Quantitative projections on climate-induced water quality degradation are sparse. Aminomethylphosphonic acid and glyphosate are projected to exceed drinking water quality standards in dry years in a high-emissions scenario in the Meuse River in Europe by 2050 (Sjerps et al., 2017). From 2020 to 2050, based on scenarios RCP2.6, RCP4.5 and RCP8.5, the incidences of total nitrogen pollution are projected as 97.3, 97.1 and 94.6%, respectively, in drought–flood abrupt alternation months compared to 69.3, 69.7 and 67.5% in normal months in the Luanhe River basin in China (Bi et al., 2019). From 2012 to 2050, freshwater river area is expected to decrease from 40.8% to 17.1–19.7% under different sea level rise scenarios in the southwest coastal zone of Bangladesh (Dasgupta et al., 2013). Under the warming scenario of +4.8°C increase by the end of the century, the average nutrient abundance is projected to triple in a shallow lake in the northwest of England (Richardson et al., 2019).

While there is some understanding of the potential effect of glacier and permafrost degradation on water quality, projections are lacking. Research is limited mainly in Europe and North America, and quantifying the future water quality changes is still incipient.

In summary, climate change is projected to increase water pollution incidences, salinisation and eutrophication due to increasing drought and flood events, sea level rise and water temperature rise, respectively, in some local rivers and lakes, but there is a dearth of exact quantification at a global scale (*medium confidence*).

4.4.8 Projected Changes in Soil Erosion and Sediment Load

4

AR5 stated that soil erosion and sediment load are projected to change (*low confidence*) due to warming and increased rainfall intensity (Jiménez Cisneros et al., 2014). SRCCL concluded that future climate change will increase, with *medium confidence*, the potential for water-driven soil erosion in many dryland areas, causing soil organic carbon decline (Mirzabaev et al., 2019). SR1.5 (Hoegh-Guldberg et al., 2018) concluded that because of the complex interactions among climate change, land cover, soil management, etc., the differences between mean annual sediment load under 1.5°C and 2°C of warming are unclear.

Globally, climate change is estimated to be responsible for 30–66% increase of soil erosion by 2070, while socioeconomic developments impacting land use may lead to ± 10% change of soil erosion (Borrelli et al., 2020). At a regional scale, different effects of the climate change impact on soil losses are found owing to the ensemble experiments with climate models coupled with regional/local models of soil erosion and sediment yield. In the 21st century, the soil erosion rates are projected to increase for the European countries (Czech Republic (Svoboda et al., 2016), Belgium (Mullan et al., 2019), Spain (Eekhout et al., 2018; Eekhout and de Vente, 2019a; Eekhout and De Vente, 2019b), Germany (Gericke et al., 2019)) by 10–80% depending on the emission scenario and time period of the projection, as well as for the USA (Garbrecht and Zhang, 2015) and Australia (Yang et al., 2015b; Zhu et al., 2020). Only a few studies demonstrated decreasing trend in soil erosion, for example, up to 9% with RCP8.5 scenario in Greece (Vantas et al., 2020). Sediment yield is projected to both increase (5–16% with the SRES A1, B1, B2 scenarios in Vietnam and Laos (Giang et al., 2017), 11% with the RCP8.5 scenario and 8% with the SRES A2 scenario in the USA (Yasarer et al., 2017 and Wagena et al., 2018, respectively), 19–37% with the RCP4.5, RCP8.5 scenarios in Burkina Faso (Op de Hipt et al., 2018)) and decrease (30% with the SRES A1B scenario in the southwest USA (Francipane et al., 2015), 8–11% with the SRES A1B scenario in Spain (Rodríguez-Blanco et al., 2016), 11–52% with the RCP4.5, RCP8.5 scenarios in Ethiopia (Gadissa et al., 2018), 13–62% with the RCP2.6, RCP8.5 scenarios in Canada (Loiselle et al., 2020)) over the different regions of the world in the 21st century.

Post-fire sedimentation is projected to increase for nearly nine tenths of watersheds by >10% and for more than one third of watersheds by >100% by the 2041 to 2050 decade in the western USA with the SRES A1B scenario (Sankey et al., 2017).

In summary, soil losses mainly depend on the combined effects of climate and land use changes. Herewith, recent studies demonstrate increasing impact of the projected climate change (increase of precipitation, thawing permafrost) on soil erosion (*medium confidence*).

4.5 Projected Sectoral Water-Related Risks

Observed sectoral water-related impacts have been documented across world regions. Climate change is projected to further exacerbate many of these risks, especially at warming levels above 1.5°C (Figure 4.20). For some sectors and regions, climate change may also hold the potential for beneficial outcomes, though feedback and cascading effects as well as risks of climate extremes are not always well understood and often underestimated in impact projections. Risks manifest as a consequence of the interplay of human and natural vulnerability, sector-specific exposure as well as the climate hazard as a driver of climate change. Challenges to water security are driven by factors across these components of risk, where climate change is but one facet of driving water insecurity in the face of global change. While the focus of this chapter is on climate change and its effects on water security, for many sectors and regions the dynamics of socioeconomic conditions is a core driver. They play an essential role in understanding and alleviating water security risks. The following sections outline sectoral risks for both, risks driven by water-related impacts, such as drought, flood or changes in water availability, as well as risks with effects on water uses, mainly focusing on changing water demand as a consequence of climate change. It therefore does not cover all climate change-driven risks to the respective sectors, but is limited to those that stand in relation to water. The focus within this chapter is on global to regional processes (additional regional to local information in Table SM4.4; Figure 4.20 as well as across regional chapters of this report).

4.5.1 Projected Risks to Agriculture

AR5 concluded that overall irrigation water demand would increase by 2080, while the vulnerability of rain-fed agriculture will further increase (Jiménez Cisneros et al., 2014). SR1.5 concluded that both the food and the water sectors would be negatively impacted by global warming with higher risks at 2°C than at 1.5°C, and these risks could coincide spatially and temporally, thus increasing hazards, exposures and vulnerabilities across populations and regions (*medium confidence*). SR1.5 further reinforced AR5 conclusions in terms of projected crop yield reductions, especially for wheat and rice (*high confidence*), loss of livestock and increased risks for small-scale fisheries and aquaculture (*medium confidence*) (Hoegh-Guldberg et al., 2018), conclusions which are further corroborated by SRCCL (Mbow et al., 2019).

Climate change impacts agriculture through various pathways (5.4 – Crop-based Systems), with projected yield losses of up to 32% by 2100 (RCP8.5) due to the combined effects of temperature and precipitation. Limiting warming could significantly reduce potential impacts (up 12% yield reduction by 2100 under RCP4.5) (Ren et al., 2018a). Though overall changes differ across models, regions and seasons, differences in impacts between 1.5°C and 2°C can also be identified (Ren et al., 2018a; Ruane et al., 2018; Schleussner et al., 2018). Globally, 11% (± 5%) of croplands are estimated to be vulnerable to projected climate-driven water scarcity by 2050 (Fitton et al., 2019).

Overall drought-driven yield loss is estimated to increase by 9–12% (wheat), 5.6–6.3% (maize), 18.1–19.4% (rice) and 15.1–16.1% (soybean) by 2071–2100, relative to 1961–2016 (RCP8.5) (Leng and Hall, 2019). In addition, temperature-driven increases in water vapour deficit could have additional negative effects, further exacerbating drought-induced plant mortality and thus impacting yields (Grossiord et al., 2020) (see also Cross-Chapter Box 1 in Chapter 5 of WGI report). Currently, global agricultural models do not fully differentiate crop responses to elevated CO_2 under temperature and hydrological extremes (Deryng et al., 2016) and largely underestimate the effects of climate extremes (Schewe et al., 2019).

Flood-related risks to agricultural production are projected to increase over Europe, with a mean increase of expected annual output losses of approximately €11 million (at 1.5°C GWL); €12 million (at 2°C GWL) and €15 million (at 3°C GWL) relative to the 2010 baseline (Koks et al., 2019). In parts of Asia, where flooding impacts on agriculture are already significant, projections indicate an increase in damage to area under paddy by up to 50% in Nepal, 16% in the Philippines, 55% in Indonesia, 23% in Cambodia and Vietnam and 13% in Thailand (2075–2099 compared with 1979–2003; RCP8.5) (Shrestha et al., 2019a).

Global crop water consumption of green water resources (soil moisture) is projected to increase by about 8.5% by 2099 relative to 1971–2000 as a result of climate drivers (RCP6.0), with additional smaller contributions by land use change (Huang et al., 2019) (Sections 4.4.1.3, 4.4.8). In India, a substantial increase in green and blue water consumption is projected for wheat and maize, with a slight reduction of blue water consumption for paddy fields (Mali et al., 2021). Temperate drylands, especially higher latitude regions, may become more suitable for rain-fed agriculture (Bradford et al., 2017). Locally and regionally, however, some of those areas with currently larger areas under rain-fed production, for example, in Europe, may become less suitable for rain-fed agriculture (Table 1 to 4.5.1) (Bradford et al., 2017; Shahsavari et al., 2019).

While global crop models and estimates of yield impacts often focus on major staple crops relevant for global food security, crops of high economic value are projected to become increasingly water dependent. For example, climate-driven yield increases for tea are projected for various tea-producing regions if no water limitations and full irrigation is assumed, but decreases in yields are projected under continued present-day irrigation assumptions (Beringer et al., 2020). Water-related impacts on global cotton production are highly dependent on the CO_2-fertilisation effect, with increases projected for higher CO_2 concentration if no water limitations are implemented. However, substantial decreases in cotton production are projected if lower or no fertilisation effects are accounted for due to increasing water limitations (Jans et al., 2018). Reductions in economically valuable crops will probably increase the vulnerability of population groups, especially small-holder farmers with limited response options (Morel et al., 2019).

To stabilise yields against variations in moisture availability, irrigation is the often the most common adaptation response (Section 4.6.2, Box 4.3). Projections indicate a potentially substantial increase in irrigation water requirements (Boretti and Rosa, 2019). Increasing agricultural water demand is driven by various factors, including population growth, increased irrigated agriculture, cropland expansion and higher demand for bio-energy crops for mitigation (Chaturvedi et al., 2015; Grafton et al., 2015; Turner et al., 2019; 4.7.6). Depending on underlying assumptions and the constraints on water resources implemented in the global agricultural models, irrigation water requirements are projected to increase two- to three-fold by the end of the century (Hejazi et al., 2014; Bonsch et al., 2015; Chaturvedi et al., 2015; Huang et al., 2019). While the combined effects of population and land use change as well as irrigation expansion account for the significant part of the projected increases in irrigation water demand by the end of the century, around 14% of the increase is directly attributed to climate change (RCP6.0) (Huang et al., 2019).

With various degrees of water stress being experienced under current conditions and further changes in regional water availability projected, as well as continuing groundwater depletion as a consequence of over-abstraction for irrigation purposes (Sections 4.2.6 and 4.4.6), limitations to major irrigation expansion will occur in some regions, including South and Central Asia, the Middle East and parts of North and Central America (Grafton et al., 2015; Turner et al., 2019). Constraining projections of available irrigation water through consideration of environmental flow requirements further reduces the potential for irrigation capacity and expansion (Bonsch et al., 2015). Changes in land use and production patterns, for example, expansion of rain-fed production and increasing inter-regional trade, would be required to meet growing food demand while preserving environmental flow requirements, though this may increase local food security-related vulnerabilities (Cross-Chapter Box INTERREG in Chapter 16) (Pastor et al., 2014). Where climate impacts on yields are not a consequence of water limitations (mainly for C4 crops), irrigation cannot offset negative yield impacts (Levis et al., 2018).

Over 50% of the global lowlands equipped for irrigation will depend heavily on runoff contributions from the mountain cryosphere by 2041–2050 (SSP2–RCP6.0) and are projected to make unsustainable use of blue water resources (Viviroli et al., 2020). Projected changes in snowmelt patterns indicate that for all regions dependent on snowmelt for irrigation during warm seasons, alternative water sources will have to be found for up to 20% (at 2°C GWL) and up to 40% (at 4°C GWL) of seasonal irrigation water use, relative to current water use patterns (1986–2015) (Qin et al., 2020). Regional studies further corroborate these global findings (Biemans et al., 2019; Malek et al., 2020). Basins where such alternate sources are not available will face agricultural water scarcity.

Elevated CO_2 concentrations play an important role in determining future yields in general and have the potential to beneficially affect plant water use efficiency (Deryng et al., 2016; Ren et al., 2018a; Nechifor and Winning, 2019). The elevated CO_2 effects are projected to be most prominent for rain-fed C3 crops (Levis et al., 2018). Combined results from field experiments and global crop models show that CO_2 fertilisation could reduce consumptive water use by 4–17% (Deryng et al., 2016). To account for uncertainties, global agricultural models provide output with and without account for CO_2 fertilisation effects, though recent progress on reducing model uncertainty indicates that non-CO_2 model runs may no longer be needed for adequate projections of yield impacts (Toreti et al., 2019).

Due to the complex interactions among determinants for livestock production, the future signal of water-related risks to this sector is unclear. Globally, 10% (± 5%) of pasture areas are projected to be vulnerable to climate-induced water scarcity by 2050 (Fitton et al., 2019). Water use efficiency gains through elevated CO_2 concentrations have the potential to increase forage quantities, though effects of nutritional values are ambiguous (Augustine et al., 2018; Derner et al., 2018; Rolla et al., 2019). In addition, spatial shifts in temperature/humidity regimes may shift suitable regions for livestock production, opening up new suitable areas for some regions or encouraging shifts in specific breeds better adapted to future climatic regimes (Rolla et al., 2019) (5.5 – Livestock Systems and 5.10 Mixed Systems).

Projections of climate impacts on freshwater aquaculture are limited (5.9.3.1 – Projected Impacts; Inland freshwater and brackish aquaculture). In particular, in tropical regions, reductions in water availability, deteriorating water quality, and increasing water temperatures pose risks to terrestrial aquaculture, including temperature-related diseases and endocrine disruption (Kibria et al., 2017, Section 4.4.7). On the other hand, freshwater aquaculture in temperate and arctic polar regions may benefit from temperature increases with an extension of the fish-growing season (Kibria et al., 2017).

Global crop models, which provide the basis for most projections of agricultural risk, continue to have limitations in resolving water availability. For example they do not fully resolve the effects of elevated CO_2 for changing water use efficiency (Durand et al., 2018), potentially overestimating drought impacts on maize yield (Fodor et al., 2017) and may underestimate limitations to further expansion of irrigation (Elliott et al., 2014; Frieler et al., 2017b; Winter et al., 2017; Jägermeyr and Frieler, 2018; Kimball et al., 2019; Yokohata et al., 2020a).

In summary, agricultural water use is projected to increase globally due to cropland expansion and intensification and climate change-induced changes in water requirements (*high confidence*). Parts of temperate drylands may experience increases in suitability for rain-fed production based on mean climate conditions; however, risks to rain-fed agriculture increase globally because of increasing variability in precipitation regimes and changes in water availability (*high confidence*). Water-related impacts on economically valuable crops will increase regional economic risks (*medium evidence*, *high agreement*). Regions reliant on snowmelt for irrigation purposes will be affected by substantial reductions in water availability (*high confidence*).

4.5.2 Projected Risks to Energy and Industrial Water Use

AR5 concluded with *high confidence* that climate-induced changes, including changes in water flows, will affect energy production, and the actual impact will depend on the technological processes and location of energy production facilities (Arent et al., 2014). SR1.5 concluded with *high confidence* that climate change is projected to affect the hydropower production of northern European countries positively. However, Mediterranean countries like Greece, Spain and Portugal are projected to experience approximately a 10% reduction in hydropower potential under a 2°C warming level, which could be reduced by half if global warming could be limited to 1.5°C (Hoegh-Guldberg et al., 2018). In addition, SROCC concluded with *high confidence* that an altered amount and seasonality of water supply from snow and glacier melt is projected to affect hydropower production negatively (IPCC, 2019a).

Since AR5, a large number of studies have modelled future changes in hydropower production due to climate-induced changes in volume and seasonality of streamflow and changes in sediment load due to accelerated melting of cryosphere at both global (van Vliet et al., 2016b; Turner et al., 2017) and regional scales (Tarroja et al., 2016; Ali et al., 2018; de Jong et al., 2018; Tobin et al., 2018; Arango-Aramburo et al., 2019; Carvajal et al., 2019; Arias et al., 2020; Meng et al., 2021).

For hydropower production at a global scale, Turner et al. (2017) projected an uncertainty in the direction of change in global hydropower production to the tune of +5% to –5% by the 2080s, under a high-emissions scenario. On the other hand, van Vliet et al. (2016b) projected an increase in global hydropower production between +2.4% to +6.3% under RCP4.5 and RCP8.5, respectively, by the 2080s, as compared to a baseline period of 1971–2000, but with significant regional variations (*high confidence*). For example, regions like central Africa, India, central Asia and northern high-latitude areas are projected to see more than 20% increases in gross hydropower potential (*high confidence*). On the other hand, southern Europe, northern Africa, southern USA and parts of South America, southern Africa and southern Australia are projected to experience more than 20% decreases in gross hydropower potential. The Mediterranean region is projected to see almost a 40% reduction in hydropower production (*high confidence*) (Turner et al., 2017). On the other hand, northern Europe and India are projected to add to their hydropower production capacity due to climate change by mid-century (*high confidence*) (van Vliet et al., 2016b; Turner et al., 2017; Emodi et al., 2019).

In hydropower plants located in the Zambezi basin, electricity output is projected to decline by 10–20% by 2070 compared to baseline (1948–2008) under a drying climate; only marginal increases are projected under a wetting climate (Spalding-Fecher et al., 2017). In the