WORLD RESOURCES INSTITUTE

TECHNICAL NOTE

GLOBAL FOREST WATCH WATER METADATA DOCUMENT

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EXECUTIVE SUMMARY

Communities around the world face a growing water crisis. Surging water demand, aging water infrastructure, continued changes in land use, and increasingly extreme weather events drive water management costs higher. The need is growing for lower-cost means to secure ample and clean water. Natural infrastructure approaches—such as forest protection, watershed restoration, and sustainable management of landscapes—have a major role to play in confronting water crisis. As awareness grows on the linkage between the health of watersheds and their capacity to supply sufficient, clean water, watershed stakeholders—water utilities, business, government, and communities—face many challenges and a lack of information as they explore opportunities for integrating natural infrastructure approaches in managing their water resources.

To fill the gap, the World Resources Institute (WRI) has developed Global Forest Watch Water (GFW Water), a publicly available global interactive mapping tool and database that allow users to glean key information about using natural infrastructure to enhance water security. GFW Water aims to help downstream beneficiaries, financing and development institutions, and civil society and research groups apply natural infrastructure as a strategy to enhance water security and improve watershed management.

Anyone with internet access can now visualize critical watershed-related information and threats to watershed health, and screen for cost-effective, sustainable natural infrastructure solutions based on watershed characteristics and risk profiles. GFW Water provides spatial data sets, summary statistics, and watershed risk scores for 230 major watersheds around the globe. It also

CONTENTS

Technical notes document the research or analytical methodology underpinning a publication, interactive application, or tool.

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allows users to locate and delineate subwatersheds for analysis. GFW Water is a portal to resources for planning natural infrastructure initiatives, including publications, guidelines, decision-support frameworks, and case studies.

Finally, GFW Water scores each watershed's ability to deliver critical ecosystem services based on its exposure to four key watershed risks: (1) recent forest loss; (2) historical forest loss; (3) erosion; and (4) fire. The risks are considered in the context of each watershed's baseline water stress. The results show that watersheds around the world face different types of risks at varying degrees. Further assessment and appropriate management response are warranted for watersheds with high-risk scores.

This document explains the underlying science and assumptions of natural infrastructure for water, describes the data layers and information, documents data sources, and details the methodology used to generate watershed risk scores in GFW Water. All data and maps are publicly available.

KEY TERMS

- **Baseline water stress** — Baseline water stress measures the ratio of total annual water withdrawals to total available annual renewable supply, accounting for upstream consumptive use (ISciences 2011).
- **Ecosystem service** — An ecosystem service is any positive benefit that ecosystems provide to people (Daily et al. 1997). In this paper, we focus on freshwater-related watershed services, such as minimizing erosion and pollutants, purifying water, and reducing the impact of floods and droughts (Baron et al. 2002).
- **Erosion** — Erosion is the detachment and transportation of soil particles by rainfall, runoff, or wind (Renard et al. 1997). In this paper, we focus on erosion from rainfall and runoff.
- **Evapotranspiration** — Evapotranspiration is the sum of evaporation and plant transpiration from Earth's land and ocean surface to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and water bodies (Bosch and Hewlett 1982).
- **Infiltration** — Infiltration is the process by which water on the ground surface enters the soil. In soil science, the infiltration rate is the rate at which soil is able to absorb rainfall or irrigation water (Saxton and Rawls 2006).
- **Interception** — Canopy interception is the rainfall that is intercepted by the canopy of a tree and successively evaporates from the leaves (Carlyle-Moses and Gash 2011).
- **Natural infrastructure** — Natural infrastructure (sometimes called green or sustainable infrastructure) is defined as a strategically planned and managed network of natural lands, working landscapes, and other open spaces that conserves ecosystem values and functions and provides associated benefits and services to human populations, including erosion control, water purification, and flow regulation (Benedict and McMahon 2006).
- **Streamflow** — Streamflow, or discharge, is the rate of flow by volume of the water including any sediment or other solids that may be dissolved or mixed with it (Buchanan and Somers 1969).
- **Tree cover** — Tree cover is all vegetation taller than 5 meters in data developed by Hansen et al. (2013). Tree cover is the biophysical presence of trees and may take the form of natural forests or plantations existing over a range of canopy densities.
- **Turbidity** — Turbidity is the measure of relative clarity of a liquid (The United States Geological Survey 2015). Material that causes water to be turbid includes clay, silt, finely divided inorganic and organic matter, algae, soluble colored organic compounds, and plankton and other microscopic organisms.
- **Water yield** — Long-term (monthly or yearly) average flow in a stream (The United States Department of Agriculture 2009).
- **Watershed** — A watershed, or river basin, is an area of land where all of the water that falls in the boundary drains to a common outlet (USGS 2015). Watersheds can be subdivided into smaller units known as subwatersheds. Watershed health describes how well ecological systems are functioning. In this paper, we focus on watershed functions related to regulating water quality and flow.
- **Watershed risk** — Potential adverse effects on a watershed's ability to deliver critical ecosystem services to water utilities, businesses, and communities—including water flow regulation, water purification, and water temperature regulation—from a particular watershed condition such as deforestation, erosion, or fire.

1. INTRODUCTION

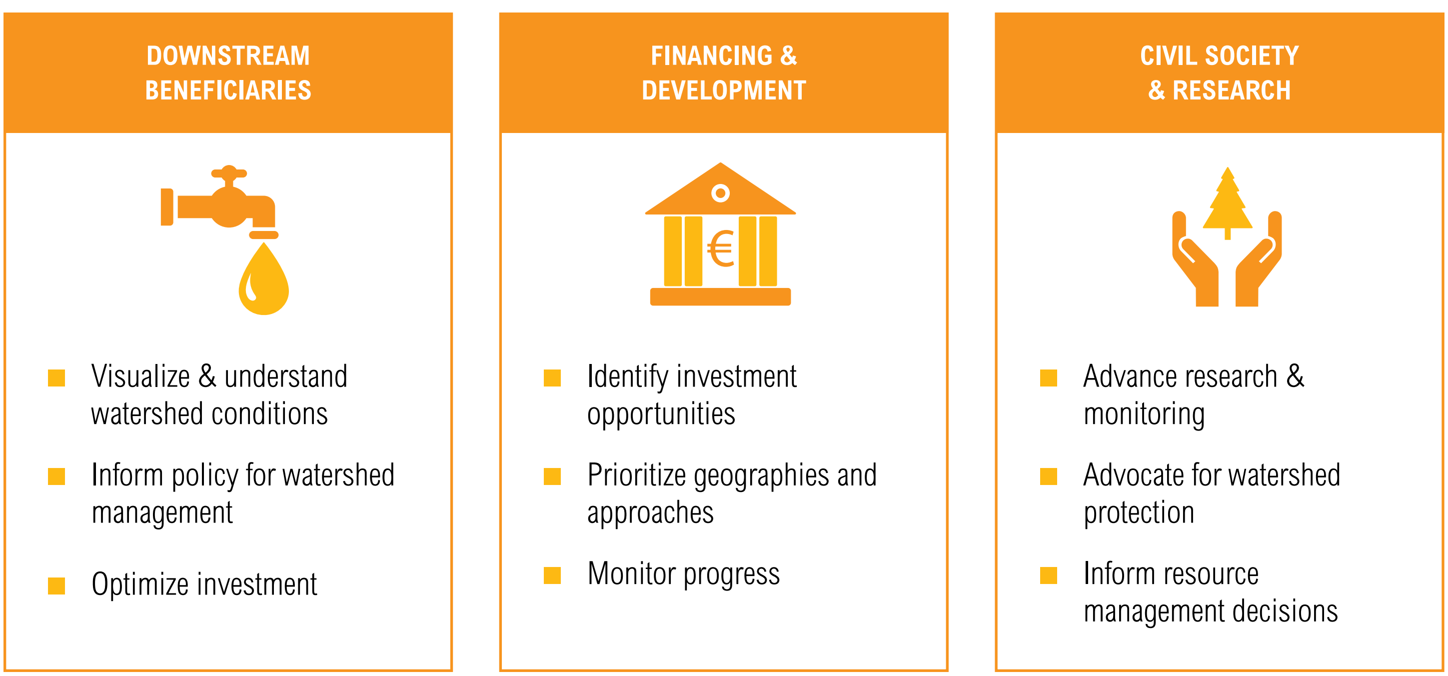
By 2030, an estimated $10 trillion will be needed to repair and expand the world's water infrastructure (Dobbs et al. 2013). As water demand surges, dams and treatment plants age, and more frequent extreme weather events threaten water security and drive up water management costs, the need is growing for lower-cost approaches to secure ample clean water. Natural ecosystems like forests and wetlands provide essential services—from water flow regulation and flood control to water purification and water temperature regulation—to water utilities, businesses, and communities (Gartner et al. 2013). Although concrete-and-steel built infrastructure will continue to be critical to water storage and treatment, strategic investment in networks of natural lands, working landscapes, and other open spaces as "natural infrastructure" can reduce or avoid costs and enhance water services and security (Gartner et al. 2014, Bennett and Carroll 2014, Costanza et al. 2014).

Around the world, efforts are expanding to safeguard water resources with innovative natural infrastructure approaches as part of an integrated system to cost-effectively deliver safe drinking water (Bennett and Carroll 2014). However, the natural infrastructure approach is far from achieving the necessary scale to meet growing water challenges.

Many barriers lead to default investments that lock in capital expenditures and other operating costs in traditional infrastructure that will struggle to function under growing water stress and changing climate conditions. These barriers commonly include a lack of awareness and understanding of the benefits of natural infrastructure, a lack of capacity and experience in evaluating and implementing natural infrastructure projects, and a lack of the means and resources to finance natural infrastructure projects (Bennett and Carroll 2014, Gartner et al. 2013, Gartner et al. 2015, Ozment, DiFrancesco, and Gartner 2015). Although many watershed stakeholders explore opportunities to integrate natural infrastructure in water resources management, information is often scattered, inconsistent, or presented in an obscure manner, limiting their ability to effectively adopt natural infrastructure approaches to meet growing water challenges.

To help overcome these barriers and fill the information gap, the World Resources Institute (WRI) has developed Global Forest Watch Water (GFW Water), a publicly available global database and interactive mapping tool designed to help watershed stakeholders identify risks to their watersheds and opportunities for natural infrastructure solutions. GFW Water allows anyone with internet access to visualize critical watershed-related information, threats to watershed health, and screen

Figure 1.1 | **Target User Groups and Use Cases of Global Forest Watch Water**



for cost-effective, sustainable natural infrastructure solutions based on watershed characteristics and risk profiles. GFW Water can help downstream beneficiaries, financing and development institutions, civil society, and research groups apply natural infrastructure as one of their strategies to enhance water security and improve watershed management. These three target user groups and use cases are shown in Figure 1.1.

GFW Water compiles key data sets, models, near-real-time remotely sensed information, and advancements in data processing and visualization in a framework with three sections—know your watershed, identify watershed risks, and plan for action—as illustrated in Figure 1.2.

The sections of the framework are described below.

KNOW YOUR WATERSHED: Users can visualize critical watershed information and important water infrastructure on an interactive map. This section provides spatially explicit data and summary statistics on wetlands and waterbodies, tree cover, land cover, major dams, and urban water intakes.

IDENTIFY WATERSHED RISKS: Users can identify the types and severity of risks to watershed health through visualization of watershed conditions and a straightforward scoring of potential adverse impacts from changes in forest coverage, erosion, and fire, in the context of water stress. The four main risks to watersheds are recent forest loss, historical forest loss, erosion, and fire. GFW Water gives each major watershed a score in each risk category.

PLAN FOR ACTION: Users find relevant recommendations for natural infrastructure interventions in watershed conservation, restoration, and sustainable management practices according to watershed risk scores. This section also serves as a portal of resources on natural infrastructure, empowering users with guidance, decision-support tools, and case studies.

GFW Water provides summary statistics and watershed risk scores for 230 global watersheds, a layer developed by the Land and Water Division of the Food and Agriculture Organization of the United Nations (2011). In addition to using global watersheds, GFW Water allows users to select a point of interest as the effective watershed outlet and the tool will then locate and delineate subwatersheds for obtaining summary statistics and watershed risk scores. This custom analysis function is powered by the watershed geoprocessing service from Environmental Systems Research Institute (Esri) (2015).

This paper explains the underlying science and assumptions of natural infrastructure, describes data layers and information, documents the data sources, and details the methodology used to generate watershed risk scores in GFW Water. All data and maps are publicly available.

Figure 1.2 | **Global Forest Watch Water Tool Framework**

KNOW YOUR WATERSHED

- ■ Watershed
- ■ Wetlands and waterbodies
- ■ Tree cover (year 2000)
- ■ Land cover
- ■ Major dams
- ■ Urban water intakes

IDENTIFY WATERSHED RISKS

RECENT DEFORESTATION
- ■ Tree cover loss 2001–14
- ■ Tree cover (year 2000)

HISTORICAL DEFORESTATION
- ■ Tree cover (year 2000)
- ■ Potential forest coverage

EROSION
- ■ Erosion

FIRE
- ■ Average annual fire occurrence

PLAN FOR ACTION

- □ Spatial mapping tools and platforms
- □ Guidance and roadmaps
- □ Economics and finance
- □ Other WRI projects

KEY

■ Data Layer □ Natural Infrastructure Resources **WATERSHED RISK INDICATOR**

2. UNDERPINNING SCIENCE

GFW Water focuses on forest landscapes because they are one of the most important types of natural infrastructure for water. This section sets the foundation for selecting data sets and the four main risk indicators related to changes in a forested watershed, showing the potential impacts of these risks on the watershed's response to flow regulation and water quality control.

Forests have a number of characteristics that qualify them alongside retention ponds, filtration technology, and pre-sedimentation basins as critical natural water infrastructure. Abundant scientific evidence shows that healthy forested land can largely regulate the quantity and quality of water flowing through it to sustain essential watershed services (Asquith and Wunder 2008, Gartner et al. 2013, Neary, Ice, and Jackson 2009). Watersheds with more forest cover generally have higher groundwater recharge, lower stormwater runoff, and lower levels of sediment and nutrients in streams than areas dominated by urban and agricultural uses (Brett et al. 2005, Matteo, Randhir, and Bloniarz 2006, de la Cretaz and Barten 2007).

2.1 Natural infrastructure and flow regulation

With sturdy, long-lived roots, multi-layered canopies, and thick litter layers, forests help regulate water yield and streamflow and improve water availability especially at the regional scale (Ice 2004, de la Cretaz and Barten 2007, Ellison, Futter, and Bishop 2012).

The litter layer and roots. The litter layer, the underlying organic layer (humus), and the roots of an intact forest floor provide most of the forest's beneficial hydrologic functions of regulating flow and protecting soil from excessive erosion (Satterlund and Adams 1992). The litter and organic layers allow water to infiltrate the soil, slow down water movement, and reduce erosive forces from rainfall (Dudley and Solton 2003). Strong root systems anchor soil against erosion and create complex pore structures that keep forest soil permeable and allow it to absorb water (Beeson and Doyle 1995, Hornberger, Raffensperger, and Wiberg 1998, Neary, Ice, and Jackson 2009). Without an intact forest floor, the force of raindrops compacts the soil slightly and dislodges tiny particles that fill in the soil pores, resulting in reduced soil infiltration and increased overland flow of water (Stuart and Edwards 2006).

The canopy. Forests with multiple layers of foliage are more effective in intercepting rainfall than other vegetative assemblages (Neary, Ice, and Jackson 2009). The surface roughness and architecture of the leaves and stems and the shape of the canopy determine how effectively the canopy intercepts rainfall. These characteristics, in turn, depend on the canopy trees' species, age and density, and the management of the forest(Xiao et al. 2000). Forest canopies not only buffer the soil from erosion and compaction from raindrops, but their fallen leaves and other organic debris regularly replenish the forest floor with organic matter (Stuart and Edwards 2006).

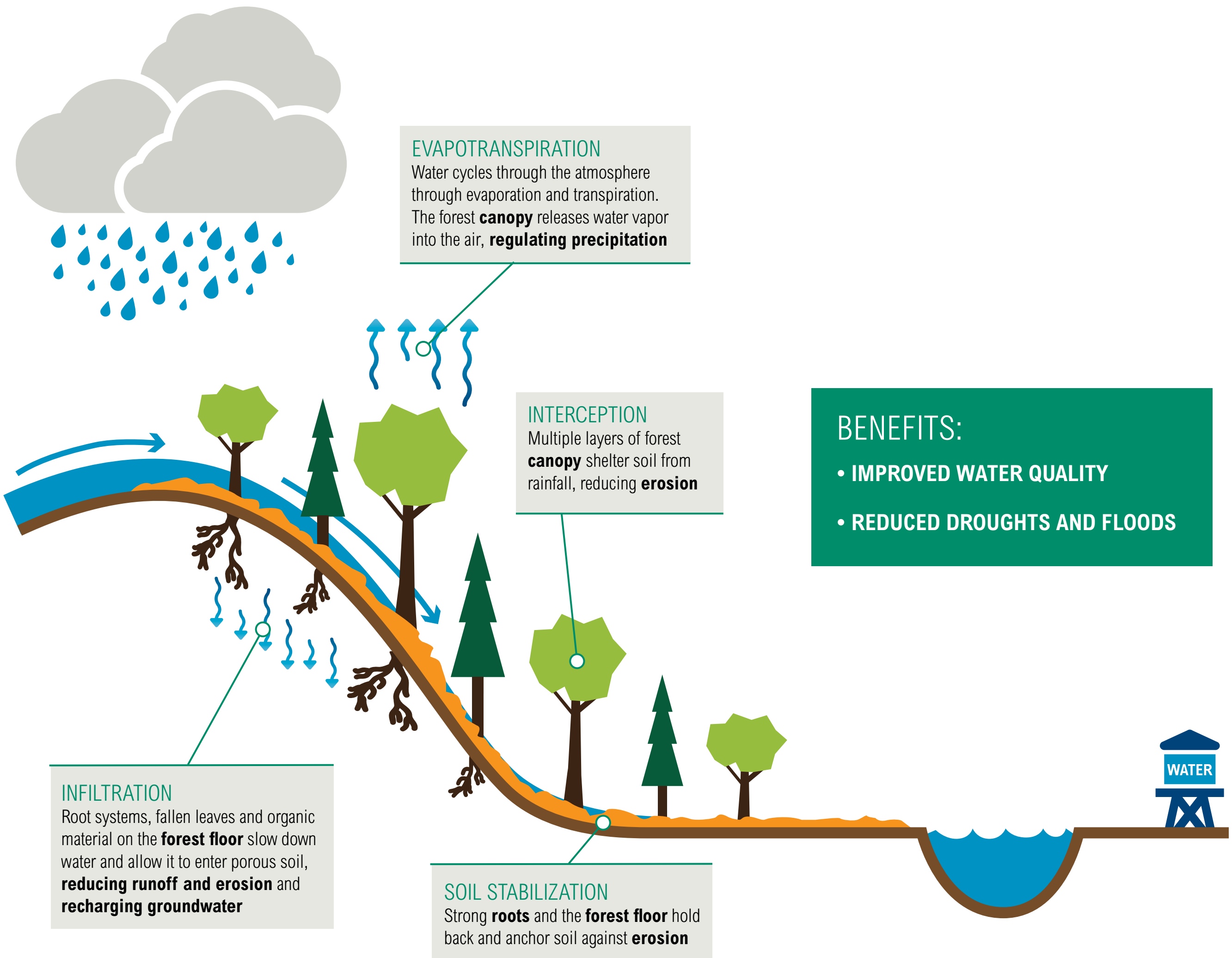
Forest cover can even intensify the water supply regionally and globally because evapotranspiration from trees helps generate atmospheric pressure differences that leads to precipitation (Ellison, Futter, and Bishop 2012, Trabucco et al. 2008, Sheil and Murdiyarso 2009). Precipitation recycling not only raises the likelihood of local rainfall, but also drives the cross-continental transport of moisture vapor and thus increases precipitation in locations distant from the ocean-based hydrologic cycle (Ellison, Futter, and Bishop 2012).

2.2 Natural infrastructure and water quality control

Most of waterways' turbidity and organic pollution—which comes from excess organic carbon, nitrogen, and phosphorous—is caused by sediment and nutrients flowing from the soil into the streams (Freeman, Madsen, and Hart 2008). Forests, especially vegetation along streambanks, help improve water quality by minimizing the amount of sediment and nutrients that flow into streams by holding the water in the soil where the nutrients can be taken up by plants and soil microbes.

Streamflow is a primary factor determining the turbidity level of a waterbody (Stuart and Edwards 2006). To transport suspended sediment, streamflow must have sufficient energy to lift and move the sediment particles and overcome forces that might inhibit them from settling on the streambed. During storms, energy from the increased volume and velocity of the streamflow displaces and carries more sediment from disturbed areas, such as those with exposed soils. In most forested watersheds, where the forest floor holds back organic material and soil, the amount of sediment supply is limited, reaching maximum sediment or turbidity levels before streamflow peaks and returning quickly to pre-storm conditions (Stuart and Edwards 2006, Sharp 2007). Nutrients are retained, even

Figure 2.1 | **Natural Infrastructure Supports Water Security**



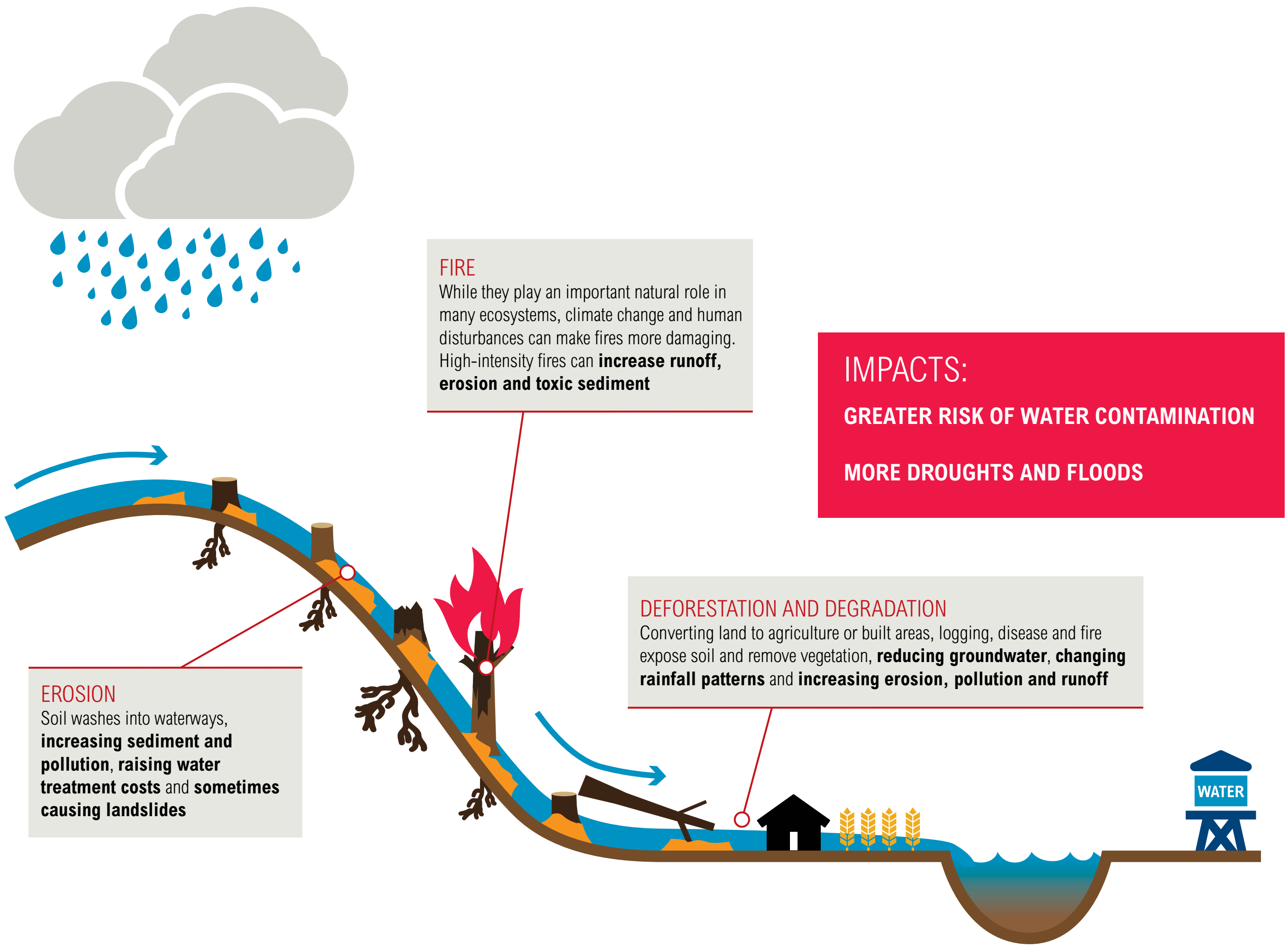
after agricultural fertilizer application and harvesting, because perennial plant uptake and organic matter in soils help retain nutrients in runoff through forested watersheds (Sanders and McBroom 2013, McBroom et al. 2008).

In short, the forest floor characteristics that promote infiltration, subsurface flow, and soil moisture storage also minimize surface erosion and reduce storm flow peaks, rendering overland water flow and associated erosion unlikely for all but the most intense storms (Neary, Ice, and Jackson 2009). The water flow path of a forested watershed, showing the important components of a healthy forested watershed and their role in regulating water flow and water quality, is illustrated in Figure 2.1.

2.3 Impacts of disturbances on watershed services

As forests are converted to other land uses or otherwise disturbed, the benefits of their watershed services usually diminish, putting communities at risk of flood, drought, higher water treatment costs, and greater threat of drinking water contamination (Ice 2004, de la Cretaz and Barten 2007). Forest disturbances affect the pathways of water within the forest system, affecting the interception, evapotranspiration, infiltration, and overland flow in a watershed, and leading to changes in water flow and quality (National Research Council 2008). Deforestation, tree harvesting, spread of insects or disease, construction of roads and

Figure 2.2 | **Deforestation and Land Degradation Threaten Water Supplies**



trails, and high-severity fires are among the most common threats to watershed services. Impacts from disturbances on watershed services provision is illustrated in Figure 2.2.

Effects of disturbances on flow regulation

The effects of disturbances on water yield (the long-term average water flow) and streamflow (the rate of flow by volume) are generally commensurate with the scope and scale of the disturbance. The impact of forest cover on water quantity varies across forested watersheds (Trabucco et al. 2008, Ellison, Futter, and Bishop 2012, Jones et al. 2009).

When canopy trees are removed, rainfall interception is reduced, and rain disturbs the forest floor decreasing its capacity to retain water (National Research Council 2008). Studies have found that removing a forest generally leads to a period of increased water yield as the soil loses its ability to hold water (Ellison, Futter, and Bishop 2012). When forests are cleared or converted to shallow-rooted plants or to roads and other impervious surfaces (e.g., roofs, trails, and parking lots), the forest floor is altered so it can no longer hold water, resulting in increases in peak flow and leading to flooding and scouring (de la Cretaz and Barten 2007). The magnitude and duration of increased water runoff and streamflow following forest removal

depends on the amount, age, and type of forest that was removed, the season and climate, the size of precipitation events, and other factors, such as watershed size and topography (Ellison, Futter, and Bishop 2012, Jackson et al. 2005, Farley, Jobbagy, and Jackson 2005, National Research Council 2008). Removal of forests can also lead to a decrease in precipitation locally as well as regionally because canopy evapotranspiration can no longer facilitate precipitation (Ellison, Futter, and Bishop 2012, National Research Council 2008, Nobre 2014).

Effects of disturbances on water quality control

Although sediment and nutrient yields from forested watersheds can vary naturally, many studies have shown that when forests are disturbed or converted to cropland, pasture, or urban areas, water flow pathways change resulting in degraded water quality from increases in organic pollutants and sediment discharges (Brooks et al. 2003, Renard et al. 1997, Freeman, Madsen, and Hart 2008).

As subsurface flows in forested land change to overland flows in disturbed land, increased sediment is delivered to streams and water bodies (Endreny 2002, Stuart and Edwards 2006). Long-term shifts in the types of land cover and concurrent changes in water yield and streamflow often alter stream channel morphology leading to erosion with long-term impacts. Conversion of forests to cropland, pasture, or urban areas can lead to significant increases in sedimentation, nutrient, and other pollutants and change biogeochemical cycling (Freeman, Madsen, and Hart 2008). Finally, high-severity fires can cause massive erosion and an increased flow of toxic sediments into the water system (National Research Council 2008).

While the effects of any given land-cover change on water resources can vary across and within watersheds, improving the quality, scale, and type of forest is likely to lead to better access to water for downstream communities across a broad region and over the long term.

3. DATA AND METHODS

Building on the scientific underpinnings of the relationship between natural infrastructure and watershed services, GFW Water brings together most relevant global spatial data sets to help users visualize watershed conditions, understand the types and severity of risks facing watersheds around the world, and obtain guidance on planning natural infrastructure initiatives.

The process for selecting GFW Water data sets and developing watershed risk scores involved three steps: (1) a literature review on the scientific justification of natural infrastructure and the risks posed to a watershed's capacity to deliver essential services when natural conditions are altered; (2) a survey and review of relevant data sources, publications, and existing spatial analytical tools in the public domain; and (3) a compilation of expert reviews of available data sets and methodologies. Descriptions and sources of the data sets and the methodology used to incorporate these data into GFW Water are specified below according to the three sections of GWF Water. All data sets have global coverage unless otherwise stated.

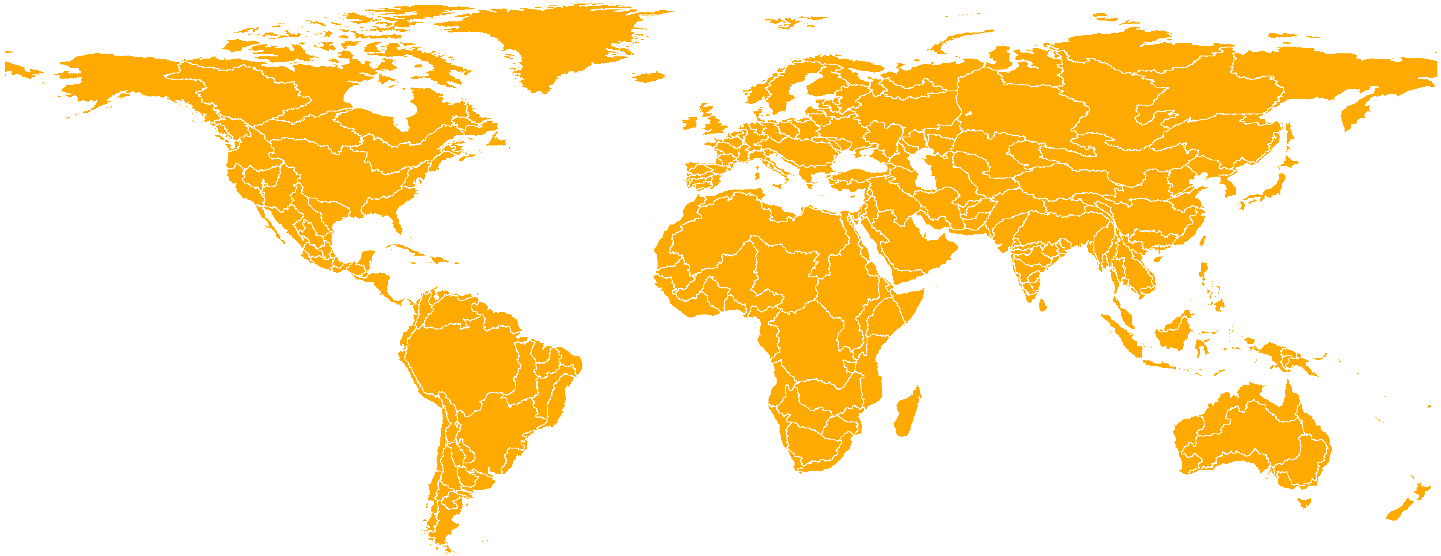
3.1 Know Your Watershed

This section of GFW Water uses six spatial data sets—watersheds, wetlands and waterbodies, tree cover, land cover, major dams, and urban water intakes—and produces the summary statistics described in Table 3.1 on key watershed-related information and water infrastructure. The data sets are described below.

Table 3.1 | **Summary Statistics Provided in Global Forest Watch Water**

SPATIAL DATA SET	SUMMARY STATISTICS
Watersheds	Area
Wetlands and Waterbodies	Area of wetlands
Tree Cover	Area
Land use	Percent and area for each class
Major dams	Count
Urban Water Intakes	Count

Figure 3.1 | **Global Watersheds in Global Forest Watch Water**



Watersheds

This data set is a series of polygons that delineates boundaries of 230 watersheds of the world (Figure 3.1). GFW Water provides summary statistics and watershed risk scores at this watershed scale. We define a watershed as an area of land in which all of the water that falls in its boundary drains to a common outlet. Watershed boundaries were extracted from the World Map of the Major Hydrological Basins based on HydroSHEDS (FAO 2011).

DATA INPUTS:

VARIABLE	WATERSHEDS
Author	Food and Agriculture Organization of the United Nations
Title	World map of the major hydrological basins (Derived from HydroSHEDS)
Resolution	15 seconds between 60° N and 60° S latitude (based on SRTM), and 30 seconds for higher latitudes (based on GTOPO30)
Date of content	2011
URL	http://www.fao.org/geonetwork/srv/en/metadata.show?id=38047

Wetlands and Waterbodies

This data set estimates large-scale wetland distributions and important wetland complexes, including areas of marsh, fen, peatland, and water (Lehner and Döll 2004). Large rivers (lotic wetlands) are also included; it is assumed that only a river with adjacent wetlands (floodplain) is wide enough to appear as a polygon on the coarse-scale source maps. Wetlands are a crucial part of natural infrastructure because they help protect water quality, hold excess floodwater, stabilize shoreline, and help recharge groundwater (Beeson and Doyle 1995, Stuart and Edwards 2006). Limited by sources data, the data set defines lakes as permanent still-water bodies (lentic water bodies) without a direct connection to the sea, including saline lakes and lagoons, but excluding intermittent or ephemeral water bodies. Human-made lakes are classified as reservoirs. The Global Lakes and Wetlands Database combines best-available sources for lakes and wetlands on a global scale (1:1 to 1:3 million resolution). This data set includes information on 3,067 large lakes (equal to or greater than 50 square kilometers) and reservoirs (storage capacity equal to or greater than 0.5 cubic kilometers), permanent open water bodies with a surface area equal to or greater than 0.1 square kilometers, and maximum extents and types of wetlands.

DATA INPUTS:

VARIABLE	WETLANDS AND WATERBODIES
Author	B. Lehner and P. Döll
Title	The Global Lakes and Wetlands Database
Resolution	30 seconds
Date of content	2004
URL	https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database

Tree Cover

This data set displays tree cover over all global land for the year 2000 at 30-meter resolution. It is the best available global data estimating the extent of global forest cover. For this study, "tree cover" is defined as all vegetation taller than 5 meters. Tree cover is the biophysical presence of trees and may take the form of natural forests or plantations existing over a range of canopy densities. Natural forests occur at many canopy densities; to encompass these differences, we analyzed forest cover in terms of percentage of tree cover, defined as the density of tree canopy coverage of the land surface. Data were generated using multispectral satellite imagery from the Landsat 7 thematic mapper plus (ETM+) sensor. The clear surface observations from over 600,000 images were analyzed using Google Earth Engine, a cloud platform for earth observation and data analysis, to determine per pixel tree cover using a supervised learning algorithm (Hansen et al. 2013).

DATA INPUTS:

VARIABLE	TREE COVER
Author	M. C. Hansen, P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend
Title	High-Resolution Global Maps of 21st-Century Forest Cover Change
Resolution	30 meters
Date of content	2000
URL	http://earthenginepartners.appspot.com/science-2013-global-forest

Land Cover

Land cover at a watershed level provides a glimpse into the health of a watershed because some types of human-dominated landscapes, such cropland and urban areas, may lead to adverse impacts on water quality and flow (de la Cretaz and Barten 2007, Ice 2004). Land cover is displayed by type. GlobCover Land Cover contains 22 classes of land cover at 300-meter resolution, drawing on the UN Land Cover Classification System. Land cover classes were grouped into six categories of similar intensity and potential impact on watershed health: crop, forest, shrub/grassland, urban, bare, and other (Table 3.2). Satellite imagery comes from the ENVISAT satellite mission's MERIS sensor, covering the period from January–December 2009.

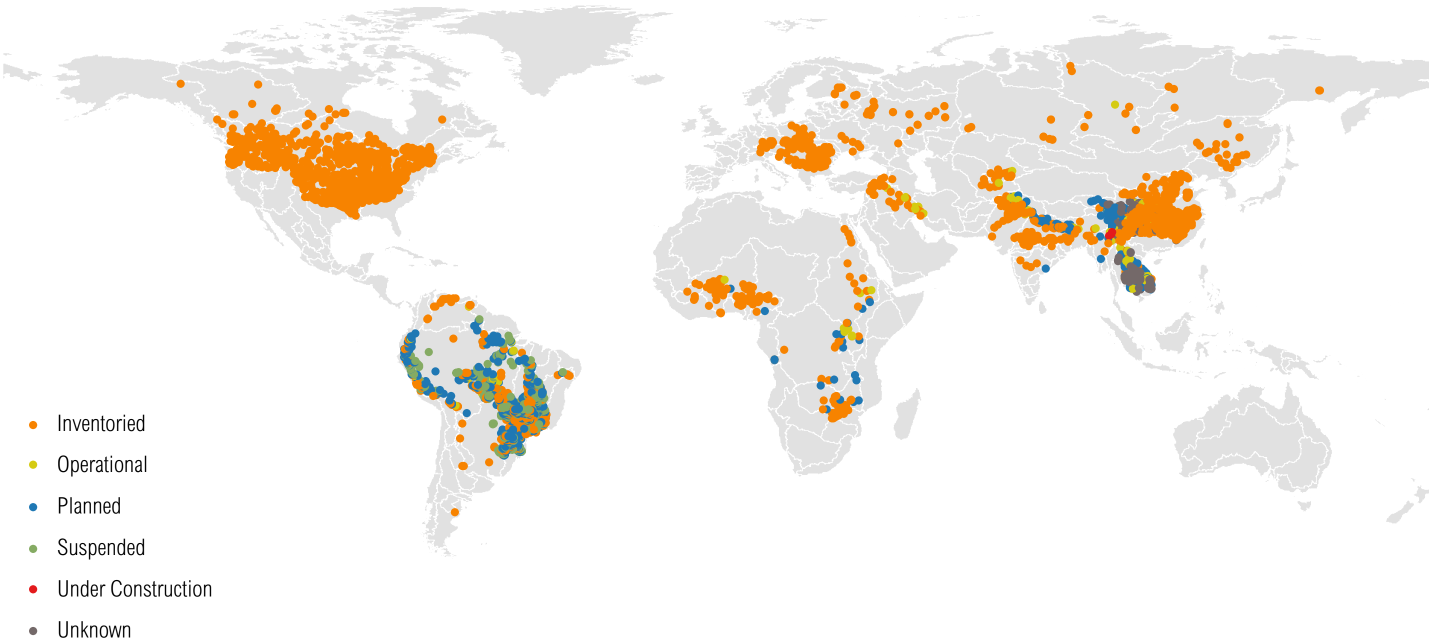
DATA INPUTS:

VARIABLE	LAND COVER
Author	O. Arino, J. J. Ramos Perez, V. Kalogirou, S. Bontemps, P. Defourny, and E. Van Bogaert
Title	Global Land Cover Map for 2009
Resolution	300 meters
Date of content	2010
URL	http://dup.esrin.esa.int/page_globcover.php

Table 3.2 | **Land Cover Classes and Corresponding Labels Used in GlobCover Land Cover v2.**

LAND COVER CLASS	GLOBCOVER LABEL
Crop	Post-flooding or irrigated croplands (or aquatic)
	Rainfed croplands
	Mosaic cropland (50–70%) / vegetation (grassland/shrubland/forest) (20–50%)
	Mosaic vegetation (grassland/shrubland/forest) (50–70%) / cropland (20–50%)
Forest	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
	Closed (>40%) broadleaved deciduous forest (>5m)
	Open (15–40%) broadleaved deciduous forest/woodland (>5m)
	Closed (>40%) needleleaved evergreen forest (>5m)
	Open (15–40%) needleleaved deciduous or evergreen forest (>5m)
	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)
	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) – Fresh or brackish water
	Closed (>40%) broadleaved forest or shrubland permanently flooded – Saline or brackish water
	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil – Fresh, brackish or saline water
Shrub/Grassland	Mosaic forest or shrubland (50–70%) / grassland (20–50%)
	Mosaic grassland (50–70%) / forest or shrubland (20–50%)
	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)
	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
	Sparse (<15%) vegetation
Urban	Artificial surfaces and associated areas (Urban areas >50%)
Bare	Bare areas
Other	Water bodies
	Permanent snow and ice
	No data (burnt areas, clouds, and so on)

Figure 3.2 | **Locations of Over 5,000 Dams in the World's 50 Major River Basins**



Source: International Rivers 2014.

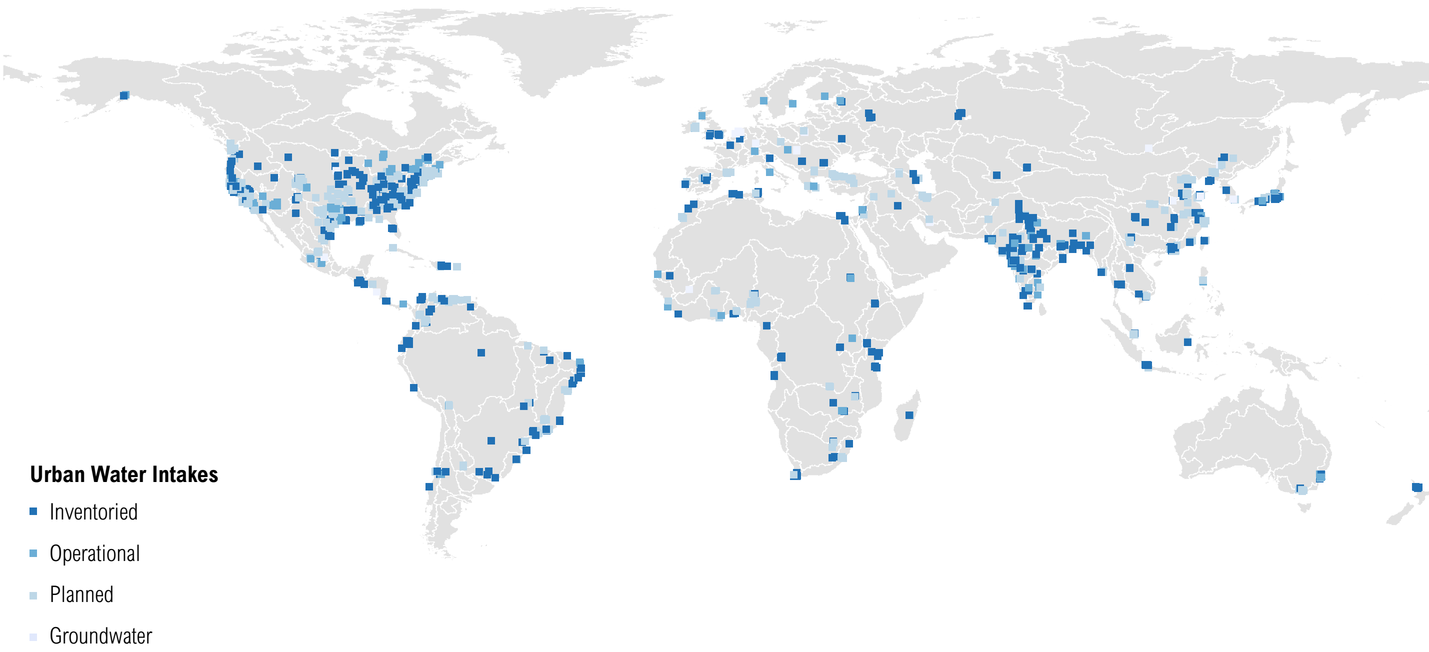
Major Dams

This data set identifies locations of over 5,000 dams in 50 major river basins (Figure 3.2). The data set is not global and is limited by information availability. The benefits of natural infrastructure are important for dam function and longevity because forested landscapes reduce the amount of sediment flowing into the reservoir thus prolonging the storage capacity of dams and decreasing the need for costly dredging (Freeman, Madsen, and Hart 2008). The data are derived from the State of the World's Rivers interactive web database, which illustrates data on ecological health in the world's 50 major river basins. The data set comes from multiple sources, and was corrected for location errors by International Rivers, a nongovernmental organization. The dams' status were determined by official government data, as well as by primary research from the University of California-Berkeley and five International Rivers' regional offices.

DATA INPUTS:

VARIABLE	MAJOR DAMS
Author	International Rivers
Title	The State of the World's Rivers: Mapping the Health of the World's Fifty Major River Basins
Resolution	Varies by watershed
Geographic coverage	This data set is not global. The data is confined to the world's 50 major river basins.
Date of content	2014
URL	http://tryse.net/googleearth/irivers-dev3/
Cautions	Data results are biased toward publicly available data, so gaps may exist.

Figure 3.3 | **Urban Water Intake Locations for Over 500 International Cities**



Source: Robert McDonald and The Nature Conservancy 2016.

Urban Water Intakes

This data set contains over 1,500 water intake locations determined by latitude and longitude coordinates from the first global survey of the water sources for over 500 large cities (Figure 3.3). Watershed condition and disturbances directly affect water utilities' ability to provide ample, clean water in a timely manner. The dataset was created and published by Robert McDonald and The Nature Conservancy (2016). These locations come from research on water utilities and their annual reports. The locations were recorded as accurately as possible and freshwater withdrawal points were adjusted to match the underlying hydrographic river system. Some intake points serve multiple water utilities and cities.

DATA INPUTS:

VARIABLE	URBAN WATER INTAKES
Author	Robert McDonald and The Nature Conservancy
Title	City Water Map (version 2.2)
Resolution	Varies by watershed
Geographic coverage	This data set is not global. The data is confined to over approximately 500 international cities.
Date of content	2016
URL	https://knb.ecoinformatics.org/#view/doi:10.5063/F1J67DWR
Cautions	Information is restricted by availability. Some cases of interbasin transfer for water supply may not be reflected.

3.2 Identify Watershed Risks

This section of GFW Water presents type and severity of risks to watershed health from changes in forest coverage, erosion, and fire, in the context of baseline water stress. The data is shown through spatial visualization and scoring.

Given the inherent heterogeneity among and within watersheds around the world, we do not intend to provide a definitive, causal relationship between the indicators and a specific watershed's ability to deliver ecosystem services. Based on abundant scientific evidence on the linkage between the condition of a watershed and its ability to deliver essential services, we created a relative measure of critical indicators of watershed condition that are comparable across the globe to allow users to prioritize areas for further assessment and appropriate response. Information on baseline water stress sets the context for landscape water-related risk for a given watershed.

Watershed risk is defined as the potential adverse effects on a watershed's ability to deliver critical ecosystem services—including water flow regulation and water quality control—from a particular stressor. To assess risk, we selected indicators that concisely capture different aspects of watershed conditions and evaluate the health of the watershed. Based on scientific evidence and available data, we selected four risk indicators: (1) recent forest loss; (2) historical forest loss; (3) erosion; and (4) fire, all set in the context of baseline water stress. These risk indicators are known to affect the hydrological responses of a forested watershed in various ways (see section 2, "Underpinning Science"). Some of these indicators are correlated; for example, forest loss and fire both lead to erosion. But these risk indicators are presented separately because their causes are various and they lead to different management implications described in the GFW Water "Plan for Action" section. Indicator values were calculated for all 230 global watersheds. Risk scores can be generated for subwatersheds based on user-selected outlets.

To place all indicators on a comparable scale, we normalized raw values (*r*) of each indicator over a set of thresholds and divided them into scores (*x*) between 0 and 5, where a higher score indicates greater risk. For each indicator, we determined thresholds based on existing literature, range and distribution of indicator values, and expert judgment. We sought to create meaningful risk scores based on sound scientific evidence and best practices while avoiding creating an overly complex system that could confuse users. Given the numerous factors affecting the magnitude and duration of a watershed's hydrologic responses to changes across the globe, we determined risk scores for each indicator based on the distribution of the raw values (*r*), where some exceptions were applied and explained in the following sections. For each risk indicator, we ranked the r of applicable watersheds, where those in the lowest quantile (q1) received a score of 1 and the highest quantile (q5) received a score of 5. The normalization of raw scores and descriptions of the risk categories are given in Table 3.3.

Table 3.3 | **Definitions of GFW Water Watershed Risk Scores**

SCORE (X)	RISK CATEGORY	DESCRIPTION
1	Low	Probability of adverse effect from stressor is low. No advice to response.
2	Low to Medium	Probability of adverse effect from stressor is low to medium. No advice to response.
3	Medium	Probability of adverse effect from stressor is medium. Consider further analysis to evaluate the condition.
4	Medium to High	Probability of adverse effect from stressor is medium to high. It is advisable to conduct further investigation and take appropriate action.
5	High	Probability of adverse effect from stressor is high. It is highly recommended to conduct further investigation and take immediate appropriate action.

A score of 4 or above, for which the probability of an adverse effect is medium to high, indicates a need for further investigation and appropriate action. GFW Water Section 3, "Plan for Action" provides recommendations on potential natural infrastructure approaches for watersheds with risk indicators of 4 or above.

The following sections detail the definitions, methodology, data specifications, and normalization of raw values to risk scores. Descriptions of each indicator, its data sources, and calculation methods are given.

Recent Forest Loss

Description: The recent forest loss indicator estimates the potential of damaging impact from recent changes (2001–14) in the extent of forest cover in a watershed. Removal of forest in recent years may lead to changes in water yield, overland runoff and risk of flooding, as well as water quality degradation. In addition to the amount of forest removed, the duration and magnitude of a watershed's response depends on factors, including age and type of forest removed, climate, topography, and size of the watershed.

DATA INPUTS:

Tree Cover Loss. This data set measures areas of tree cover loss across all global land at approximately 30-meter resolution. The data were generated using multispectral satellite imagery from the Landsat 5 thematic mapper (TM), the Landsat 7 thematic mapper plus (ETM+), and the Landsat 8 Operational Land Imager (OLI) sensors. Over 1 million satellite images were processed and analyzed, including over 600,000 Landsat 7 images for the 2000–12 interval, and approximately 400,000 Landsat 5, 7, and 8 images for updates for the 2011–14 interval. The clear land surface observations in the satellite images were assembled and a supervised learning algorithm was applied to identify per pixel tree cover loss. Tree cover loss is defined as "stand replacement disturbance," or the complete removal of tree cover canopy at the Landsat pixel scale. Tree cover loss may be the result of human activities, including forestry practices such as timber harvesting or deforestation (the conversion of natural forest to other land uses), as well as natural causes such as disease or storm damage. Fire is another widespread cause of tree cover loss, and can be either natural or human-induced.

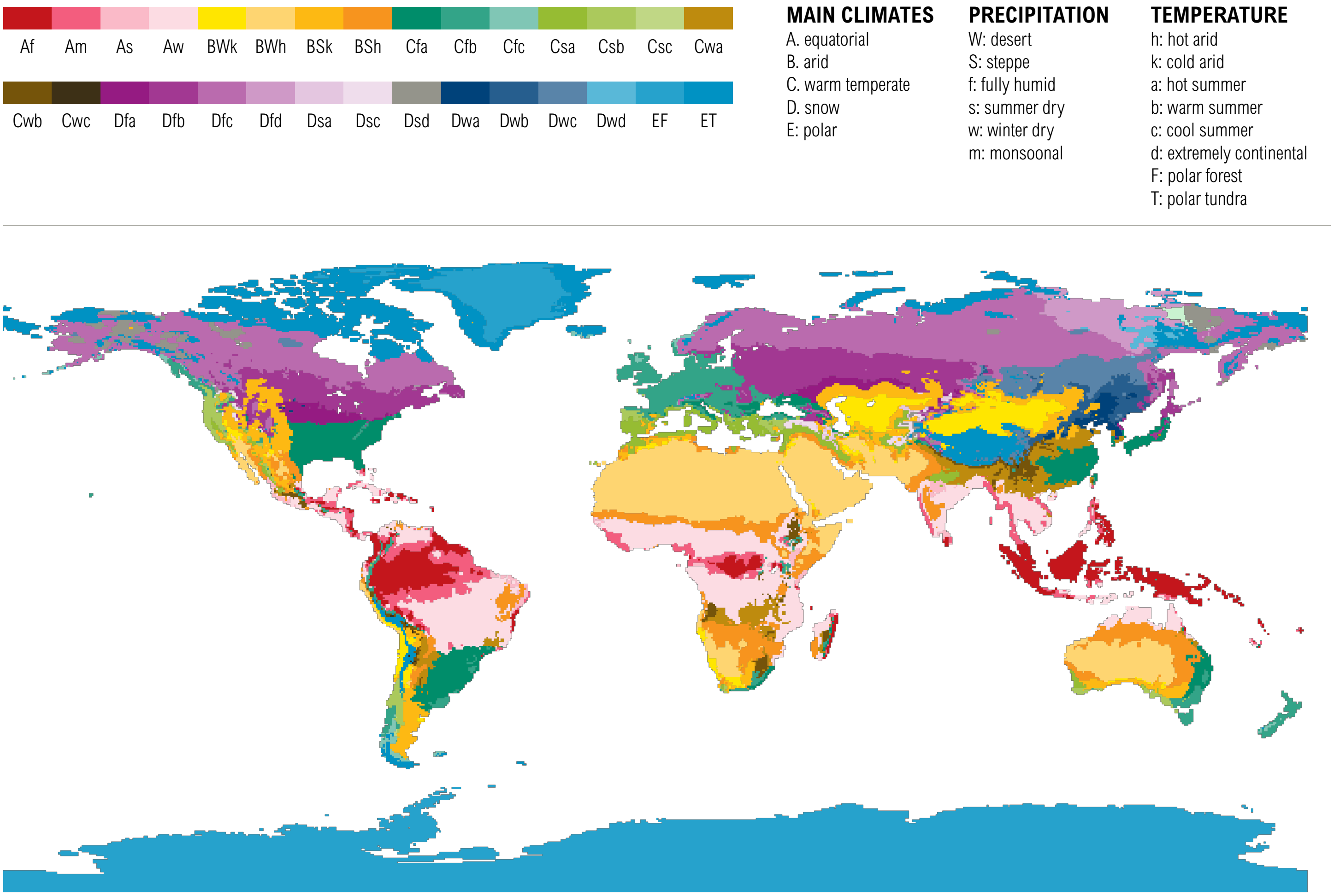
VARIABLE	TREE COVER LOSS
Author	M. C. Hansen, P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend
Title	High-Resolution Global Maps of 21st-Century Forest Cover Change
Resolution	30 meters
Date of content	2001–14
URL	http://earthenginepartners.appspot.com/science-2013-global-forest

Tree Cover. See section 3.1, "Know Your Watershed."

Climate Zones. Climate zones present Köppen–Geiger climate classification for the globe based on temperature and precipitation observations from 1976–2000, derived from recent data sets from the Climatic Research Unit (CRU) of the University of East Anglia and the Global Precipitation Climatology Centre (GPCC) at the German Weather Service. The global distribution of climate zones is shown in Figure 3.4.

VARIABLE	CLIMATE ZONES
Author	F. Rubel, and M. Kottek
Title	Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification
Resolution	0.5°
Date of content	2010
URL	http://koeppen-geiger.vu-wien.ac.at/shifts.htm

Figure 3.4 | World Map of Köppen–Geiger Climate Classifications, 1976–2000



Source: Rubel and Kattek 2010

Calculation: The risk indicator on recent forest loss (r_1) was measured by the area of total forest loss from 2001 to 2014 as a share of total forest extent (year 2000). The threshold of canopy density for identifying forest and forest loss is set to greater than 30 percent across the globe, which may include natural forest, plantations, and other forms of vegetation depending on the region. We masked out watersheds where the percentage of arid area is greater than 80 percent or where forest cover (year 2000) is less than 10 percent; these areas are more prone to error in estimating tree cover change and the impact of forest cover on regulating water regimes (National Research Council 2008). Arid areas include cold and hot desert and steppe, identified under codes BWh, BWk, BSh, and BSk according to the Köppen–Geiger climate classification (see Figure 3.4).

$$r_1 = \frac{tl}{tc}, \quad \frac{arid}{ws} \leq 80\% \text{ and } \frac{tc}{ws} \geq 10\%$$

where

$\boldsymbol{r_1}$ = recent forest loss

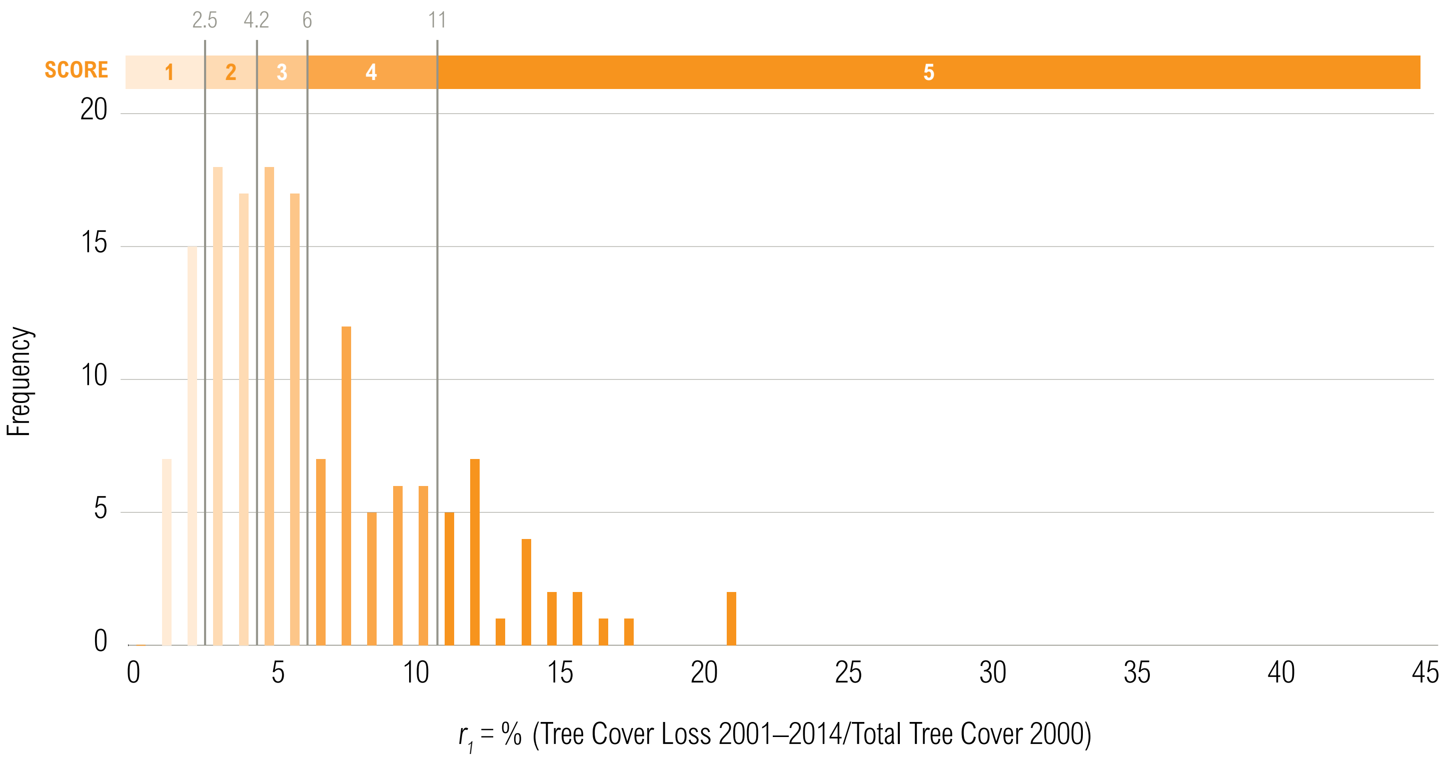
tl = area of forest loss from 2001 to 2014, canopy density at 30%

tc = area of forest extent in year 2000, canopy density at 30%

arid = arid area identified under BWh, BWk, BSh, and BSk according to the Köppen–Geiger climate classification

ws = area of watershed

Figure 3.5 | **Distribution of Recent Forest Loss (r_1) in Global Watersheds and Risk Scoring Thresholds**



We then normalized r_1 for the remaining 153 global watersheds into five quantiles and assigned scores between 1 and 5. Figure 3.5 illustrates the distribution of r_1 and summarizes the threshold value for each score category.

Historical Forest Loss

Description: The indicator on historical forest loss measures the potential threat to a watershed's capacity to deliver ecosystem services as a result of forest cover change in the past (prior to 2000). Compared with recent forest loss, forest loss that took place decades ago may lead to different hydrological responses with greater uncertainty in a watershed (National Research Council 2008). In addition to the extent of forest removed, other factors that contribute to a watershed's capacity to regulate flow and control water quality include age and type of forest removed, climate, and land management since forest removal.

DATA INPUTS:

Potential forest coverage. The map of potential forests represents an estimate of where forests would grow under current climate conditions without human influence. The main source of data for defining potential forest extent is the terrestrial ecoregions of the world (Olson et al. 2001). Each ecoregion was classified as belonging to one of four categories: dense forests, open forests, woodlands, or non-forest, depending on its description (including current and potential vegetation) and its proportion of different forest types, with additional input from the following data sets: current forest extent; bioclimatic zoning and original forest cover extent; and a forest distribution map produced by modeling based on global climate variables and elevation (Hansen et al. 2013, Zomer et al. 2007). The data set is based on significant simplifications due to limited availability of globally consistent data. The maps are at a relatively coarse scale and should only be used to estimate potential forest coverage at regional or global scale. Estimates of potential forest coverage are based on current climate conditions and the absence of human disturbance.

VARIABLE	POTENTIAL FOREST COVERAGE
Author	P. Potapov, L. Laestadius, and S. Minnemeyer
Title	Global Map of Potential Forest Cover
Resolution	1 kilometer
Date of content	2011
URL	www.wri.org/forest-restoration-atlas

Tree Cover. See section 3.1, "Know Your Watershed."

Climate Zones. See section "Recent Forest Loss" in section 3.2, "Identify Watershed Risks."

Calculation: The historical forest loss indicator (r_2) was approximated by comparing total forest extent (year 2000) to potential forest coverage. The threshold of canopy density for identifying forest and forest loss is set to greater than 30 percent across the globe. The indicator is not applicable to watersheds where the percentage of arid area is greater than 80 percent or where potential forest coverage is less than 10 percent, as estimates for these areas are more likely to result in erroneous estimation of the significance of tree cover condition and change. Arid areas include cold and hot desert and steppe, identified under codes BWh, BWk, BSh, and BSk according to the Köppen–Geiger climate classification. In cases where total tree cover (year 2000) exceeds potential forest coverage due to different data origins, we capped r_2 at 0.

$$r_2 = 1 - \frac{tc}{pfc}, \quad \frac{arid}{ws} \leq 80\% \text{ and } \frac{pfc}{ws} \geq 10\%$$

where

r_2 = historical forest loss

pfc = potential forest coverage

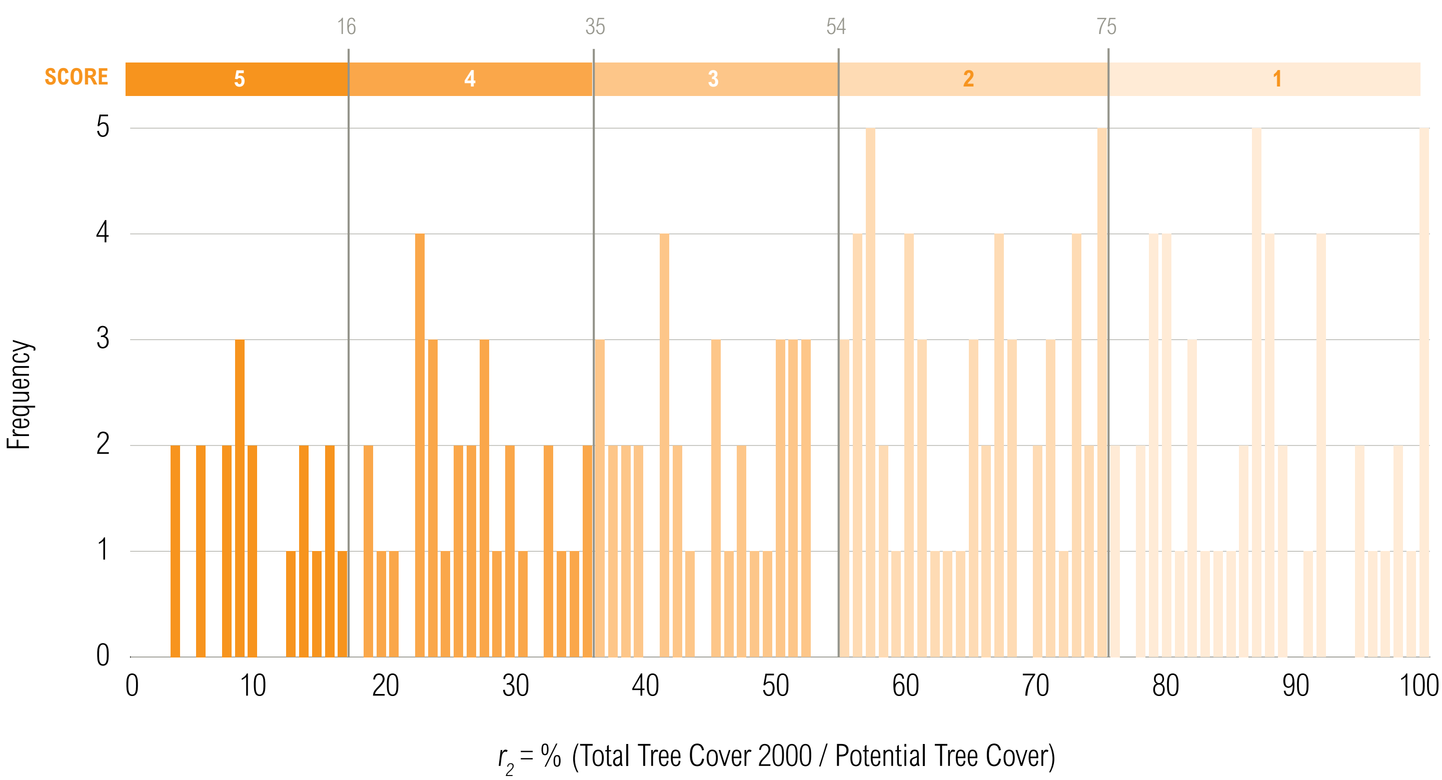
tc = area of forest extent in year 2000, canopy density at 30%

arid = arid area identified under BWh, BWk, BSh, and BSk according to the Köppen–Geiger climate classification

ws = area of watershed

We then categorized r_2 for the remaining 183 global watersheds into five quantiles and assigned scores of 1 to 5. Figure 3.6 displays the distribution of r_2 and lists the threshold values for the score categories.

Figure 3.6 | **Distribution of Historical Forest Loss (r_2) in Global Watersheds and Risk Scoring Thresholds**



Erosion

Description: This indicator estimates the potential threat to water quality in a watershed from erosion resulting from rainfall and runoff. Erosion is a significant problem that affects both water quality and quantity (i.e., reservoir capacity). High erosion deteriorates water quality and reduces capacity of reservoirs, increasing cost of water treatment and capital expenses, and damaging safety of water supplies. High erosion risk is usually linked to erodible soil, intense rainfall, steep topography, conversion of forest and other natural land covers to pasture or cropland, and other human activities.

DATA INPUTS:

Average Annual Precipitation. Average annual precipitation was generated through interpolation of average monthly climate data from weather stations on a 30 arc-second resolution grid from 47,554 locations from 1995 to 2000 (Hijmans et al. 2005). The interpolated annual precipitation layer was derived from major climate databases compiled by the Global Historical Climatology Network (GHCN), the FAO, the World Meteorological Organization, the International Center for Tropical Agriculture (CIAT), R-HYdronet, and other minor databases for Australia, New Zealand, the Nordic European Countries, Ecuador, Peru, and Bolivia, among others; and the Shuttle Radar Topography Mission (SRTM) elevation database (aggregated to 30 arc-seconds).

VARIABLE	AVERAGE ANNUAL PRECIPITATION
Author	R. J. Hijmans, S. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis
Title	Very high resolution interpolated climate surfaces for global land areas
Resolution	30 seconds
Date of content	2005
URL	http://www.worldclim.org/current

Elevation. Global elevation data were derived from elevation data of the SRTM. The original SRTM data have been hydrologically conditioned using a sequence of automated procedures. Existing methods of data improvement and newly developed algorithms have been applied, including void filling, filtering, stream burning, and upscaling techniques (Lehner, Verdin, and Jarvis 2006). Manual corrections were made where necessary.

VARIABLE	ELEVATION
Author	B. Lehner, K. Verdin, and A. Jarvis
Title	15 sec GRID: Conditioned digital elevation model (DEM)
Resolution	15 seconds
Date of content	2006
URL	http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=15demg

S Factor. S factor is the slope steepness factor used in the Revised Universal Soil Loss Equation (RUSLE). Naipal et al. (2015) developed the S factor for the globe to account for detailed spatial variability using arelatively coarse global data set. Assuming topography to be fractal, slope was expressed as a function of the spatial scale by applying the variogram equation to approximate the fractal dimension of topography. For more detail, see Naipal et al. (2015).

VARIABLE	S FACTOR
Author	V. Naipal, C. Reick, J. Pongratz, and K. Van Oost
Title	Improving the global applicability of the RUSLE model adjustment of the topographical and rainfall erosivity factors
Resolution	5 minute
Date of content	2015
URL	http://www.geosci-model-dev-discuss.net/8/2991/2015/gmdd-8-2991-2015.pdf

Soil Properties. Soil properties (K factor and organic content) were derived from the Harmonized World Soil Database, which is a 30 arc-second raster database with over 15,000 soil mapping units that combines regional and national updates of soil information worldwide. The database includes data on organic carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum content, sodium exchange percentage, salinity, textural class, and granulometry.

VARIABLE	SOIL PROPERTIES
Author	F. Nachtergaele, H. van Velthuizen, L. Verelst, N. Batjes, K. Dijkshoorn, V. van Engelen, G. Fischer, A. Jones, L. Montanarella, M. Petri, and S. Prieler
Title	Harmonized World Soil Database (version 1.2)
Resolution	30 second
Date of content	2012
URL	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

Land Cover. See section 3.1, "Know Your Watershed."

Calculation: Erosion and sedimentation by water involves the process of detachment, transport, and deposition of soil particles, driven by forces from raindrops and water flowing over the land surface (Renard et al. 1997). Because soil erosion is difficult to measure at large scales, soil erosion models are crucial estimation tools to extrapolate limited data to other localities and conditions. The Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997), which predicts annual soil loss from rainfall and runoff, is most frequently used at large spatial scales due to its relatively simple structure and empirical basis (Kinnell 2010, Naipal et al. 2015, Yang et al. 2003). RUSLE computes the expected average annual erosion as:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where

A = computed potential average soil loss per unit of area and time period.

R = rainfall erosivity factor that measures the impact of kinetic energy and intensity of raindrops on soil surface, which leads to detachment and transport of soil particles. The greater the intensity and duration of the rain storm, the higher the erosion potential. Erosive forces due to snowmelt, snow movement, rain on frozen soil, or irrigation are not included.

K = soil erodibility factor that measures soil loss rate for a specified type of soil as measured on a standard plot, which is defined as a 22.1-meter length of 9 percent slope in continuous clean-tilled fallow. K measures the susceptibility of soil particles to detachment and transport by rainfall and runoff. Texture is the principal factor affecting K, but structure, organic matter, and permeability also contribute.

L = slope length factor that measures the ratio of soil loss from the field slope length to soil loss from a 22.1-meter length under identical conditions.

S = slope steepness factor that describes the ratio of soil loss from the field slope gradient to soil loss from a 9 percent slope under identical conditions.

C = cover-management factor that measures the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow. It is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss.

P = support practice factor that measures the ratio of soil loss with a support practice like contouring or terracing to soil loss with straight-row farming up and down the slope. It reflects the effects of practices that will reduce the amount of erosion.

Because the RUSLE model was developed based on agricultural plot scales and parameterized for environmental conditions in the United States, modifications of the methods and data inputs are necessary to make the equation applicable globally. The RUSLE model does not contain sediment deposition and sediment transport terms. We estimated erosion potential (E) based on the RUSLE model, adjusted to extend its applicability to a global scale:

$$E = R \cdot K \cdot S \cdot C$$

***L* and *P* factors** were not included in this model to calculate global erosion potential due to data limitations and their relatively minor contribution to the variation in soil erosion at the continental to global scale compared to other factors (Doetterl, Van Oost, and Six 2012, Naipal et al. 2015).

***R* factor** was estimated from average annual precipitation (P) and mean elevation (Z) based on regression equations developed by Naipal et al. (2015) for the different Köppen–Geiger climate zones (see Figure 3.4). Because rainfall intensity data are often limited, various studies on global soil erosion estimation using the RUSLE model (Yang et al. 2003, Doetterl, Van Oost, and Six 2012, Van Oost et al. 2007) applied the R factor calculation method developed by Renard and Freimund (1994). The method related R factor to P, based on available erosivity data for 155 stations in the United States:

$$R = 0.0483 \cdot P^{1.61},\ P \leq 850\ mm$$
$$R = 587.8 - 1.219 \cdot P + 0.004105 \cdot P^2,\ P > 850\ mm$$

To better represent the R factor at the global scale, climate and topographic factors are included in erosivity models (Goovaerts 1999, Lu et al. 2004, Naipal et al. 2015). The Köppen–Geiger climate classification is based on vegetation distribution linked to annual precipitation and temperature cycles, therefore partly accounting for rainfall intensity (Rubel and Kottek 2010). Naipal et al. (2015) modeled the relationship between R and explanatory variables (P, Z, and the precipitation intensity index (SDII)) by fitting linear multiple regression equations to observed R values in the United States and Switzerland. The United States is the largest region with available R values and covers most of the world's climate zones. Observed R values from Switzerland were used to derive regression equations for the R factors for the polar climate zones that are not present in the United States. R factors based on equations developed by Renard and Freimund (1994) were used when: (1) regression equations from Naipal et al. (2015) that involve SDII, as SDII are only available on a very coarse resolution for limited regions of the world; or (2) there is no clear improvement when using a new regression equation for a specific climate zone.

The linear multiple regression equations for different R factors in this paper are listed in Table A1 in Appendix A. Mean R factors and uncertainty ranges for different climate zones compared with available observed R values from the United States and Switzerland are found in Table A2 in Appendix A.

***K* factors** for different soil texture classes were derived from estimation by Stone and Hilborn (2012). Soil texture classes were identified from the Harmonized World Soils Database v 1.2 (Nachtergaele et al. 2012). The K factors for the soil texture classes used in this paper are in Table A3 in Appendix A.

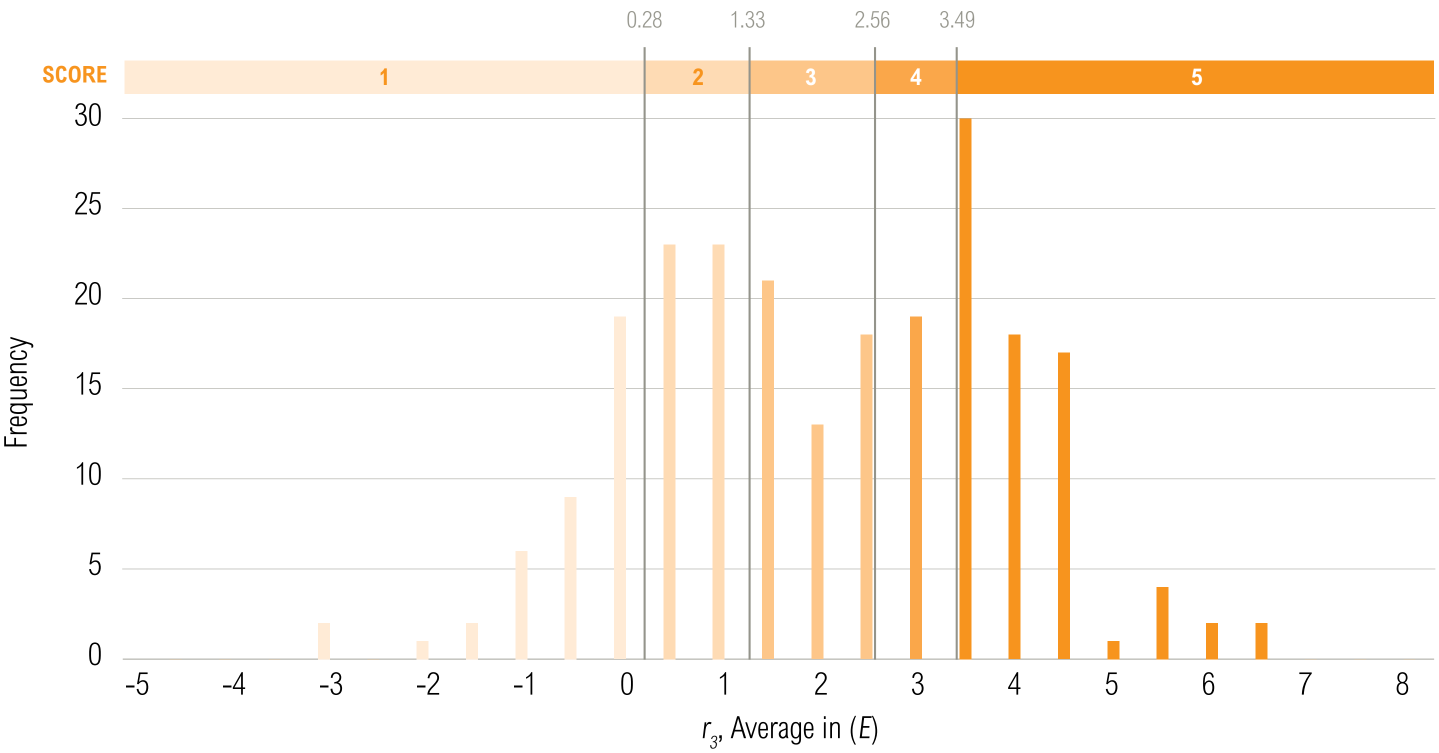
***S* factor** for the globe was developed by Naipal et al. (2015) using the fractal method (Klinkenberg and Goodchild 1992, Zhang et al. 1999, Pradhan, Tachikawa, and Takara 2006) to account for problems associated with coarse global digital elevation models (DEMs). Calculated S factor ranges from 0.056 to 14.92 ($\sigma = 1.68$).

***C* factors** for different land cover types were estimated based on values from Yang et al. (2003). Land cover types were classified based on Global Land Cover Map for 2009 (Arino et al. 2012). A complete list of estimated C factors for different land cover types used in the model is given in Table A4 of Appendix A.

To adjust for resulted overestimation and wide range of distribution of E, a natural log transformation was applied.

Calculation: The indicator on erosion (r_3) was derived from the modeled erosion potential (E) based on the RUSLE model. Erosion indicator (r_3) was developed from the mean value for each of the 230 global watersheds. We then normalized r_3 and categorized the scores into five quantiles, assigning a score from 1 to 5. Figure 3.7 displays the distribution of r_3 and details the threshold values for the score categories.

Figure 3.7 | **Distribution of Average Erosion Potential (r_3) in Global Watersheds and Risk Scoring Thresholds**



Fire

Description: The fire indicator estimates the probability of adverse effects from fire on the health of a watershed. High-intensity or large fires can result in significant increases in runoff and erosion as well as tree mortality, which can negatively affect water quality. Although the effects are usually short-lived, there is uncertainty about effects beyond a few years as well as the magnitude and persistence of downstream effects.

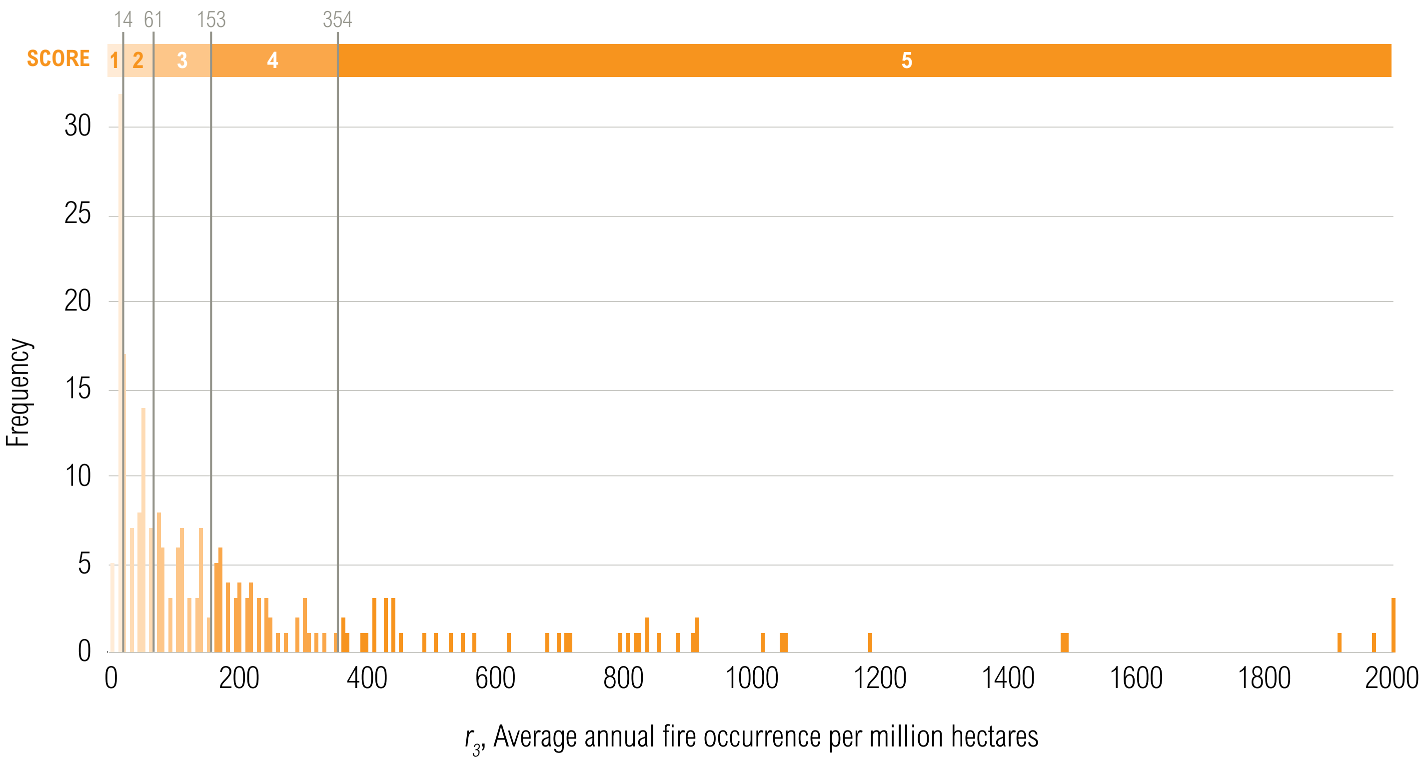
DATA INPUTS:

Fire Occurrence. The Fire Information for Resource Management System (FIRMS) delivers global MODIS-derived hotspots and fire locations. The active fire locations represent the center of a 1-kilometer pixel that is flagged by the MOD14/MYD14 Fire and Thermal Anomalies Algorithm as containing one or more fires within the pixel. The near-real-time active fire locations are processed by the National Aeronautics and Space Administration (NASA) Land and Atmosphere Near Real-Time Capability for EOS (LANCE) using the standard MODIS Fire and Thermal Anomalies product (MOD14/MYD14).

VARIABLE	AVERAGE ANNUAL FIRE OCCURRENCE
Author	NASA
Title	Fire Information for Resource Management System (FIRMS)
Resolution	1 kilometer
Date of content	2006–15
URL	https://firms.modaps.eosdis.nasa.gov/download/request.php

Calculation: The indicator on fire (r_4) is measured by averaging annual fire occurrence per million hectares in a watershed in the most recent 10 years (January 1, 2006 to December 31, 2015) to account for impacts from seasonality and El Niño/La Niña events, which occur on average every two to seven years. Major fire years tend to follow the change from El Niño to La Niña conditions, during which El Niño conditions enhance the production of fuels, which create conditions for widespread wildfires when desiccated by La Niña conditions (Kitzberger, Swetnam, and Veblen 2001). We then categorized r_4 into five quantiles and assigned scores ranging from 0 to 5. Figure 3.8 displays the distribution of r_4 and details the threshold values for the score categories.

Figure 3.8 | **Distribution of Average Annual Fire Occurrence (r_4) In Global Watersheds and Risk Scoring Thresholds**



Baseline Water Stress

Baseline water stress (BWS) measures the ratio of total water withdrawals relative to the annual available renewable surface water supplies (ISciences 2011). We use this data to set the context for landscape water-related risk for a given watershed. BWS serves as a good proxy for water-related challenges more broadly because areas of higher water stress are likely subject to higher depletion of surface and groundwater resources and to more competition among users, as well as to associated impacts on water quality and other ecosystem services. Watersheds with high baseline water stress may warrant greater need for appropriate action to alleviate watershed risks.

A long time series of supply (1950–2010) was used to reduce the effect of multiyear climate cycles and ignore complexities of short-term water storage (e.g., dams, floodplains) for which global operational data are nonexistent. Baseline water stress thus measures chronic stress rather than drought stress. Watersheds with less than 0.012 m/m^2/year of withdrawal and 0.03 m/m^2 /year of available blue water [Fresh surface and groundwater) were masked as "arid and low water use" since watersheds with low values were more prone to error in the estimates of baseline water stress. Additionally, although current water use in such catchments is low, any new withdrawals could easily push them into higher stress categories. For more information on this indicator and its development as part of the Aqueduct Water Risk Atlas, please visit: www.wri.org/aqueduct.

DATA INPUTS:

VARIABLE	BASELINE WATER STRESS
Author	F. Gassert, M. Luck, M. Landis, P. Reig, and T. Shiao
Title	Aqueduct Global Maps 2.1 Data
Date of content	2014
URL	http://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

3.3 Plan for Action

Cognizant of the different socioeconomic, governance, and environmental conditions of watersheds around the world, we do not provide watershed or site-specific management recommendations. Instead, this section of the tool provides first-level screening for natural infrastructure solutions based on risk scores. Table 3.4 summarizes natural infrastructure approaches, examples, and case study locations for each risk indicator. Additionally, this section serves as a portal to decision-support resources for planning natural infrastructure initiatives, including publications, guidelines, decision support frameworks, and case studies.

4. RESULTS AND DISCUSSION

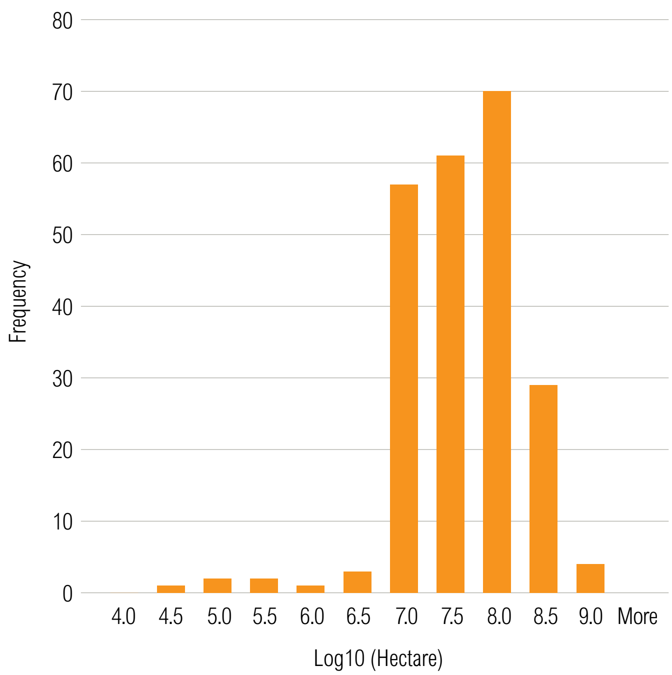
4.1 State of the Global Watersheds

The areas of the world's 230 watersheds range from about 11,000 to over 600 million hectares, with a median of 27 million hectares and distribution skewed to the left (Figure 4.1). On average, about 7 percent of the world's watershed area consists of wetlands and about 31 percent is covered by forests (with a 30 percent canopy density). The most common land cover type is cropland at 31 percent, followed by shrub and grassland, forest, urban, bare, and other (Table 4.1).

Table 3.4 | **Examples of Natural Infrastructure Approaches in Response to Risk**

RISK INDICATOR	STRATEGIES	EXAMPLES	CASE STUDY
Recent Forest Loss	Ecosystem Protection	**Conservation zones:** Setting aside natural areas with high conservation value to preserve biodiversity and maintain forests, wetlands, and other open lands as natural infrastructure to regulate water flow and improve quality **Sustainable forestry:** Engaging in best forestry practices to minimize negative environmental impacts and disturbance to forests to deliver critical watershed services such as water purification and flood mitigation **Road network regulation:** Limiting road creation near vulnerable forests. Access roads are heavily linked to deforestation that diminishes forests' ability to regulate flow and purify water	**New York**, New York, United States **Portland**, Maine, United States **Quito**, Ecuador
Historical Tree Cover Loss	Landscape Restoration	**Reforestation:** Planting seedlings in burnt or deforested areas to stem the rate of erosion and restore the land **Assisted natural regeneration:** Enhancing the establishment of secondary forest from degraded grassland and shrub vegetation by protecting and nurturing the mother trees and their wildlings inherently present in the area which may enhance aquifer recharge **Agroforestry:** Managing forests together with crops and/or animal production systems in agricultural settings	**Beijing**, China **Multiple locations**, India **Multiple locations**, Brazil **Multiple locations**, Costa Rica **Humbo**, Ethiopia
Erosion	Erosion Control	**Vegetation buffering:** Planting or maintaining trees/ shrubs along the sides of roads and waterways to capture runoff and pollutants **Slope erosion reduction:** Slowing the rate of erosion on steep sloped lands by creating various barriers to sediment movement, such as contour felling of trees, silt fences, and terracing **Agricultural best management practices:** Reducing the amount of pesticides, fertilizers, animal waste, and other pollutants entering water resources, and conserving water supply. Examples include contour farming, cover crops, and terrace construction	**Eugene**, Oregon, United States **Lima**, Peru **Paris**, France
Fire	Fire Management	**Forest fuel reduction:** Reducing wildfire severity and related sediment and ash pollution through mechanical forest thinning and controlled burns **Alternative land clearing:** Preventing fire from slash-and-burn by using alternative land-clearing and management solutions such as alley cropping	**Denver**, Colorado, United States **Rio Grande**, New Mexico, United States **Riau**, Indonesia

Figure 4.1 | **Distribution of global watershed size**



Source: FAO 2011.

4.2 World Watersheds with the Highest Risks

The global top 10 watersheds facing the highest potential of threat for each indicator based on their raw values are identified in Table 4.2 and shown on the maps in Figure 4.2. Note that watersheds in different regions face different types of risks in varying degrees. The findings in each risk category are summarized below.

Recent forest loss. Around the globe, from 2000 to 2014, watersheds experienced an average of 6 percent tree cover loss. The greatest loss—about 23 percent—occurred in Sumatra, Indonesia. Of the 230 global watersheds, 140 watersheds presented a positive trend in forest loss (30 percent canopy density).

Historical forest loss. On average, watersheds experienced 55 percent of their historical forest loss prior to 2000.

Erosion. The calculated global erosion potential (E) ranged from 0 to 508,596.97 metric tons per hectare per year with a mean of 74.11 metric tons per hectare per year (σ = 1353.40). Although the model was adjusted to extend its application to the globe, the output still contains considerable uncertainly and overestimation compared to observed data (Yang et al. 2003, Naipal et al. 2015). Because of the coarse resolution of S factor, the resulting E does not cover some coastal areas. Finally, due to model and data limitations, uncertainly is especially noticeable in tropical regions, polar climate zones, and high mountainous regions (Naipal et al. 2015, Cooper 2011).

Table 4.1 | **Average Percentage of Different Land Cover Types in Global Watersheds**

LAND COVER TYPE	AVERAGE COVERAGE IN GLOBAL WATERSHEDS (PERCENT)
Crop	31.42
Forest	26.27
Shrub/Grassland	27.33
Urban	9.61
Bare	0.58
Other	4.90

Fire. The average number of fires per million hectares (2012–15) was about 168, and watersheds in tropical regions had the highest average annual number of fires (Figure 4.2).

4.3 Model and Data Limitations

Five limitations to the model and data in this paper are pointed out below that involve the coarseness of global data sets, limits to comparing subwatersheds with watersheds, the limitations of environmental models, the methods of normalizing risk indicators, and the inherent subjectivity of and the difficulty in validating the scoring system.

First, the global data sets used in GFW Water are best suited for analyses in relatively large watersheds and for comparative studies across large geographies to prioritize regions that merit further investigation. Global data sets and models often face significant challenges in their ability to capture the reality of watershed conditions. Due to the tremendous resources and effort required to generate global data sets, some are incomplete or require updates.

Errors in remotely sensed data are common and global data sets are extremely difficult to validate especially for places where observed data are limited. Limited by computational and storage capacity, some global data sets may be deemed too coarse by users interested in evaluating smaller watersheds.

Table 4.2 | **Top 10 Watersheds Facing the Highest Risks for Each Watershed Risk Indicator**

RANK	RECENT FOREST LOSS	HISTORICAL FOREST LOSS	EROSION	FIRE
1	Sumatra	Iceland	Philippines	Angola, Coast
2	Gulf of Mexico, North Atlantic Coast	Mahi	Solomon Islands	Zambezi
3	Gulf Coast	South America, Colorado	Java–Timor	Congo
4	North Borneo Coast	Pampas Region	India West Coast	Volta
5	South China Sea Coast	Tapti	Sulawesi	Bay of Bengal, North East Coast
6	South Africa, South Coast	North Argentina, South Atlantic Coast	South Pacific Islands	Africa, West Coast
7	Fraser	Krishna	Papua New Guinea Coast	Africa, Indian Ocean Coast
8	Tocantins	Pennar	Palau and East Indonesia	Africa, East Central Coast
9	Kalimantan	Yasai	New Zealand	North Brazil, South Atlantic Coast
10	Peninsula Malaysia	Volta	Bay of Bengal, North East Coast	Madagascar

Second, users should take care in analyzing subwatersheds. GFW Water's custom analysis function allows users to obtain summary statistics and risk scores for subwatersheds of interest. However, the output subwatershed is a result of topographic and hydrologic models that may not align with the scale and location of the area of user interest. Additionally, because risk scores are calculated based on ranking the 230 global watersheds, results for subwatersheds of very different scales may lead to different implications compared to those listed in Table 3.3.

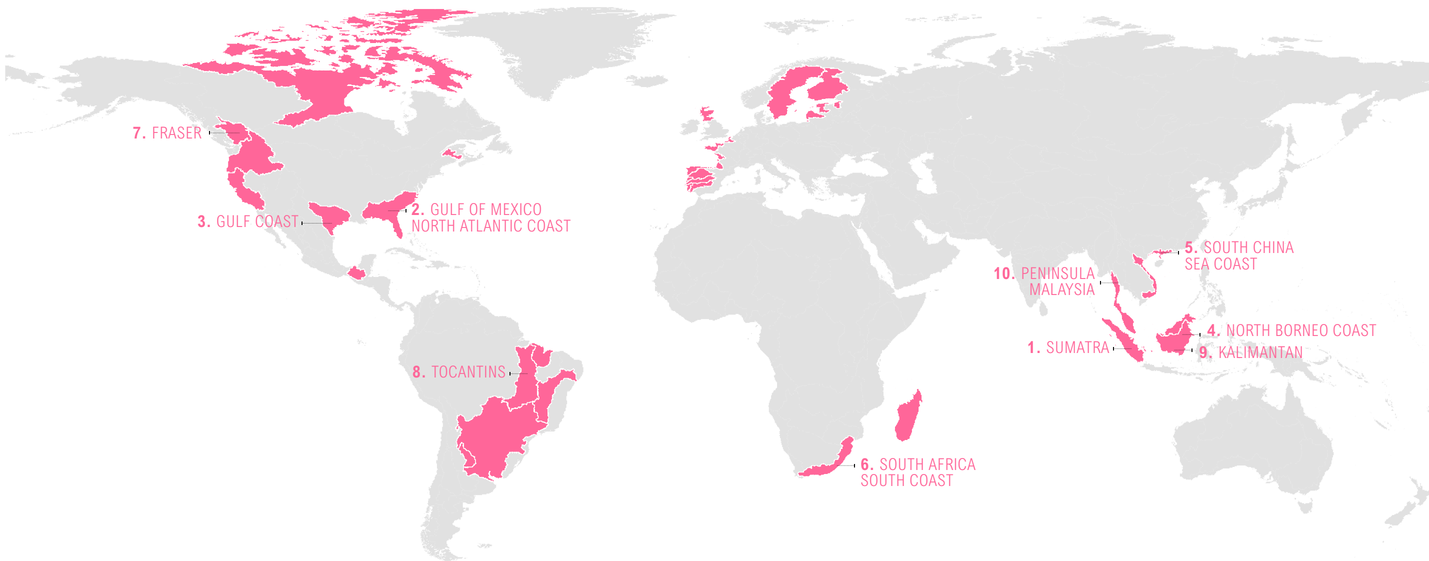
Third, although environmental models, such as the RUSLE model, have been much improved and widely used as crucial estimation tools to extrapolate limited data to other locations and conditions, some issues remain. Errors and uncertainty from calculations for large geographies are inevitable, and some regions present a greater margin of error. Due to data limitations and knowledge gaps, environmental models for large scales are often simplified to exclude some otherwise meaningful explanatory inputs. For example, consistently measured, geographically explicit data on rainfall intensity would greatly improve estimation of erosivity and erosion potential. For areas highlighted by GFW Water, models based on local conditions can greatly help refine decision-making processes and optimize natural infrastructure investments.

Fourth, due to the differences across and within watersheds around the world and the lack of globally applicable thresholds, normalization of watershed risk indicators is based mainly on statistical distribution.

Finally, although we aimed for a robust and objective framework, creation of a scoring system is inherently subjective, including the definition and associated guidelines as well as the adjustment process. In addition, validation of watershed risk scores is challenging because of the difficulty of measuring the probability of risk-related events and the complex linkage between changes in watershed conditions and watersheds' abilities to deliver environmental services.

Figure 4.2 | **Map of Top 10 Watersheds Facing the Highest Risks (Score of 5) and the Top Ten Identified in Global Forest Watch Water in Each Indicator Category**

A. Recent Forest Loss



B. Historical Forest Loss

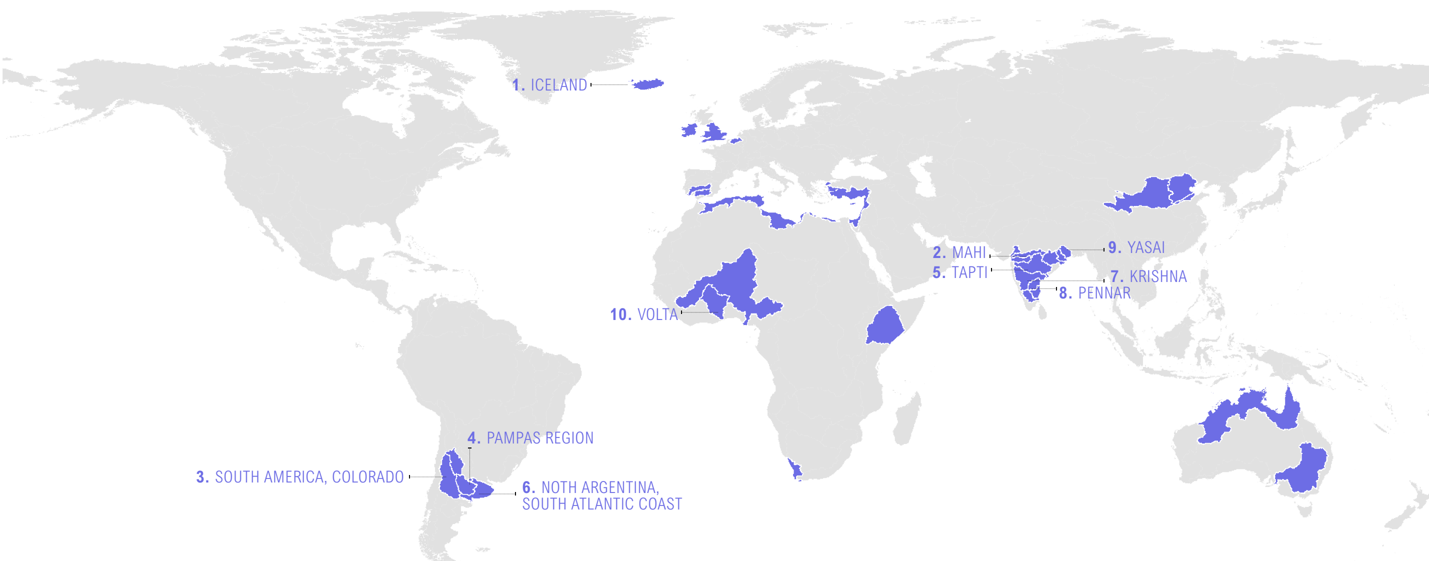
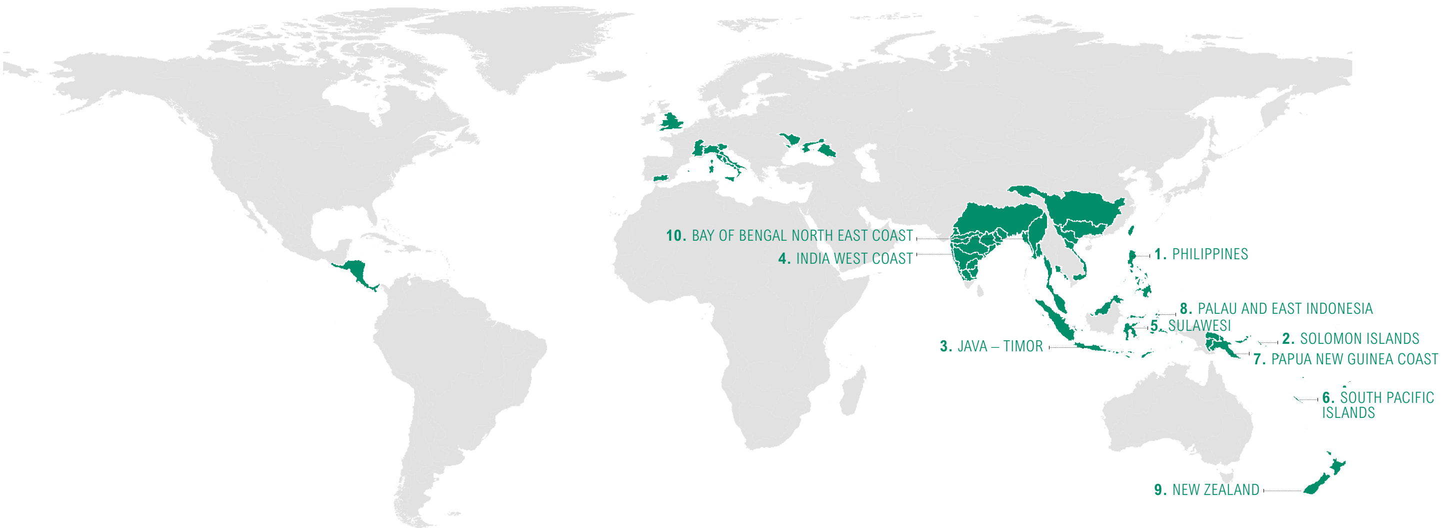
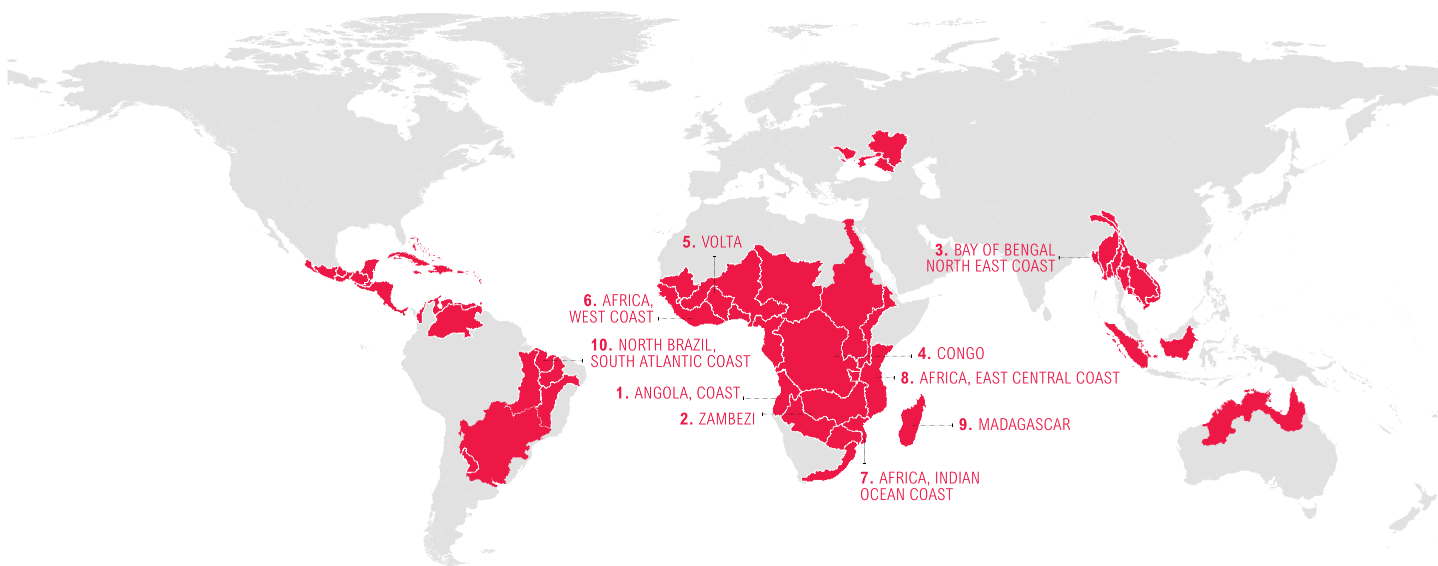


Figure 4.2 | **Map of Top 10 Watersheds Facing the Highest Risks (Score of 5) and the Top Ten Identified in Global Forest Watch Water in Each Indicator Category (continued)**

C. Erosion



D. Fire



5. CONCLUSIONS

The watershed risk scores highlight which watersheds face potential threats to their capacity to deliver ecosystem services for water. The scores are possible because of GFW Water's efforts to create normalized watershed risk indicators. The scoring system simplifies complex environmental conditions and processes to create clear categories that allow for comparisons across regions and risk types. These comparison allow users to identify areas at high-risk from recent or historical forest loss, erosion, or fire and to prioritize risk reduction efforts in each category using natural infrastructure.

It is hoped that highlighting the watersheds with the highest risk can help key user groups—downstream beneficiaries, financing and development institutions, and civil society and research groups—search for natural infrastructure solutions appropriate for each type of risk. For example, impacts on a watershed from recent forest loss would be mitigated through the establishment of conservation zones, sustainable forestry, and regulation of roads, whereas a watershed at high risk for fire could be made healthier by reducing the amount of forest fuel and conducting controlled burns (see Table 3.4).

GFW Water users can call up and compare the indicator scores for watersheds and subwatersheds of interest around the globe. As the database in the GFW Water Plan for Action section expands, they can find recommendations and detailed information on how to address the risk factors facing their watersheds through natural infrastructure initiatives. With this analysis and information in hand, it is hoped that watershed stakeholders will be more likely to pursue various natural infrastructure approaches to obtaining abundant and clean water.

Building on advances in global spatial data and models, near-real-time remotely sensed information, and data processing and visualization, GFW Water, for the first time, brings a capacity to visualize spatial information, a means to compare watershed risks around the globe, and resources and guidance to help plan for natural infrastructure initiatives.

6. FUTURE RESEARCH

WRI plans to continue to improve and update the GFW Water platform as follows: (1) continue to survey and improve global data sets and models when new information becomes available; (2) supplement global data sets with locally relevant information; (3) fill in knowledge gaps in the relationship between changes in watershed condition and ability to deliver critical ecosystem services in order to improve our risk scoring methodology; and (4) enrich the decision-support tool kit to help users identify the most appropriate natural infrastructure solutions.

We welcome comments and suggestions from interested parties. For more information on Global Forest Watch Water, please visit http://water.globalforestwatch.org/.

APPENDIX A: TABLES USED IN CALCULATION OF THE EROSION INDICATOR

The four tables in this appendix show data used in calculating the erosion indicator scores.

Table A1 | **Linear multiple regression equations to estimate *R* factor (MJ · mm · ha^{-1} · h^{-1} · year^{-1}) for different Köppen—Geiger climate zones from average annual precipitation, P (mm), and mean elevation, Z (m), for RUSLE model**

CLIMATE ZONE	OPTIMAL REGRESSION FUNCTION	R_2	RESIDUAL SE
BSh	$\log R = -8.164 + 2.455 \times \log P$	0.86	0.5
Cfa	$\log R = 3.378 + 0.852 \times \log P - 0.191 \times \log Z$	0.57	0.23
Cfb	$\log R = 5.267 + 0.839 \times \log P - 0.635 \times \log Z$	0.81	0.5
Csb	$R = 98.35 + 0.000355 \times P^{1.987}$	–	0.16
Dfa	$\log R = -2.396 + 1.5 \times \log P$	0.65	0.29
Dfb	$\log R = 1.96 + 1.084 \times \log P - 0.34 \times \log Z$	0.74	0.48
Dfc	$\log R = -3.263 + 1.576 \times \log P$	0.56	0.49
Dsa	$\log R = 7.49 - 0.0512 \times \log P - 0.272 \times \log Z$	0.48	0.06
Dsb	$\log R = 2.166 + 0.494 \times \log P$	0.45	0.25
Dsc	$\log R = 4.416 - 0.0594 \times \log P$	0.015	0.03
Dwa	$\log R = -0.572 + 1.238 \times \log P$	0.99	0.02
Dwb	$\log R = 1.882 + 0.819 \times \log P$	0.81	0.08
EF	$\log R = 16.39 - 1.286 \times \log P$	0.6	0.13
ET	$\log R = -3.945 + 1.54 \times \log P$	0.14	0.42
Others	$R = 0.0483 \times P^{1.61}$, $P \leq 850$ $R = 587.8 - 1.219 \times P + 0.004105 \times P^2$, $P > 850$	–	–

Table A2 | **Calculated *R* factor (MJ · mm · ha^{-1} · h^{-1} · year^{-1}) for different Köppen–Geiger climate zones compared to available observed *R* values from the United States and Switzerland**

CLIMATE ZONE	R MEAN OBSERVED	R MEAN	RANGE	σ
Af	–	28201.66	0 – 512263	0
Am	–	19206.81	0 – 205310	0
As	–	4529.749	0 – 52071	3835.063
Aw	–	7028.747	0 – 136858	4217.835
BWk	284	116.7543	0 – 3115	118.6422
BWh	–	150.9191	0 – 4114	191.0906
BSk	876	494.2255	0 – 30716	336.2677
BSh	2168	1764.008	0 – 55968	1365.779
Cfa	5550	4727.628	0 – 69891	1973.678
Cfb	1984	2532.651	0 – 266558	3157.223
Cfc	–	12442.13	0 – 146094	0
Csa	–	1604.016	0 – 22971	1229.477
Csb	192	350.9986	0 – 33895	369.6398

Table A2 | **Calculated *R* factor (MJ · mm · ha^{-1} · h^{-1} · year^{-1}) for different Köppen—Geiger climate zones compared to available observed *R* values from the United States and Switzerland (continued)**

CLIMATE ZONE	R MEAN OBSERVED	R MEAN	RANGE	σ
Csc	–	1050.871	61 – 5772	742.7827
Cwa	–	6514.164	0 – 520269	5176.861
Cwb	–	5088.51	0 – 77160	4870.663
Cwc	–	1519.487	4 – 29576	1770.38
Dfa	2572	1443.806	0 – 11428	940.5516
Dfb	1101	1219.439	0 – 51024	790.2124
Dfc	483	793.5012	0 – 62322	643.9371
Dfd	–	397.416	0 – 1548	131.6544
Dsa	172	199.682	0 – 3601	74.03647
Dsb	175	190.9709	54 – 19619	74.77437
Dsc	115	60.29722	0 – 4991	36.62558
Dsd	–	255.6395	0 – 673	69.21088
Dwa	1549	1765.158	0 – 11198	881.8728
Dwb	1220	1179.496	0 – 17943	312.2623
Dwc	–	1007.399	0 – 36866	788.4329
Dwd	–	519.1711	80 – 1524	159.6062
EF	1468	3884.765	0 – 56667	4260.625
ET	1352	228.5312	0 – 117314	504.8106

Table A3 | ***K* Factors for Different Soil Texture Classes for RUSLE Model**

SOIL TEXTURE CLASS	K (TONNE · H · MJ^{-1} · MM^{-1})	
	Less than 2% OMC*	More than 2% OMC
Clay (heavy)	0.43	0.34
Silty clay	0.61	0.58
Clay	0.54	0.47
Silty clay loam	0.79	0.67
Clay loam	0.74	0.63
Silt loam	0.92	0.83
Sandy clay	0.45	0.45
Loam	0.76	0.58
Sandy clay loam	0.45	0.45
Sandy loam	0.31	0.27
Loamy sand	0.11	0.09
Sand	0.07	0.02

* Organic matter content (%) = Total organic carbon (%) x 1.72

Table A4 | **C Factors for Different Land Cover Types for RUSLE Model**

LAND COVER TYPE	C FACTOR
Post-flooding or irrigated croplands (or aquatic)	0.1
Rainfed croplands	0.5
Mosaic cropland (50–70%) / vegetation (grassland/shrubland/forest) (20–50%)	0.25
Mosaic vegetation (grassland/shrubland/forest) (50–70%) / cropland (20–50%)	0.1
Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	0.001
Closed (>40%) broadleaved deciduous forest (>5m)	0.001
Open (15–40%) broadleaved deciduous forest/woodland (>5m)	0.001
Closed (>40%) needleleaved evergreen forest (>5m)	0.001
Open (15–40%) needleleaved deciduous or evergreen forest (>5m)	0.001
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	0.001
Mosaic forest or shrubland (50–70%) / grassland (20–50%)	0.01
Mosaic grassland (50–70%) / forest or shrubland (20–50%)	0.02
Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	0.01
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	0.08
Sparse (<15%) vegetation	0.2
Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) – Fresh or brackish water	0.001
Closed (>40%) broadleaved forest or shrubland permanently flooded – Saline or brackish water	0.001
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil – Fresh, brackish or saline water	0.001
Artificial surfaces and associated areas (Urban areas >50%)	0.1
Bare areas	0.35
Water bodies	0.01
Permanent snow and ice	0.001

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity and human well-being.

Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.