 2f is "No."

3a. Undertake a detailed historical drought characterization—if answered "short term (current)" to question 1e, but no drought conditions prevail in the area at the time of the study or are not predicted for the near future.

Part i. Detailed characterization of the historical drought hazard

In this phase, drought hazard indices from the relevant sectors population and agriculture (see 2b) are computed or derived for the historical drought for drought-prone areas in Ethiopia at a spatial scale of at least 1 × 1 kilometer grid and a temporal scale with dekadal or monthly time intervals. Ideally, historic drought indices are computed over a long period of time; 30 years of data are generally used. This requires expert technical work, such as, for example, using NDVI data derived from satellite-based images (from 2b) to characterize the spatial distribution and severity of the ongoing agricultural drought. Likewise, local rainfall, evapotranspiration, runoff, and groundwater datasets can be analyzed to compute SPI, SPEI, SSFI, and GWDT indices for detailed characterization of meteorological and hydrological droughts that affect population and agriculture.

During the inception phase (2c), areas were identified with high correlation between El Niño conditions and drought occurrences. Hence, an analysis of climate variability (for example, ENSO indices) should be included in the assessment of the drought history.

Part ii. Detailed characterization of exposure and vulnerability

Perform a detailed analysis of the exposure and vulnerability of the sectors population and agriculture by mapping the exposure and vulnerability indices (see 2b) at the community level. Such information is generally available through national or subnational bureaus of statistics. To characterize changes in exposure and vulnerability over time, data from different periods can be used, if available. Create a good understanding of the areas that are normally impacted by droughts (and how) and the reason for this. This assessment can be enriched with subnational to local data and information of historical impacts on communities or population groups and historical economic drought damage to the sectors (for example, decreased drinking water availability, agricultural yield loss). Detailed agro-hydrological modeling can be combined with historical data series to calculate yield losses for the local communities during periods of drought with varying severity.

3b. Undertake a detailed "ongoing" drought characterization—if answered "short term (current)" to question 1e and drought conditions prevail in the area at the time of the study or are predicted for the near future.

Part i. Detailed characterization of the "ongoing" drought hazard

In this phase drought hazard indices from the relevant sectors population and agriculture (see 2b) are computed or derived for the ongoing drought for drought-prone areas in Ethiopia at detailed scales, a spatial scale of at least 1 × 1 kilometer grid and a temporal scale with dekadal or monthly time intervals. This requires expert technical work, such as, for example, using NDVI data derived from satellite-based images (from 2b) to characterize the spatial distribution and severity of the ongoing agricultural drought. In case a complete overview of water resources and water demands exists for the local communities, the WaterGAP index can be calculated for the ongoing drought period. During the inception phase (2c) areas were identified with high correlation between El Niño conditions and drought occurrences. Hence, an analysis of the relation between ENSO and the ongoing drought should be included in the analysis.

If a characterization of historical drought hazards (see 3b) has been carried out previously, these results can be used as a reference for the ongoing drought hazard.

Part ii. Detailed characterization of "ongoing" exposure and vulnerability

Perform a detailed analysis of the exposure and vulnerability of the sectors population and agriculture by mapping the exposure and vulnerability indices (see 2b) at the community level. Such information is generally available through national or subnational bureaus of statistics. In the case of ongoing drought, it is important that the data used are as recent as possible and/or that they are updated if the available data are outdated. Create a good understanding of the areas that are normally impacted by droughts (and how) and the reason for this. This assessment can be enriched with subnational to local data and information of historical impacts to communities or population groups and historical economic drought damage to the sectors (for example, agricultural yield loss).

3c. Undertake a detailed future drought characterization—if answered "long term (future)" to question 1e.

This analysis is not necessary since the answer to question 1e was "short term (current)."

3d. Combine current and/or future drought hazard, exposure, and vulnerability for an overall drought risk assessment for the sectors identified in 1c.

The risk assessment for population and agriculture can be carried using different methods, depending on the type of information available from phase 3. Overall, two main methods are applied:

The first approach is to combine the detailed maps of the historical drought hazard characteristics (severity and frequency) of the available indices related to population and agriculture respectively (see 2b) with detailed maps of exposure and vulnerability of population and agriculture respectively. A map of exposure or vulnerability may consist of a singular proxy (see 2b), but can also consist of a combination of proxies. Based on these maps, a spatial and temporal analysis can be made of the overlap between areas with relatively severe and/or frequent drought hazards (drought hotspots) and communities with high exposure and vulnerability. Another possibility is to compute and map risk levels for each community by multiplying hazard, exposure, and vulnerability. For this purpose, hazard, exposure, and vulnerability numbers need to be re-classified and/or normalized (between 0 and 1). Although the analysis is currently not available for Ethiopia, examples for other countries are described in online reports (Carrão, Naumann, and Barbosa 2016).

If information is available or computed concerning the decline of yield loss, health effects, or another economic or human impact resulting from drought (from 3a), another approach can be followed. The drought risk can be expressed in terms of annual average losses (AAL) or annual expected damages (AED) through a probabilistic analysis of either potential annual damages or potential damages for drought events for different return periods. Although this analysis is currently not available for Ethiopia, examples for other countries are described in online reports.

To establish a social protection system, an analysis must be carried out to determine the drought index levels that trigger a certain impact on the population and agriculture (for example, risk level, damage to the local economy, human health effects). Such trigger levels can be included in an operation system for drought hazard and risk detection and forecasting. In this analysis, it is important that the trigger levels are chosen in such a way that the number of false positives and false negatives resulting from the trigger levels is under an agreed-upon acceptable level.

Phase 4: Implementation phase

The action to take and or measure(s) to implement depend on the answer to question 1f and the results from step 2 (and 3). The implementation phase needs to be carried out by the decision maker in close collaboration with technical experts and involved stakeholders.

4a. Identify just-in-time actions to mitigate the impact of a (forecasted) drought, activate standard operating procedures (SOPs) for the sectors identified in 1c.

Not relevant.

4b. Design short- and/or long-term drought risk reduction measures (for example, social protection

systems, increased surface and groundwater storage, irrigation systems).

Designing a social protection system to reduce risk is the main aim of this risk assessment. Any available just-in-time actions and national SOPs should be evaluated and, after some adjustments, provide a basis for the social protection system at community level. Because of its urgency, just-in-time actions (4a) are built on information from the inception phase and relative risk levels. For the design of a more long-term social protection system, detailed information (for example, yield loss, food shortage, drinking water shortage, financial impacts due to drought) is required. Drought risk can then be expressed in terms AAL or AED, enabling the construction of well-attuned financial, food, and/or water buffers. To ensure timely action in case of future droughts, a drought hazard and risk detection and forecasting system should be designed—including tools for drought warning and alert triggering (see 4c).

Review and update the social protection system every five years to account for climate change (for example, increased drought frequency or severity) and socioeconomic changes (for example, population increase, land use change, and/or change in economic activities). This also includes updating the drought early warning system that provides drought alerts.

4c. Design preparedness measures (for example, drought monitoring, drought detection/forecasting systems, early warning systems, establish SOPs).

Co-design a useful drought early warning system in cooperation with the local communities and involved users. The requirements of this system are case-specific and should be tailor-made to the findings of the drought risk assessment (drought characteristics, hazard and risk hotspots, trigger levels) and the design of the social protection system. Before starting the actual design or improvement of the warning system, the following actions should be taken:

- Thoroughly review the design and operation of early warning systems that are used to trigger food and cash support.
- Establish an understanding of what is needed for these systems to provide accurate estimates of drought impacts and food needs on a beneficiary level.
- Identify which indicators need to be assessed/monitored to meet the objectives and to ensure that the number of false negatives and false positives are minimized. The problem owner (decision maker) should agree to the acceptable level of false positives and false negatives.
- Discuss and agree on which information and indices are understandable and useful for the local stakeholders and users of the systems.

During the design of the warning system, the following actions should be included:

- Design improved forecasting and monitoring systems and tools for alert triggering. This requires expert technical work such as, for example, using a modeling tool or software to set up a (hydrological) drought forecasting system to forecast the local drought impact on agriculture (the Soil Moisture Deficit Index, or SMDI) at the appropriate scale. Account for climate variability (for example, ENSO) in the design of the forecasting system. Ideally, this expert work and tools have been developed during step 3 of the drought risk assessment.
- Design a drought monitoring system to monitor the development of the drought. This requires expert technical work. For examples of drought detection and forecasting systems, as well as an overview of best practices, refer to the comparative model assessment report (Deltares 2018b).
- Set up a (simple) system to deliver useful information about the number of people impacted by the drought in the district. This system combines collected information on drought impact and warnings with population distribution maps. It is vital that the early warning information systems are well embedded within government systems or linked to the capacities at national and district levels and that the information is communicated in an effective way.
- Update the warning system every five years in order to account for climate change (for example, increased drought frequency or severity) and socioeconomic changes (such as population increase, land use change, and/or change in economic activities). Does the hydrometeorological model require updating to detect and forecast any changed drought characteristics? Verify whether trigger levels are still sufficient to estimate the number of beneficiaries (whether the false positives and false negatives are still in an acceptable range). Is a change in indicators required to provide the needed social protection? If economic activities change from agriculture dominated to industry, this requires a shift from agricultural drought indicators to hydrological and socioeconomic drought indicators.

Just in-time-actions can be established based on the risk assessment made during step 2 and step 3. SOPs can be developed that focus on the areas, population groups, and communities that suffer most from the droughts. Based on the type(s) of drought impact established in step 2 and step 3, suitable just-in-time actions can be prepared that provide the social protection that is most needed in the impacted communities (for example, supply of crops and food, additional drinking water supply, and/or financial support).

4d. Define and implement drought management plans and operational rules.

Not relevant.

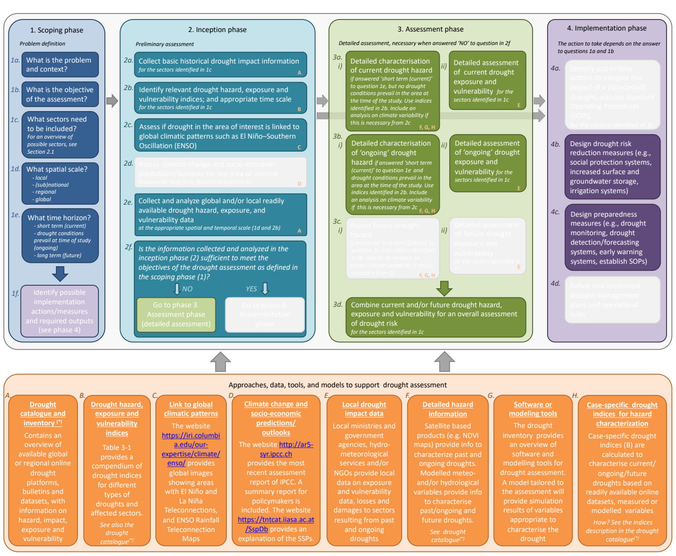
5.3 Drought-proof design of a hydropower dam in Colombia

This section presents an application of the workflow to the following hypothetical example:

A hydropower dam operator assesses the design of a hydropower project situated in a medium-sized basin in the tropical Andes of Colombia. The new dam and its functional goals need to be able to cope with the occurrence of extreme climatic conditions such as droughts.

Figure 5.16 shows the workflow of this application; the steps that are not needed in this example have been grayed out.

FIGURE 5.16 Workflow Steps that Apply to the Design of a Hypothetical Hydropower Dam



* www.droughtcatalogue.com

Phase 1: Scoping phase

A decision maker contextualizes and frames the problem in consultation with relevant identified stakeholders and the intended recipient audience of the drought risk assessment by answering the following questions:

1a. What is the problem and context?

For a hydropower project in Colombia, an assessment needs to be made of how well the design of the proposed project can cope with the occurrence of extreme climatic conditions such as droughts, and the influence these have on the project meeting its functional goals. These goals include primarily power generation, but also relate to other aspects such as environmental impacts, socioeconomic impacts downstream, dam safety, and other issues. The outcome will provide insight into how resilient the design is to changing climatic conditions and, where applicable, how measures can be taken that can improve resilience.

1b. What is the objective of the assessment?

The objective of the assessment is to estimate the plausible climate risk (Mott MacDonald 2017) of the proposed design of the hydropower project not meeting its functional goals because of insufficient water availability as a consequence of drought. The assessment should include evaluating drought hazard in the current and future climate, as well as the impacts (financial, environmental, social) of failing to meet established goals. Where available, design alternatives are to be evaluated on how well these ameliorate risks.

1c. What sectors need to be included (are affected)?

The primary sector to be considered is the energy sector. However, several other sectors are also relevant and will need to be considered: social and environmental (project scale as well as downstream). In addition, the aspect of dam (structural) safety is relevant.

1d. What is the spatial scale of the problem?

This is a regional scale analysis to gain full insight into the occurrence of drought and its impacts. Specific focus will be needed on the river basin in which the hydropower project is to be developed.

1e. What is the time horizon?

The time horizon is one of the current and future climate. The time scale of the future climate depends on the projected lifespan of the project, which will typically be > 50 years.

1f. Identify possible implementation actions and/or measures and required outputs.

To improve the resilience of the dam design to changing climatic conditions, various types of implementation action and measures are relevant, ranging from drought risk reduction measures and preparedness measures to the implementation of drought management plans and operational rules. The drought risk assessment should provide input that helps to design these different types of measures.

Outputs required to support these measures include:

- Information and time series of historical hydrological droughts in the catchment (at the scale of 3rd order hydrographic basins; typical sizes range from 3,000 to 5,000 square kilometers)
- Broad overview of drought exposure and risk at the scale of the basin in which the project is situated
- Insight into the effect of drought on energy price in the area

Phase 2: Inception phase

Preliminary assessment to be carried out by a technical team of water resources and drought risk professionals to have a better understanding of the problem.

A preliminary assessment for Colombia following the steps defined in the inception phase for a variety of sectors is presented in the comparative model assessment report (Deltares 2018b). The following paragraphs summarize the results of that analysis for the sectors identified in the scoping phase (phase 1) for this particular use case, as well as providing additional sector-specific information.

2a. Collect basic historical drought impact information for the sectors.

The objective of this step is to develop an overview of how the energy sector, as well as sectors related to the operation of hydropower projects, is impacted by droughts. The energy sector in Colombia is dominated by hydropower, with some 64 percent of the installed generating capacity coming from hydropower (IDEAM 2014). Lower-than-normal water resources that may occur during drought events will therefore influence the generating capacity. Historically, major drought events such as the 1992–93 drought have resulted in major blackouts as a result of insufficient generating capacity, though these blackouts were in part also attributed to mismanagement (Larsen et al. 2004). Since the introduction of the open energy market and regulation (Larsen et al. 2004), blackouts have not occurred. However, availability of water resources does have a significant impact on energy prices, with these increasing significantly during drought events (Zapata et al. 2018). The reduced generation capacity during low runoff conditions as a consequence of drought means generation capacity will need to be moved to thermal power stations. The map in figure 5.17 taken from the *Aqueduct Water Risk Atlas* shows a low level of water stress with respect to electric power generation (which includes hydropower). This, however, represents the average availability of water. The position of the country between the Pacific Ocean, the Atlantic Ocean, and the Caribbean Sea, as well as the Amazon

FIGURE 5.17 Baseline Water Stress with Respect to Electric Power

Source: Aqueduct Water Risk Atlas, accessed October 2018.

Basin, has a profound influence on the complex hydro-climatology of the country. The Andes Mountains, which dominate the most populated part of the country, further influence climatic variability. Most hydropower projects are situated in the Andes, predominantly in the Magdalena-Cauca River Basin. The National Water Study (IDEAM 2014) is an analysis that is carried out very four years. This study shows that average runoff of basins across Colombia varies significantly, ranging from below 100 millimeters (mm)/year in the arid to semi-arid Caribbean coast to over 5,000 mm/year on the Pacific coast. In the Andes, runoff varies widely, from 300–400 mm/year in the inter-Andean valleys to some 2,000–3,000 mm/year at higher elevations. During drought events, impacts to the environment as well as to socioeconomic sectors can be extensive, and conflicts arise on the use of water among sectors such as agriculture, energy, and domestic supply. In the 2015–16 drought event, over 120 municipalities were cut off from the public water supply as a result of insufficient available surface water in rivers and reservoirs (Alarcón 2016). It is clear that during these periods the trade-offs with water for hydropower generation are critical.

Additional details of how droughts influence the energy and related sectors can be obtained through the Colombian Ministry of Mines and Energy (www.minminas.gov.co), the Ministry of Environment and Sustainable Development (www.minambiente.gov.co), and in particular the national environmental licensing authority (Autoridad Nacional de Licencias Ambientales, ANLA http://www.anla.gov.co/), as well as through the various public-private companies involved in hydropower generation and operation (for example, Empresas Públicas de Medellín (EPM), ENEL-EMGESA, and others).

2b. Identify relevant drought hazard, exposure, and vulnerability indices for the sectors: Population and agriculture, see section 2.1.1 (hazard indices in table 3.1), section 2.1.2 (exposure indices), and section 2.1.3 (vulnerability indices). The drought catalogue (www.droughtcatalogue.com) provides descriptions and other relevant information for many drought indices. When analyzing drought hazard, it is preferable to combine multiple relevant drought indices and analyze differences occurring between the observed drought patterns.

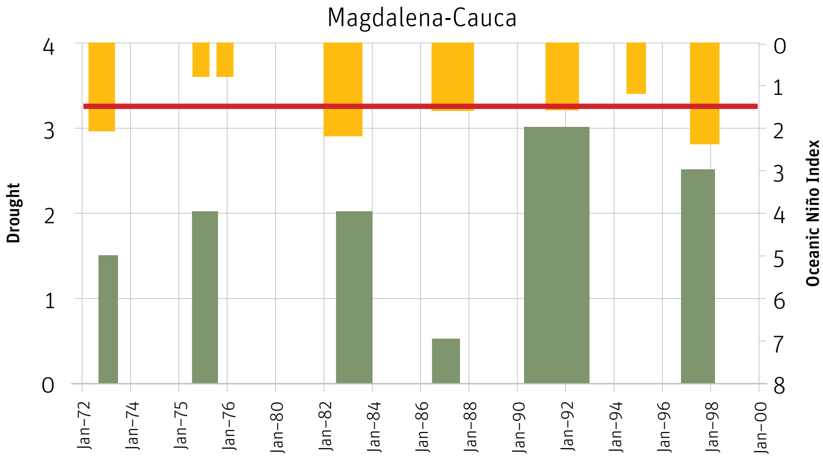
To evaluate how drought proof the design is of a hydropower project in the river basin/region where the hydropower project is to be developed, drought indicators that can help establish drought risk include indicators focusing on hazard and exposure as well as drought impacts:

- The main drought indices relevant to the design of a hydropower project in a basin are related to the hydrology of the basin. These are drought indices such as the Standardized Streamflow Index (SSFI) and the Standardized Reservoir Supply Index (SRSI). Depending on the hydrogeology of the upstream basin, the variability of groundwater resources captured through an index such as the Standardized Groundwater Index (SGI) may be relevant. Key meteorological variables, including precipitation and evaporation, are also important to consider; these may be quantified through indices such as Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), which explicitly considers evaporation (for example, from the reservoir surface).
- To quantify the exposure to drought of the hydropower project, exposure indices establish the (projected) population that will depend on energy generated and what options are available for alternative power sources (for example, whether the hydropower generated fed into an interconnected network). The size of the population that depends on water resources from the (planned) reservoir or downstream water resources, including use of domestic, industrial, and agricultural water, must be determined. Environmental indices will need to be considered to take into account natural assets such as (sensitive) wetlands that are connected to the downstream river system. Indicators related to the management of sediments in the basin upstream of the reservoir, in the reservoir as well as the downstream river, will need to be considered.
- Vulnerability can be assessed using indices relevant to energy and the environment: economic vulnerability proxies (GDP per capita in urban areas, agricultural value added) and infrastructural vulnerability proxies (agricultural irrigated land, irrigation efficiencies, road density) can be used.

2c. Assess whether climate variability (for example, ENSO) needs to be included.

The climate in Colombia is strongly influenced by El Niño and La Niña events, which will therefore need to be considered in the assessment. The strong teleconnection is evidenced through a quick analysis of the correlation between the Oceanic Niño Index (ONI) and drought

FIGURE 5.18 Historical Droughts and Oceanic Niño Index for the Magdalena-Cauca Region



Note: Green bars = drought classification; yellow bars = ONI value; red line = ONI value for very strong Niño events.

The Magdalena-Cauca region is shown in pink in the map.

indices in figure 5.18 (see also the comparative model assessment report, Deltares 2018b) and information on the link between ENSO global patterns and precipitation. This shows, in the ENSO rainfall teleconnection maps, a high probability of below-normal rainfall conditions (drought) during El Niño events for the largest part of the country. There is a strong consequent connection between the occurrence of El Niño events and hydrological flows (figure 5.18), with both precipitation and river discharge being below normal for El Niño events and above normal for La Niña events across the country (Poveda, Álvarez, and Rueda 2011). The teleconnection with the ENSO phenomenon is shown to be strong. However, several other climatic indices can help explain climate variability, including the North Atlantic Oscillation (NAO), the position of the Chocó jet, and so on (Poveda, Álvarez, and Rueda 2011). As a result, a detailed analysis in the next phase of the influence of climatic phenomena such as ENSO on the basin of interest will be required.

2d. Assess whether climate change and socioeconomic changes need to be accounted for—Yes if answered "long-term (future)" to question 1e.

Evaluating whether the design of a dam is drought proof will require detailed analysis of the current climate and socioeconomic conditions, and also how these are both projected to evolve through the life cycle of the dam. The *Fifth Assessment Report*, which is the most recent climate assessment developed by the IPCC, includes an assessment of the climate change in Central and South America, including Colombia (IPCC 2014). Although the high variability of the climate in Colombia makes this an area that is particularly uncertain in terms of climate change projections, there are several clear signals. The report concludes with high confidence that temperatures are expected to be higher in a future climate across Colombia, with consequent impacts on the remaining glaciers. There is less confidence in the climate predictions on changes in precipitation, with higher annual precipitation expected in some areas and lower in others. However, the report is clear that significant changes to hydrological regimes can be expected. These are compounded by land use changes due to increasing agricultural development and increasing urbanization (high confidence). These changes will have profound impact on the occurrence of hydrological extremes and therefore also on the climate resilience of the hydropower projects in the country. The occurrence of climatic extremes such as droughts is strongly linked to climatic phenomena such as ENSO (see also the previous section). Though research does indicate that the frequency, severity, and geographical extent of ENSO events are projected to change, there is as yet little certainty on how such ENSO events will develop in a future climate (Chen et al. 2017; Perry et al. 2017). The population of Colombia is expected to increase at least until 2050 (with some projections showing a continued increase after 2050, while others project a moderate decline). The GDP is expected to continue to rise, as well as the already high degree of urbanization (see database on impacts of social development pathways; see also Riahi et al. 2017).[5] These changes (increasing GDP and more frequent/longer dry periods) will influence energy demand significantly. Given these changes, a more detailed assessment of projected changes to climate and climatic variability in the river basin and region of the hydropower project will need to be developed in the next phase.

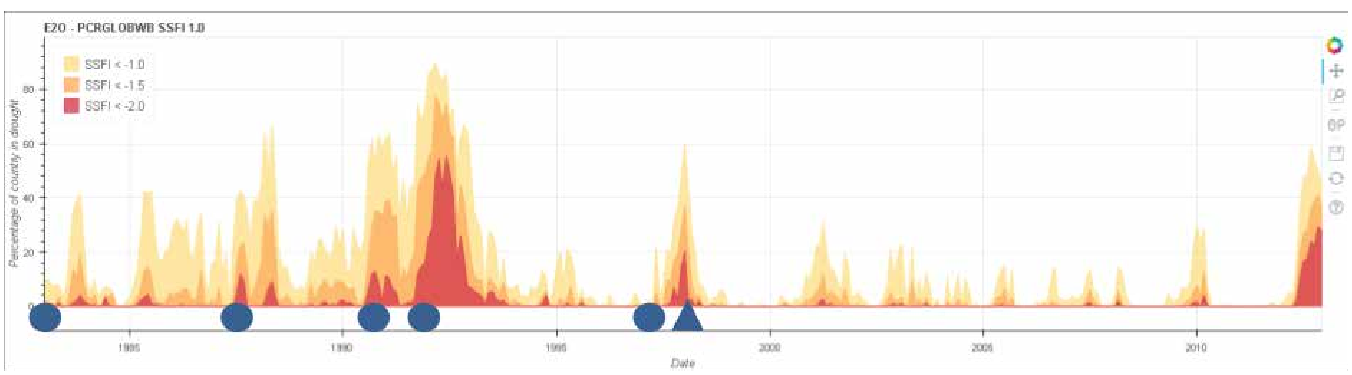
2e. Collect and analyze global and/or local readily available drought hazard, exposure, and vulnerability data at the appropriate spatial and temporal scale (1d).

A range of information on climatic variability in Colombia is readily available and can be consulted to provide quick scan information on current drought hazard, exposure, and vulnerability in the country.

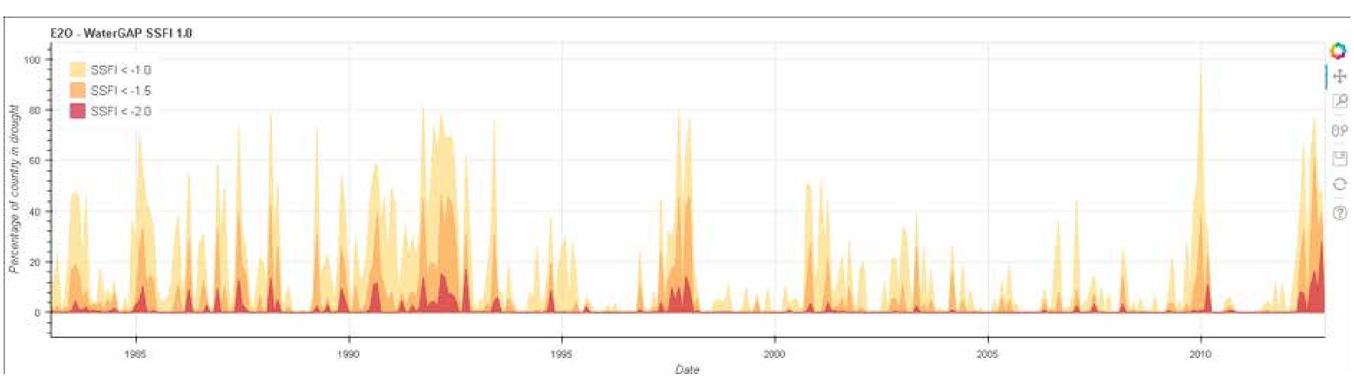
- Drought hazard indices can be derived from global datasets (see the comparative model assessment report, Deltares 2018b) showing the percentage area of the country experiencing drought conditions at three drought levels: moderately dry (index value below −1), severely dry (index value below −1.5), and extremely dry (index value below −2). In these graphs (an example of the Standardized Streamflow Index is presented in figure 5.19), the registered droughts from the International Disaster Database (EM-DAT) are also shown. This shows a reasonable comparison between datasets showing global drought hazard with reported droughts. A comparison of drought indices derived from discharges calculated using global models and datasets at key stations in major rivers, and the same indices calculated using in-situ data show a good comparison, though this comparison is best at stations with a larger upstream area (such as the Magdalena River at Calamar, figure 5.20). It should be noted that discharge data at daily time scales is readily available from the national hydro-meteorological institute IDEAM.
- Extensive information on expected climate change impacts and developments are available from the Sistema de Información Ambiental Colombia (SIAC).[7] These provide the detailed analyses carried out by IDEAM on climate change projections and how these influence hydrometeorological conditions, as well as socioeconomic

FIGURE 5.19 Hydrological Drought Index SSFI-1 for Colombia

a. PCR-GLOBWB

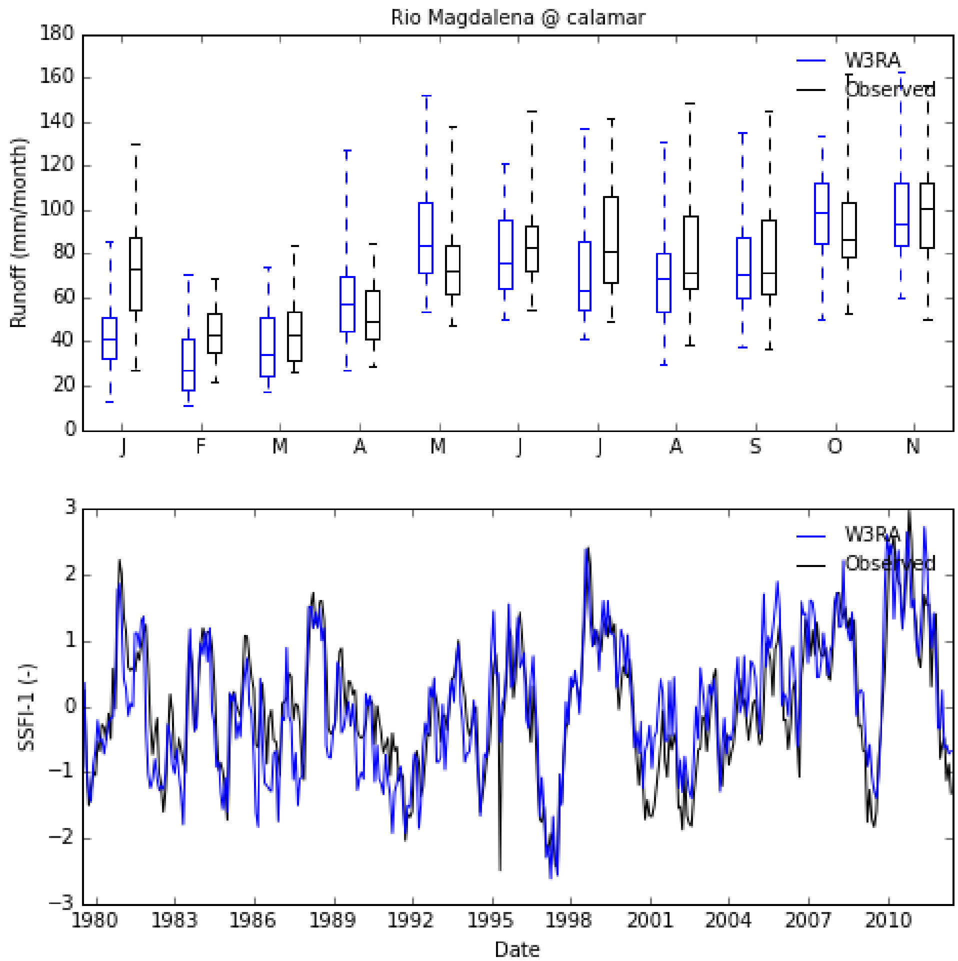


b. WaterGAP



Note: Gray dots indicate drought events recorded by IDEAM; gray triangles indicate drought events recorded by EM-DAT and IDEAM.

FIGURE 5.20 Comparison of Runoff Variability (Upper Panel) and Hydrological Drought Index SSFI-1 Lower Panel)



Data source: Observed data and simulated data from the W3RA global model for the Magdalena at Calamar.

development and proposed adaptation strategies.

2f. Decide on the next step: Does the information collected and analyzed in the inception phase (2) sufficiently meet the objectives of the drought assessment as defined in the scoping phase (1)?

Does the existing information provide accurate estimates of drought hazard, exposure, and vulnerability for your analysis, regarding resolution and data input? If not, what kind of additional information is needed?

Although extensive information is available on drought risk in Colombia, in particular with respect to drought hazard in the current and future climate, the level of detail that is presented is typically at the national to regional scale, and at best at the scale of the 3rd order hydrographic basins (typical sizes range from 3,000 to 5,000 square kilometers). The complexity and variability of the climate in Colombia, in particular in the Andean catchments where most hydropower projects are now or are being developed, means that to assess how drought proof the design of a hydropower project to be established in a particular basin is, a more detailed assessment will need to be made. This should necessarily focus on drought hazard, exposure, and risk at the scale of the basin in which the project is situated. However, for some analyses—such as the effect of drought on energy price—a more regional or even a national assessment will be required. Based on this assessment, it is concluded that a detailed assessment phase (phase 3) is to be undertaken.

Phase 3: Assessment phase

In this phase a detailed assessment is to be carried out by a technical team of water resources and drought risk professionals to develop a thorough assessment of how drought proof the design of the hydropower project is. This is necessary when the answer to question 2f is "No." Note that the description provided is only intended to serve as an example and does not pretend to be exhaustive. The local setting of the hydropower project and the information available (also from previous studies) will to a large extent determine the required steps.

3a. Undertake a detailed "ongoing" drought characterization—if answered "short term (current)" to question 1e but drought conditions do not prevail in the area at the time of the study and are not predicted for the near future.

Part i. Detailed characterization of the historical drought hazard

In this phase a more detailed analysis of the drought hazards identified in the inception phase is developed. The objective is to gain a thorough understanding of the hydro-climatological variability, including discharge in the river basin in which the hydropower project is designed, as well as key parameters such as temperature and precipitation. Particular attention is to be paid to the distribution of discharge volumes and the frequency of extreme low flow periods.

To develop this thorough understanding of drought hazard in the basin, detailed data on the hydrology and climatological conditions of the basins will need to be collected. Additional information on the geomorphology and geology will also be required. The hydrometeorological data network in Colombia is reasonably well developed, although it should be noted that the country is large and the distribution of flow gauges and meteorological stations varies significantly across the country. At the national level, the hydrometeorological agency, IDEAM, has the mandate to collect and manage these data, and in recent years a law was adopted that makes all data (at daily time scales and higher) publicly available. In some areas of the country, the regional environment agencies (Corporación Autónoma Regional, CAR) may operate additional data networks, though this is only in those areas with significant socioeconomic development. Furthermore, a wide network of universities and sectorial institutes has developed studies and may operate data networks. This includes several existing hydropower projects that have dedicated networks of meteorological and hydrological stations to support their operations (but rarely share those data). While access to data may be difficult, engaging with these agencies is a key step. For all 3rd order river basins, the local CAR is obliged, under the 2010 law on Integrated Water Resources Management, to develop a River Basin Management Plan (Planes de Ordenación y Manejo de Cuencas Hidrográficas, POMCA), as well as an evaluation of the available water resources (Evaluación Regional de Agua, ERA). For aquifers, a management plan is also developed (Plan de Manejo de Aquiferos Ambientales). Where these plans have been recently updated (which is an ongoing process), they contain valuable information and indices such as an aridity index, the water retention index, an exploitation index, and so on.

The detailed analysis of the hydrological and meteorological conditions will likely require the development of a hydrological model for the basin of interest. In some cases, such a hydrological model may already exist (for example, it may be used in the development of the river basin plans), but in most cases this will need to be developed. SIAC provides access to thematic maps (geology, land use, geomorphology) at national scale,[8] with CARs holding more local information. In some basins there will be little information available. In these cases, data can be proxied with data from hydrographically similar conditions. If the period of record of observed rainfall data is short, datasets can be extended using satellite and reanalysis datasets (for example, CHIRPS, ERA5) and combined with the local model.[9] Based on the observed data, as well as on model results (which are required to develop long time series of statistically homogenic data), several drought indices can be developed. This includes standardized indices such as SSFI and SPI but also indices used to analyze hydrograph shapes and volumes, as well as Threshold Index methods (Van Loon 2015).[10]

Note that for the establishing of the drought hazard downstream of the hydropower project, the rules with which the dam is operated will need to be considered because they will have profound impact on the flow regime.

Part ii. Detailed characterization of exposure and vulnerability

Detailed maps will need to be developed to provide insight into the exposure and vulnerability of the identified sectors related to the hydropower project and drought. These maps will include socioeconomic activities downstream of the dam (as well as in the reservoir and its surroundings) and a characterization of how they are related to release discharges and levels in the reservoirs. For the impacts to the energy sector, a detailed assessment of how drought affects the market will need to be established. The energy market is a regulated open market power pool, so this assessment can be quite complex. In any case, it should be considered that droughts will typically happen at the regional if not national scale.

Again, much relevant information can be gathered from the various basin management plans that are available, particularly from the regional environment agencies (such as the POMCAS [Planes de Ordenación y Manejo de Cuencas Hidrográficas] and PMAA [Planes de Manejo Ambiental de Acuíferos] plans available from CAR). Municipal land use planning can also be of value. The analysis will require specific attention (required also by Colombian law) of marginal and indigenous communities.

Based on this information, maps can be developed to identify where and how sectors are impacted by the occurrence of drought conditions.

3b. Undertake a detailed historical drought characterization—if answered "short term (current)" to question 1e and drought conditions prevail in the area at the time of the study or are predicted for the near future.

Part i. Detailed characterization of the ongoing drought hazard

Part ii. Detailed characterization of ongoing exposure and vulnerability

Parts i and ii are not applicable in this case.

3c. Undertake a detailed future drought characterization—if answered "long term (future)" to question 1e.

The characterization of future drought hazard will require a detailed assessment of how the basin will be affected by projected, if uncertain, changes to climatic variability. To date, there has been only limited work with regional climate models in Colombia, which makes projections of, for example, future hydrological conditions very challenging. Methods currently used include the delta method, which perturbs observed historical data (for example, precipitation and temperature data) to change its mean value and variability as informed by a global or regional climate model. The impact on hydrology can then be evaluated using the model framework developed previously.

Future socioeconomic conditions are difficult to project into the future. Although general information may be obtained at the country level, detailed information in the basin of interest will be challenging. Regional government development plans (such as the Plan de Desarrollo) as well the national development plan (developed by the Dirección Nacional de Planeación, DNP) will provide useful information. Specific attention will need to be paid to developments in the energy market, agricultural expansion and change, and urbanization. Where possible, thematic maps can be developed.

3d. Combine current and/or future drought hazard, exposure, and vulnerability for an overall drought risk assessment—for the sectors identified in 1c.

In this final phase, the detailed information on drought hazard (current and future) and drought exposure and vulnerability are combined to provide insight into current and future drought risk related to the development of the hydropower project. Where possible, thematic maps showing drought risk should be developed.

In this stage, different strategies should be evaluated to assess how they influence drought hazard as well as vulnerability and exposure. Different operational strategies as well as variations in the design of the hydropower project will need to be evaluated. A scoring system can be developed (for example, with score cards) to help prioritize design alternatives using relevant socioeconomic, environmental, and sustainability indicators. These indicators should also provide insight into the relative importance of the different contributing factors in determining drought risk.

Phase 4: Implementation phase

The actions to take and or measure(s) to implement will depend on the answer to question 1f and, in particular, the results from the assessment phase. The implementation phase needs to be carried out by the decision maker in close collaboration with technical experts and involved stakeholders. Again, the examples mentioned below are intended merely to serve as an example and are by no means exhaustive. Measures that can *be taken will depend very much on the specific setting of the hydropower project.*

4a. Identify just-in-time actions to mitigate the impact of a (forecasted) drought, activate standard operating procedures (SOPs) for the sectors identified in 1c.

Not applicable.

4b. Design short- and/or long-term drought risk reduction measures (for example, social protection systems, increased surface and groundwater storage, irrigation systems).

A range of measures can be designed and evaluated to help reduce the identified drought risks. These measures can be designed to address the different aspects of risks. A brief and by no means exhaustive list of examples of such measures follow.

Structural or infrastructural measures:

- Measures that address the design of the hydropower project, including sizing and storage, and structural aspects such as bottom outlets
- Measures to develop infrastructure to store water; this could include managed aquifer recharge schemes to balance downstream supplies in low flow periods and reduce conflicts with other users such as hydropower
- Measures to reduce the impacts of drought in the energy sector; diversification of generating capacities, development of other renewable sources
- Environmental or land use measures:
- Measures to improve the retention capacity of the catchments during droughts, including reforestation, conservation of Paramo areas (high montane wetlands)
- Measures to improve drought resilience of agriculture sector downstream (drought-resilient crops, irrigation practices)
- Measures that adapt large storage projects to alternative low head hydro projects to reduce environmental impacts[11]

Operational measures:

- The operational strategy will have a profound influence on how drought proof the hydropower project is; several alternate strategies should be evaluated, including operation under normal conditions as well as during low flow drought periods

4c. Design preparedness measures (for example, drought monitoring, drought detection/forecasting systems, early warning systems, establish SOPs).

The development of drought monitoring and early warning is a key strategy for dealing with current and future drought conditions and for taking timely actions to reduce impacts. This is very relevant to the scheduling of hydropower generation as a function of available resources. Detailed monitoring of hydrometeorological, hydrogeological, and land use conditions in the river basin provide crucial inputs to the management and operation of hydropower projects. The use of forecasts at different time scales, including short-term, subseasonal, and seasonal scales, should be considered. The strong teleconnections in Colombia entail quite some skill at the seasonal forecasting time scale. The design of the operational rules can be benefitted by this skill to help reduce impacts of droughts to the energy sector as well as to downstream users. Several examples exist in Colombia where such multiscale forecasts are used to inform the operation of multipurpose hydropower projects (for example, the Salvajina dam in the Cauca region).

It should be noted that the development of drought monitoring and forecasting should preferably be undertaken at the national or regional scale. An approach should be found that ensures sustainable continuity of monitoring and forecasting. National agencies such as IDEAM can be equipped to provide the base information, with dedicated climate services providing tailor-made information to specific users such as hydropower operators, the agriculture sector, and so on. To establish this sustainably, benefits and costs must be shared by public and private partners involved.

4d. Define and implement drought management plans and operational rules.

A key measure for improving drought resilience is to establish a drought management plan, which includes the rules that guide the operation of the hydropower plant during drought conditions. Guidance on the development of drought management plans can be found in other sources (EC, MEDA Water, and MEDROPLAN 2007). These should be developed in close participation with stakeholders from the identified sectors, communities in the basin, environmental actors, and so on. The plans should clearly set out the actions and measures to be taken during drought conditions and by whom. In most drought management plans, different levels of escalation will need to be identified—pre-alert, alert, and emergency—each with a specific set of increasingly compulsory measures to be taken.

These thresholds will be develop based on indices derived from the drought monitoring and forecasting and will include different modes of operation at hydropower project to reduce both short- and long-term impacts of drought.

5.4 Using these applications

Although each drought hazard and/or risk assessment is different, the three hypothetical examples provided in this chapter illustrate the ways to apply the steps described in the implementation guide. They are intended to provide a roadmap for how to apply the drought hazard and risk assessment methods described in the report to specific situations. These examples are country-specific and use actual data and situations, but the principles they demonstrate apply to all situations. When carrying out an assessment, it is recommended to make use of the wealth of available existing drought hazard and risk indices, modeling tools, datasets, and other resources. For this purpose, the online Catalogue of Drought Hazard and Risk Tools (www.droughtcatalogue.com).

Notes:

1. This example is presented in cooperation with UNHCR and Matano 2018.
2. See also the WaterLOUPE Water Scarcity Dashboard at https://www.deltares.nl/en/webinars/waterloupe-water-scarcity-dashboard/.
3. See for example World Bank, RMSI, IFPRI, and GFDRR, no date.
4. For ENSO Resources, see http://iri.columbia.edu/our-expertise/climate/enso.
5. The Shared Socioeconomic Pathways (SSP) Database is available at http://tntcat.iiasa.ac.at/SspDb.
6. These data are available at the IDEAM website at http://www.ideam.gov.co (in Spanish).
7. SIAC is available at http://www.siac.gov.co/infonalclimatico (in Spanish).
8. SIAC maps are available at http://www.siac.gov.co/infonalclimatico.
9. Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 30+ year quasi-global rainfall dataset, starting from 1981 to near-present, from the Climate Hazard Group from the University of Santa Barbara (See http://chg.geog.ucsb.edu/data/chirps/). ERA5 is a reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF), available at https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era5.
10. Threshold Index methods are based on defining thresholds below which, for instance, the precipitation or river flow is considered to be in a drought.
11. Low head hydro applications use a head of 20 meters or less to produce energy, so they may not need to dam or retain water to create a hydraulic head.

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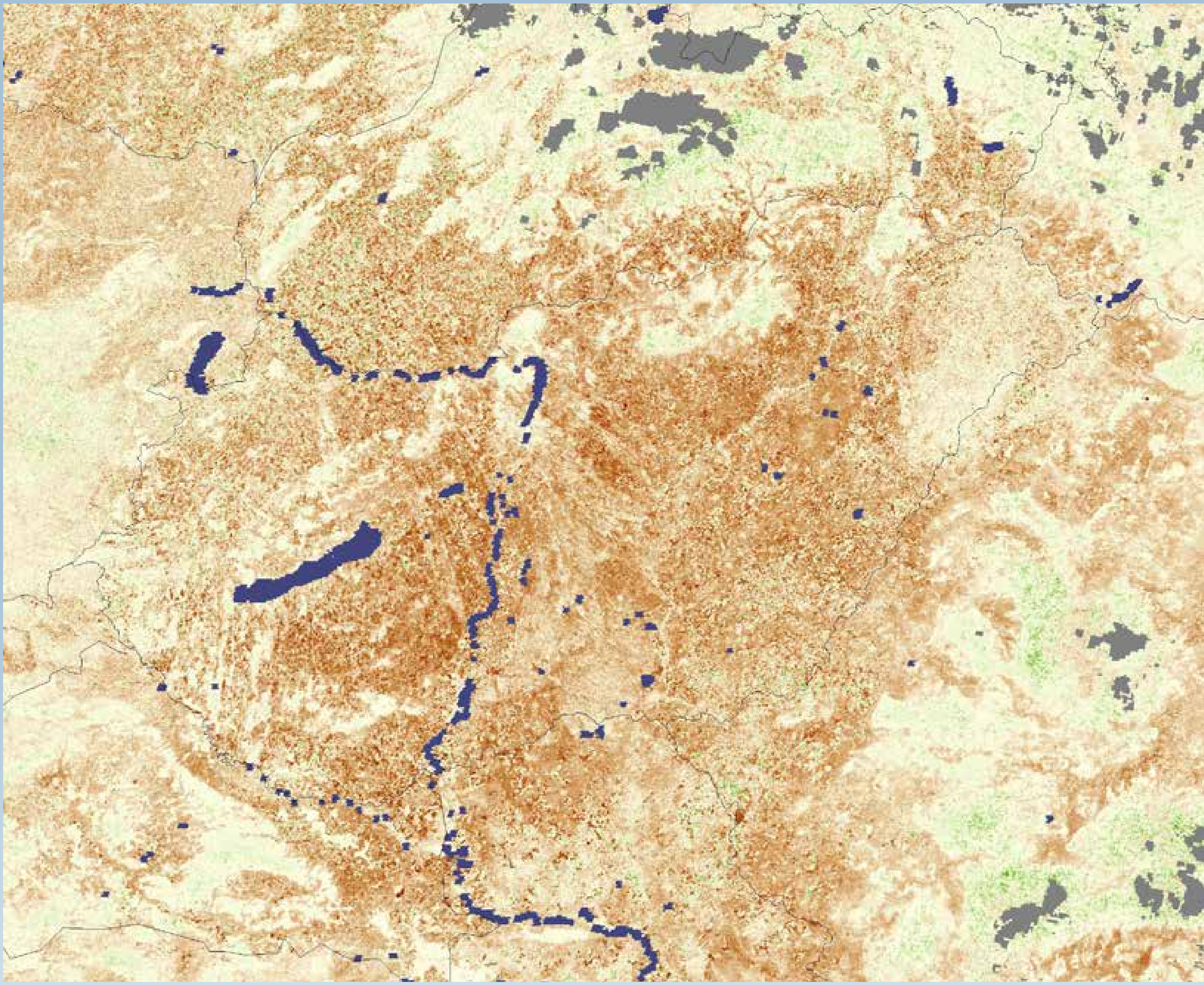

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