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Analysing trade-offs between SDGs related to water quality using salinity as a marker

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Abstract

Salinisation can have different adverse impacts on water resources that are used for drinking, irrigation, or industrial purposes. In addition, salinisation in its turn is also strongly influenced by anthropogenic activities such as irrigation. This paper maps trade-offs between water quality (SDG 6.3) and other Sustainable Development Goals (SDGs) using salinisation as an example. Many interlinkages exist between SDG 6.3 and other SDGs as identified in the literature review part. These are however not yet fully addressed in studies applying a comprehensive systems approach or modelling frameworks. In order to find solution options for achieving a sustainable future the interlinkages between SDGs related to salinisation and its impacts need to be considered as they play a key role in mitigating impacts, prioritising measures for action and hence turning trade-offs into synergies.

Highlights

- Salinisation degrades water quality in many regions worldwide.
- Irrigation, road de-icers, domestic and industrial wastewater are main sources.
- Salinisation as a marker to identify trade-offs between SDGs.
- Models as tools to identify hotspots, analyse pathways and assess solutions.

1. Introduction

Salinisation is a global problem degrading water quality, impairing the use of freshwater resources for human purposes and threatening agricultural production and aquatic ecosystems. Salinisation refers to an increase in the concentration of total dissolved solids (TDS) in water and can often be determined by an increase in chloride [1]. Four major cations [calcium (Ca++), magnesium (Mg++), sodium (Na+), and potassium (K+)] and the major anions [bicarbonate (HC03-), carbonate (C03--), sulfate (SO4--), and chloride (Cl-)] generally dominate total salinity of freshwaters [2]. The salt content of water can be easily detected either by the measure of total dissolved solids (TDS) or electrical conductivity (EC) of the solution [3]. TDS and EC are generic measures of the salt concentrations in freshwater systems; however, it should be considered that different salts induce varying degrees of toxicities to aquatic life [4]. In this context, natural and anthropogenic sources of salinity are characterised by specific ionic compositions indicating different levels of toxicity [5].

Historically, water salinisation was mainly seen as a severe problem in arid and semi-arid regions and in regions with poor irrigation management. However, it is now increasingly recognized as a worldwide environmental problem concerning also humid regions, due to anthropogenic pressures. There are two main causes of salinisation that contribute to salt emissions into river systems: (i) natural or ‘primary’ salinisation and (ii) anthropogenic or ‘secondary’ salinisation. Natural salinisation refers to the accumulation of soluble salts in soils through natural processes, mainly physical or chemical weathering of parent rock constituents, and transport of parent material in groundwater [6, 7, 8]. So called dryland salinity principally occurs in arid and semiarid regions where evapotranspiration exceeds precipitation [7]. Secondary salinisation results from human activities, in particular irrigation with saline (ground)water [9, 10] or inadequate drainage of naturally saline soils in (semi) arid zones [11, 12, 13]. However, not only poor irrigation practices contribute to salinisation of streams and rivers but also salt pollution originating from road de-icers, urban runoff, domestic and industrial wastewater, and mining operations [8, 14, 15]. High salt concentrations in rivers or lakes tend to be more severe in arid and semi-arid regions because of the lower dilution capacity [16]. In these regions water resources are also exposed to over-extraction, resulting in even lower discharge and reduced groundwater contribution to the baseflow.

Salinisation does not only have far-reaching consequences for land productivity, human well-being and ecological health but, consequently, can impact economic costs related to soil and water quality degradation. The co-management of land and water resources is a prerequisite for sustainable development and the balance of competing uses [17]. Sustainable Development Goal (SDG) 6 focuses on clean water and sanitation and aims to improve water quality by increasing the share of wastewater safely treated and preventing pollution intakes into surface and groundwater bodies. Salinisation from agriculture, industries and households affects water quality and high levels of pollution exceeding water quality standards make freshwater resources unusable for irrigation, processing and drinking water purposes and disturb the balance of aquatic ecosystems. Here, human-environment interactions become obvious in particular linkages between SDG 2 (agriculture and food production), SDG 7 (energy production and extractive processes), SDG 12 (sustainable consumption and production), SDG 15 (inland freshwater ecosystems) and SDG 6 (clean water and sanitation) and vice versa (Figure 1). Both positive and negative relations between these SDGs with salinisation and its main sources are presented. This shows that several (water use) sectors are important sources of salinisation but are, at the same time, also negatively affected by salinisation of water resources.

The main advantage of water quality models is to help understand the most important processes affecting water quality, and the opportunity of investigating the interactions between these processes. Therefore, water quality models are helpful tools to identify salinity hotspots and main sources of salinisation and hence support the development of strategies to reduce or prevent pollution emissions in order to achieve SDG 6. Moreover, models are appropriate for the analysis of scenarios [e.g. 18] and SDG interlinkages [e.g. 19, 20] and therefore also essential to evaluate if SDGs and targets will be achieved in the future. Further, modelling results can be used to fill in data gaps in data sparse regions (i.e., data and model-driven approach) [21] as well as designing the allocation of monitoring stations where no real measurements are available [22]. GIS and remote sensing techniques also provide good options in assessing and monitoring salinisation problems causing water quality degradation [23].

[Figure 1]

The objective of our paper is to review recent literature focussing on salinisation of freshwater resources, its impacts on water quality (SDG 6), which in turn is interlinked with food production (SDG 2), freshwater ecosystems (SDG 15), energy production and extraction (SDG 7), and sustainable consumption and production (SDG 12). First, we describe the status and main sources of salinisation (Section 2 ‘Hotspots of salinisation’) and how these impair freshwater resources for further use. In Section 3 (‘salinisation and linkages to other SDGs’) we discuss the challenges in a broader context of the potential for achieving other SDGs. Finally in Section 4 (‘Conclusions and outlook’) we summarize our main findings and discuss the impact of climate change and the need for dealing with potential SDG interlinkages and solution options to reduce salinisation and ways forward to convert trade-offs into synergies.

2. Hotspots of salinisation

Salinisation is a global threat to the water quality, either naturally occurring or human-induced, but tends to be more severe in arid and semi-arid regions [24, 25, 26]. Salt-affected soils occur in more than hundred countries of the world [9] with a total area of saline and sodic soils of about 831 million ha [27].

About one-tenth of the length of all rivers in Latin America, Africa and Asia are subject to severe and moderate salinisation which impairs the use of river water for irrigation, industry and other uses [21]. Hotspots of salinisation are the river basins of the Lower Nile, Euphrates, Indus and Ganges as well as the Aral Sea basin where TDS concentrations are likely to exceed a concentration of 450 mg/l in more than 6 months per year. Model results showed that salinity concentrations have increased between 1990 and 2010 in about 31% of the river stretches due to increases in loadings from anthropogenic sources (irrigation, manufacturing, domestic). Nevertheless, saline soils have been identified as the dominant source of salt loadings [21].

Globally, about 34 million ha of irrigated land is impacted by salinisation (i.e., >10% of global irrigated area), of which 77% are located in Asia, with major problems in Pakistan, China, and India, 16% in Northern America, 4% in Africa, 3% in Southern America, and 0.6% in Australia and New Zealand [13, 28]. Field studies have shown that salinity increased in some rivers across north-western China since the 1950s due to both increasing irrigation return flows and increasing evaporation [29]. In the Indus Basin poor quality groundwater is used for irrigation in combination with generally low irrigation efficiencies [10]. Like in Pakistan, waterlogging and secondary salinisation as well as irrigation with groundwater of poor quality causes major problems in North-West India [30] Irrigation return flow is also a major source of salinisation in South Korea [31]. Salinisation is also a major problem in parts of northern and southern Africa caused by salt mobilisation and accumulation due to poor soil and water management in irrigated areas including insufficient drainage systems [32, 33].

Other sources of secondary salinisation are excessive irrigation, which can raise water tables from saline aquifers and thus contributes to the seepage of saline groundwater into freshwater systems [13], and the (re)use of saline groundwater for crop irrigation [34]. Lakes in arid and semi-arid climates show increasing salinity as a result of interactions with saline groundwater, irrigation practices and evaporation losses from the lake surface [35, 36, 37].

Road salts, i.e. the wash-off of salt used to melt snow and ice on roadways, are an important source of salinity particularly in developed countries in colder climates. In northern USA, average salinity concentrations doubled in rivers and streams between 1990 and 2011 as a result of growing application of road salt from 9.6 million metric tons per year (1940s) to 19.5 million metric tons per year (2010s) [38, 39, 40, 41]. Rising trends in chloride concentrations were analysed for lakes in Midwest and Northeast North America which are surrounded by >1% impervious land cover, indicating the importance of road salt as a main source of salinisation in those regions [42].

A European scale review on the threat of soil salinity and the effects of salinisation was performed by Daliakopoulos et al. [8] who provided an overview on key drivers of salinisation processes and effects on soil functions, vegetation and damages to water supply infrastructure. Coastal Southern Europe was identified as a salinisation hotspot where the problem is aggravated by sea water intrusion due to increased groundwater extraction. Increasing concentrations in urban streams due to road salts were reported for Finland [43] and Lake Constance where de-icing salts have also been identified as a major source of increasing salinisation [44].

Further impacts of salinisation caused by sea water intrusion due to increased groundwater pumping as well as sea level rise causes serious health problems in coastal Bangladesh. High blood pressure (prehypertension and hypertension) was found significantly associated with drinking water salinity [45]. Elevated salinity levels influence the corrosivity of water which can affect mobilization of metals (e.g. lead and copper) from water distribution systems posing a risk to human health [15, 46].

Finally, there can be a considerable lag time between salt production and its persistence in the environment via soils, groundwater and sediments. The retention of salt in soils and groundwater is a complex mechanism depending on many factors, such as seasonality of precipitation and recharge, thickness of unsaturated zone and groundwater levels, geology as well as groundwater and river interactions. Due to long retention times of salts in soils and groundwater, peak concentrations due to prior salt application may not appear for several years or decades, or for the same reason, measures to reduce salt loads may not appear to be effective for many years [47, 48]. These aspects should be taken into consideration in view of the time frame to develop strategies achieve the SDGs.

3. Salinisation and linkages to SDGs

3.1 SDG 2 on agriculture and food security

Salinity threatens food security because of losing 2,000 ha of farm soil daily to salt induced degradation worldwide [49]. For the early 1990s, crop yield losses from salt-affected irrigated land resulted in income losses of about US$ 12 billion per year globally [50] which likely increased up to US$ 27.3 billion in 2013 as estimated by Quadir et al. [28]. Salinisation is the biggest water quality challenge facing the Colorado River mainly as a result of irrigation next to natural salinisation with estimated damages up to $383 million per year at 2009 concentrations [51].

However, salinisation negatively affects plant growth due to decreasing osmotic potential and resulting changes of microbial activities [52]. Therefore, increasing soil salinity does not only impact plant productivity and nutrient cycling [53], but also soil organic carbon (SOC) and net CO_2 release from the soil-plant system [54]. Modelling results indicate that the transition to saline soils resulted in a loss of 0.53 Pg soil organic carbon and a net CO_2 release from the soil-plant system of 1.94 Pg globally [54].

Restrictions on irrigated water use and reductions in crop productivity start when salinity concentrations exceed 450 mg/l [55]. The degree of salinity impacts on crop production depends on several factors such as soil texture, water content, and composition of soluble salts, nutrient status and growth stage of the plant [7, 56]. Overall, vegetable crops demonstrate higher sensitivity to soil salinisation than grains [8] and its salt tolerance decreases when saline water is used for irrigation [57]. Therefore, the use of saline (ground)water to irrigate crops poses a major risk to sustainable food production. Apart from improving the drainage characteristics and applying extra doses of irrigation water over the crop and transpiration demand for flushing or leaching the soil to reduce yield loss, research focusses on selecting salinity resistant effects of food crops [e.g. 58, 59, 60], on microorganisms to increase resistance of plants against salinity stress [61] and on improved fertilization and irrigation management strategies [57].

Using grid cell-based (5 by 5 arc minute) TDS simulations of the large-scale water quality model WorldQual for Asia [21, 62] it was estimated that agricultural yields are reduced by salinity in 49-77 million ha of irrigated land (in total 157 million ha) which is a risk to food security (SDG 2) [63]. Although most of the salinity loadings originate from natural salinisation, the main anthropogenic source is the return flows from irrigated land transporting large amounts of salts from upstream to downstream areas (Figure 2).

[Figure 2]

There are also guidelines for the use of saline waters for livestock. The main side effects of livestock consuming highly saline water are a suppression of appetite, diarrhoea and a disturbed water balance [64]. Generally, poultry is most vulnerable to high salinity levels.

3.2 SDG 15 on inland freshwater ecosystems

Humans depend on ecosystem services. Inland freshwater ecosystems provide many essential services, such as drinking water provision, water purification and flood protection. Salinisation can have negative impacts on aquatic ecosystems at the individual, population, community, and ecosystem levels, as well as on community structure [65, 66, 67, 68]. A proper understanding of these effects on different levels (e.g. individual and population) is important to realistically estimate changes at the ecosystem scale [69]. Increased salt concentrations can induce physiological stress in wetland biota, which can lead to large shifts in wetland communities (e.g. from salinity-sensitive taxa to more tolerant taxa) and associated ecosystem functions [70]. The tolerance to salinity can vary broadly between organisms. Most adult fish are tolerant to high salinities, whereas juveniles and eggs are more salt sensitive [65, 66]. Anuran amphibians are salt-sensitive across species and across life stages, too, and may therefore be vulnerable to increasing salinity concentrations of open freshwater bodies [71].

Potash mining, for example, has also the potential to significantly alter biological communities of rivers [72, 73]. However, specific consequences and ecosystem’s response to salinisation vary from case to case due to different salinity exposure thresholds of freshwater biota and ecosystem processes [66]. Although feedbacks between salinisation and ecosystem functioning are complex and non-linear, the first step for preserving inland freshwater wetlands is to determine the exposure to salinisation. The alteration of water chemistry due to salinisation alters the ability of wetlands to provide key ecosystem services such as denitrification to remove excess nitrogen [70].Other more short-term effects of increased salinisation is on the enhanced release of labile organic carbon and nitrogen from streambed substrates in human-impacted watersheds [74].

The locations of riverine wetlands as listed under the Ramsar Convention [75] in South-East Asia are shown in Figure 3 and highlight the exposure of these wetlands to the change in salinity concentrations over the 1990-2010 time period. According to the WorldQual model results most rivers in South and South-East Asia experienced increases in salinity (TDS concentrations) over the 20-years period posing a risk to the freshwater wetlands and freshwater ecosystems in general. Main reasons are physicochemical alterations of soil and water properties due to increased anthropogenic salinisation.

Preventive actions are required on the basis of ecological criteria in order to make progress in the regulation of permitted salinity levels [67].

[Figure 3]

3.3 SDG 7 on energy production and extraction

Mining and minerals industries contribute to additional exposures of salts to the surface impairing water quality in surrounding streams and rivers [76]. Important sources of salts from mining activities are mineral weathering of bedrock and spoil material, saline/acid mine drainage, mine dewatering and return flows from washing coal and equipment and dust suppression [76, 77]. Mountaintop coal mining, for instance, leads to elevated salinity levels and degraded in-stream water quality [78]. Wastes from potash extraction that are stored near the mines and salts often leak from the retention infrastructures into streams and rivers close to the mines [73]. Both of these processes negatively affect the biological conditions of aquatic ecosystems [68, 79, 80].

Surface disturbance of naturally salt-affected soils and high-salinity formation by oil and gas development activities is a reasonable source for salinisation [26, 81]. Brine from conventional oil and gas operations has led to increased salinity concentrations [82, 83], while shale gas development generates large volumes of return flows with high salinity levels [84]. Geogenic salts and salts released from rapid weathering of spoil minerals are important sources in coal mine spoils [77]. Therefore, management of water discharge, i.e. saline water and acid mine drainage, from a coal mine area is an important aspect of the salinity management [76, 77]. For example, in South Africa, the treatment of acid mine drainage consists of adding lime, which increases pH on the one hand, but also contributes to very high sulphate concentrations discharged to rivers [85].

3.4 SDG 12 on sustainable consumption and production

The oil sands industry uses huge volumes of water for hot water extraction, i.e. a flotation process to separate bitumen from sand and clay. This industry sector is increasingly dependent on process-water recycling as freshwater becomes scarce during low-flow seasons

[86]. Process-water recycling has reduced the freshwater intake, however, the decline in process water quality reduces bitumen recovery rates and threatens extraction facilities [86]. Today the role of water recycling is growing on mine sites in order to close the water loop and to reduce the impact on freshwater resources [87]. Nevertheless, treatment is required to mitigate high salinity concentrations in mine water effluents before further use, which tends to increase the costs of extraction progressively [88]. A further aspect of water recycling and treatment is the use of additional energy for water treatment which leads to higher greenhouse gas emissions [89].

Salinity is influenced by the industry sector but on its turn also impacts industrial purposes. Industrial wastewater often contains high levels of salinity [90, 91]. The discharge of high saline wastewater or reuse for irrigation without prior treatment deteriorates water quality. On the other hand, salinisation is of concern to certain industries, i.e. different industry sectors have recommended maximum threshold levels of salinity, because of infrastructure damage (e.g. pipelines) and low salinity requirements of some processes. In regions affected by water scarcity, the reuse of treated wastewater closes the water cycle within the industry or supports irrigated agriculture [92].

Another source of anthropogenic salinisation related to SDG12 is the dissolution of concrete material of buildings and infrastructure (e.g. roads, drainage systems), which could lead to increased concentrations in urban streams and water bodies [Kaushal et al. 2015, 2017]. The frequent use of de-icing salt on roads in turn further increases the dissolution and damage of concrete material.

4. Conclusions and Outlook

In this paper we have used salinisation as an example to mark the trade-offs between water quality and related SDGs. Salinisation is not only restricted to semi-arid and arid regions where saline soils are widespread. Salinisation from anthropogenic sources such as agriculture, industry, mining activities and road de-icers represent an increasing risk to freshwater resources worldwide. We showed that high salinity levels lead to a degradation of water quality and thus impact food production, energy production, aquatic ecosystems and sustainable industrial production. High salinity levels thus affect the SDGs to be achieved, i.e. SDG 2 (zero hunger), SDG 7 (affordable and clean energy), SDG 12 (responsible consumption and production), and SDG 15 (life on land) which are closely interlinked with water quality issues addressed by SDG 6.3. Current salinity hotspots as described in the literature are useful to identify existing trade-offs between SDGs. Irrigation practices to ensure food security (SDG 2) may cause water quality degradation (SDG 6) which in turn impairs agricultural and industrial production (SDG 2, SDG 12) and alters ecosystem functions (SDG 15). The analysis and evaluation of these causal links requires a systems approach based on measurements and supported by modelling tools in order to address the complex interactions and develop solutions to achieve the SDGs that turn trade-offs into synergies.

Climate change is expected to increase the rate of evaporation worldwide due to warming temperature and to decrease precipitation in some regions, which in turn increases the salinity concentration in water bodies (less dilution capacity), and the amount of irrigation water requirements. This poses serious challenges for freshwater supply for drinking, industry and agriculture, and associated SDG targets. In particular, increasing salinity likely constrains the sufficient amount of freshwater required for upscaling existing irrigation and associated food production. For major irrigated regions, excessive groundwater pumping and increasing salinity will pose serious threat for achieving food, energy, and ecosystem security.

Future research should aim at providing a better understanding of the processes behind the interlinkages, at improving models and tools to better assess impacts, at identifying and elaborating solution options to reduce risks, and thereby enhancing and prioritizing actions to achieve the SDGs. Simulations of future scenarios should facilitate interactions with stakeholders and decision makers to be better prepared for the future.

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Papers of special interest (*****) or outstanding interest (******).

Figures

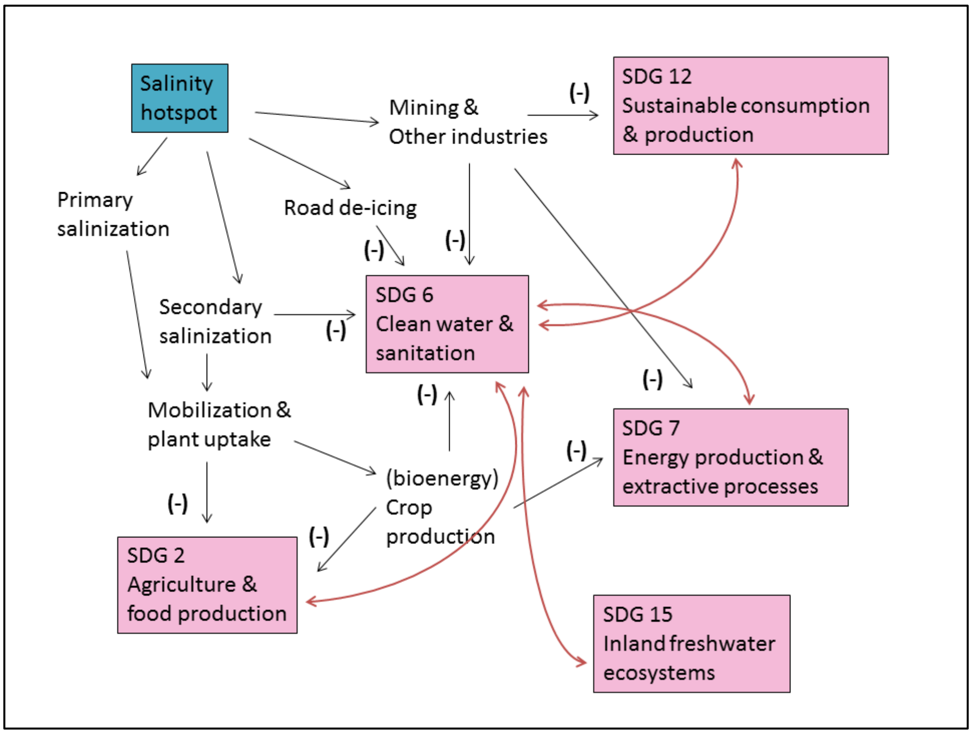

Figure 1: Conceptual scheme representing a salinity hotspot and related sources of salinisation negatively affecting SDG 6. Potential interlinkages between SDG 6 and other SDGs are depicted by red arrows. Possible pathways of water pollution from different sources and the potential interlinkages can be represented by water quality models.

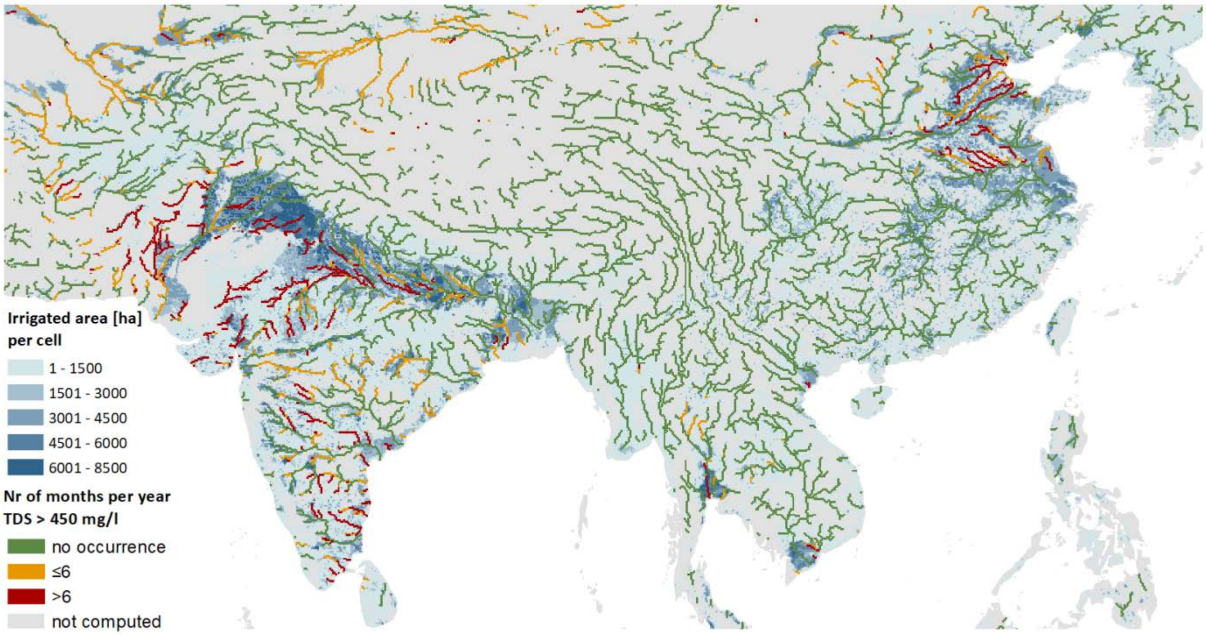

Figure 2: Modelled number of months per year in which river stretches are subject to moderate salinisation (>450 mg/l) over the period 2008-2010 and intensity of irrigated area [ha per grid cell] in South-East Asia. (Map adopted from [63] based on model results from the WaterGAP3 modelling framework [21].

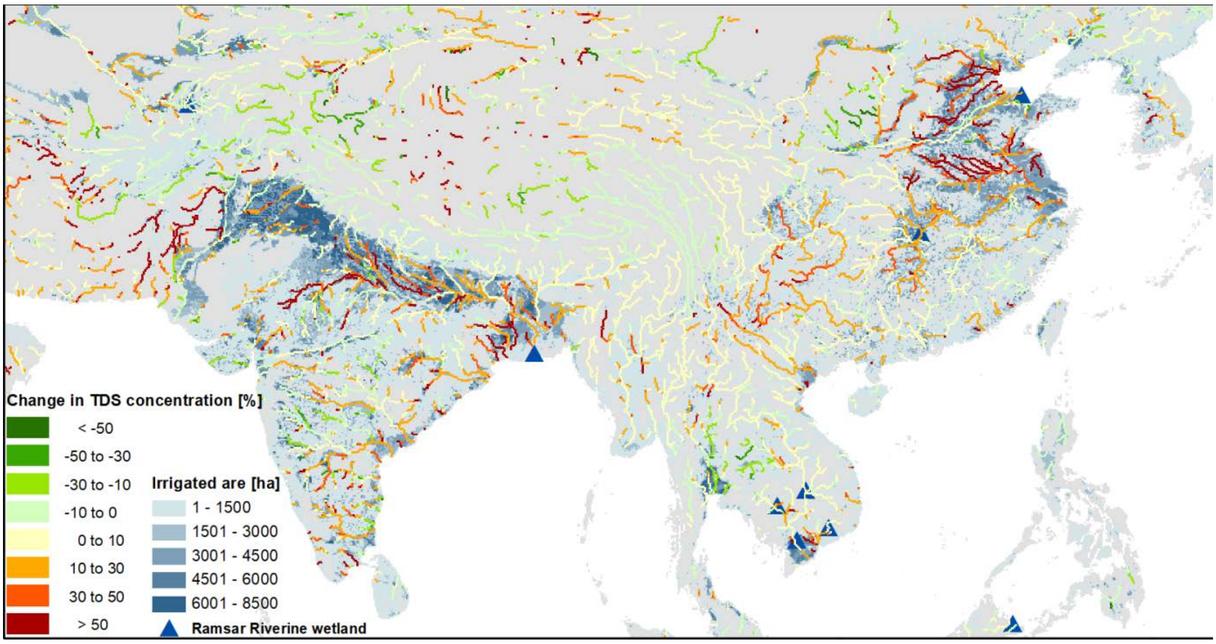

Figure 3: Simulated relative change in salinity concentrations between 1990 and 2010 based on model simulations with WorldQual [21]. Triangles indicate the location of riverine wetlands as listed under the Ramsar Convention [75].