Europe (Vanmaercke et al., 2014) and northern Africa (Achite and Ouillon, 2016). Still, such correlation is yet to be found for the other European rivers (Vanmaercke et al., 2015). Increased sediment and particulate organic carbon fluxes in the Arctic regions are caused by permafrost warming (Schiefer et al., 2018; Lafrenière and Lamoureux, 2019; Ward Jones et al., 2019). Potemkina and Potemkin (2015) demonstrate that regional warming and permafrost degradation have contributed to an increased forested area over the last 40–70 years, reducing soil erosion in eastern Siberia. The sediment dynamics of small rivers in the eastern Italian Alps, depending on extreme floods, is sensitive to climate change (Rainato et al., 2017). In the northeastern Italian Alps, precipitation change during 1986–2010 affected soil wetness conditions, influencing sediment load (Diodato et al., 2018). Regional warming in northern Africa (Algeria) dramatically changed river streamflow and increased sediment load over four decades (84% more every decade compared to the previous) (Achite and Ouillon, 2016).

A long-term global soil erosion monitoring network based on the unified methodological approach is needed to correctly evaluate erosion rates, detect their changes and attribute them to climate or other drivers.

In summary, in the areas with high human activity, factors other than climate have a more significant impact on soil erosion and sediment flux (*high confidence*). On the other hand, in natural conditions, for example, in high latitudes and high mountains, the influence of climate change on the acceleration of the erosion rate is observed (*limited evidence, medium agreement*).

4.3 Observed Sectoral Impacts of Current Hydrological Changes

The intensification of the hydrological cycle due to anthropogenic climate change has multifaceted and severe impacts for cultural, economic, social and political pathways. In this section, we assess burgeoning evidence since AR5 which shows that environmental quality, economic development and social well-being have been affected by climate-induced hydrological changes since many aspects of the economy, environment and society are dependent upon water resources. We advance previous IPCC reports by assessing evidence on the impacts of climate change-induced water insecurity for energy production (Section 4.3.2), urbanisation (Section 4.3.4), conflicts (Section 4.3.6), human mobility (Section 4.3.7) and cultural usage of water (Section 4.3.8).

Integrating qualitative and quantitative data, we show that it is evident that societies heightened exposure to water-induced disasters—such as floods and droughts—and other hydrological changes have increased vulnerability across most sectors and regions, with few exceptions. Through the assessment of literature relying on IK, we are also able to present evidence on how observed changes impact particularly Indigenous Peoples, local communities and marginalised groups, such as women, people without social protections and minorities.

Importantly, we note that climate change-induced hydrological changes are, for most sectors, one of the several factors, often coupled with urbanisation, population growth and heightened economic disparities, that have increased societal vulnerability and required communities across the globe to alter their productive and cultural practices.

4.3.1 Observed Impacts on Agriculture

AR5 concluded with *high confidence* that agricultural production was negatively affected by climate change, with droughts singled out as a major driver of food insecurity. In contrast, evidence of floods on food production was *limited* (Porter et al., 2014).

Globally, 23% of croplands are irrigated, providing 34% of global calorie production. Of these lands, 68% experience blue water scarcity at the least one month yr^{-1} and 37% up to five months yr^{-1}. Such agricultural water scarcity is experienced in mostly drought-prone areas in low-income countries (Rosa et al., 2020a). Approximately three quarters of the global harvested areas (~454 million hectares) experienced drought-induced yield losses between 1983 and 2009, and the cumulative production losses corresponded to USD 166 billion (Kim et al., 2019). Globally, droughts affected both harvested areas and yields, with a reported cereal production loss of 9–10% due to weather extremes between 1964 and 2007. Yield losses were greater by about 7% during recent droughts (1985–2007) due to greater damage—reducing harvested area—compared to losses from earlier droughts (1964–1984), with 8–11% greater losses in high-income countries than in low-income ones (Lesk et al., 2016). Globally, between 1961 and 2006, it has been estimated that 25% yield loss occurred, with yield loss probability increasing by 22% for maize, 9% for rice and 22% for soybean under drought conditions (Leng and Hall, 2019). Mean climate and climate extremes are responsible for 20–49% of yield anomalies variance, with 18–45% of this variance attributable to droughts and heatwaves (Vogel et al., 2019). Drought has been singled out as a major driver of yield reductions globally (*high confidence*) (Lesk et al., 2016; Meng et al., 2016; Zipper et al., 2016; Anderson et al., 2019; Leng and Hall, 2019).

Yields of major crops in semiarid regions, including the Mediterranean, sub-Saharan Africa, South Asia and Australia, are negatively affected by precipitation declines in the absence of irrigation (Iizumi et al., 2018; Ray et al., 2019), but this trend is less evident in wetter regions (Iizumi et al., 2018). Precipitation and temperature changes reduced global mean yields of maize, wheat and soybeans by 4.1, 1.8 and 4.5%, respectively (Iizumi et al., 2018). Of the global rice yield variability of ~32%, precipitation variability accounted for a larger share in drier South Asia than in wetter East and Southeast Asia (Ray et al., 2015). Between 1910 and 2014 agro-climatic conditions became more conducive to maize and soybean yield growth in the American Midwest due to increases in summer precipitation and cooling due to irrigation (Iizumi and Ramankutty, 2016; Mueller et al., 2016) (Box 4.3). In Australia, between 1990 and 2015, the negative effects of reduced precipitation and rising temperature led to yield losses, but yield losses were partly avoided because of elevated CO_2 atmospheric concentration and technological advancements (Hochman et al., 2017a). Overall, temperature-only effects are stronger in wetter regions like Europe and East and Southeast Asia, and precipitation-only effects are stronger in drier regions (Iizumi et al., 2018; Ray et al., 2019) (*medium evidence, high agreement*). In Asia, the gap between rain-fed and irrigated maize yield widened from 5% in the 1980s to 10% in the 2000s (Meng et al., 2016). In North America, yields of maize and soybeans have increased (1958–2007), yet meteorological drought has been associated with 13% of overall yield variability. However, yield variability was not a concern where irrigation is prevalent (Zipper et al., 2016). However, when water scarcity has reduced irrigation, yields have been negatively impacted (Elias et al., 2016). In Europe, yields have been affected negatively by droughts (Beillouin et al., 2020), with losses tripling between 1964 and 2015 (Brás et al., 2021). In West Africa, between 2000 and 2009, drought, among other altered climate conditions, led to millet and sorghum yield reductions between 10 and 20% and 5 and 15%, respectively (Sultan et al., 2019). Between 2006 and 2016, droughts contributed to food insecurity and malnutrition in northern, eastern and southern Africa, Asia and the Pacific. In 36% of these nations—mainly in Africa—where severe droughts occurred, undernourishment increased (Phalkey et al., 2015; Cooper et al., 2019). An attribution study showed that anthropogenic emissions increased the chances of October–December droughts over the region by 1.4–4.3 times and resulted in below-average harvests in Zambia and South Africa (Nangombe et al., 2020). Root crops, a staple in many tropics and subtropical countries, and vegetables are particularly prone to drought, leading to smaller fruits or crop failure (Daryanto et al., 2017; Bisbis et al., 2018). Livestock production has also been affected by changing seasonality, increasing frequency of drought, rising temperatures and vector-borne diseases and parasites through changes in the overall availability, as well as reduced nutritional value, of forage and feed crops (Varadan and Kumar, 2014; Naqvi et al., 2015; Zougmoré et al., 2016; Henry et al., 2018; Godde et al., 2019) (*medium confidence*).

Floods have led to harvest failure and crop and fungal contamination (Liu et al., 2013; Uyttendaele et al., 2015). Globally, between 1980 and 2018, excess soil moisture has reduced rice, maize, soybean and wheat yields between 7 and 12% (Borgomeo et al., 2020). Changes in groundwater storage and availability, which are affected by the intensity of irrigated agriculture, also negatively impacted crop yields and cropping patterns (Section 4.2.6, Box 4.3, 4.7.2). Moreover, extreme precipitation can lead to increased surface flooding, waterlogging, soil erosion and susceptibility to salinisation (*high confidence*). For example, in Bangladesh, in March and April 2017, floods affected 220,000 ha of a nearly harvest-ready summer paddy crop and resulted in almost a 30% year-on-year increase in paddy prices. An attribution study of those pre-monsoon extreme rainfall events in Bangladesh concluded that anthropogenic climate change doubled the likelihood of the extreme rainfall event (Rimi et al., 2019). Moreover, floods, extreme weather events and cyclones have led to animal escapes and infrastructure damage in aquaculture (Beveridge et al., 2018; Islam and Hoq, 2018; Naskar et al., 2018; Lebel et al., 2020) (see Section 5.9.1).

Worldwide, the magnitudes of climate-induced water-related hazards and their impact on agriculture are differentiated across populations and genders (Sections 4.3.6; 4.8.3). Evidence shows that hydroclimatic factors pose high food insecurity risks to subsistence farmers, whose first and only source of livelihood is agriculture, and who are situated at low latitudes where the climate is hotter and drier (Shrestha and Nepal, 2016; Sujakhu et al., 2016). Historically, they have been the most vulnerable to observed climate-induced hydrological changes (Savo et al., 2016). Indigenous and local communities, often heavily reliant on agriculture, have a wealth of knowledge about observed changes. These are important because they shape farmers' perceptions, which in turn shape the adaptation measures farmers will undertake (Caretta and Börjeson, 2015; Savo et al., 2016; Sujakhu et al., 2016; Su et al., 2017) (Section 4.8.4) (*high confidence)*.

In summary, ongoing climate change in temperate climates has some positive impacts on agricultural production. In subtropical/tropical climates, climate-induced hazards such as floods and droughts negatively impact agricultural production (*high confidence*). People living in deprivation and Indigenous Peoples have been disproportionally affected. They often rely on rain-fed agriculture in marginal areas with high exposure and high vulnerability to water-related stress and low adaptive capacity (*high confidence)*.

4.3.2 Observed Impacts on Energy and Industrial Water Use

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that hydropower negatively impacts freshwater ecosystems. SROCC (IPCC, 2019a) concluded with *medium confidence* that climate change has led to both increases and decreases in annual/seasonal water inputs to hydropower plants.

Water is a crucial input for hydroelectric and thermoelectric energy production, which together account for 94.7% of the world's current electricity generation (Petroleum, 2020). Climate change impacts hydropower production through changes in precipitation, evaporation, volume and timing of runoff; and impacts cooling of thermoelectric power plants through reduced streamflow and increased water temperatures (Yalew et al., 2020). In addition, extreme weather events, like tropical cyclones, landslides and floods, damage energy infrastructure (MCTI, 2020; Yalew et al., 2020), while high temperature and humidity increase the energy requirement for cooling (Maia-Silva et al., 2020).

With 1308 GW installed capacity in 2019, hydropower became the world's largest single source of renewable energy (IHA, 2020) (also see Figure 6.12, WGIII). While hydropower reduces emissions relative to fossil fuel-based energy production, hydropower reservoirs are being increasingly associated with GHG emissions caused by submergence and later re-emergence of vegetation under reservoirs due to water level fluctuations (Räsänen et al., 2018; Song et al., 2018; Maavara et al., 2020). A recent global study concluded that reservoirs might emit more carbon than they bury, especially in the tropics (Keller et al., 2021) (*medium confidence*).

In Ghana, between 1970 and 1990, rainfall variability accounted for 21% of interannual variations in hydropower generation (Boadi and Owusu, 2019). In Brazil's São Francisco River, following drought events in 2016 and 2017, hydropower plants operated with an average capacity factor of only 23% and 17%, respectively (de Jong et al., 2018). In Switzerland, increased glacier melt contributed to 3–4% of hydropower production since 1980 (Schaefli et al., 2019) (Section 4.2.2). In the USA, hydropower generation dropped by nearly 27% for every standard deviation increase in water scarcity. Equivalent social costs of loss in