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Abstract It is estimated that 884 million people do not have access to clean drinking water in the world. Increasing salinity of natural drinking water sources has been reported as one of the many problems that affect low-income countries, but one which has not been fully explored. This problem is exacerbated by rising sea-levels, owing to climate change, and other contributing factors, like changes in fresh water flow from rivers and increased shrimp farming along the coastal areas. In some countries, desalination plants are used to partly remove salt and other minerals from water sources, but this is unlikely to be a sustainable option for low-income countries affected by high salinity. Using the example of Bangladesh as a model country, the following research indicates that the problem of salinity can have serious implications with regard to rising rates of hypertension and other public health problems among large sectors of the worldwide population.

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1. Introduction

The following research paper explores the delicate balance between sea-level rise, increasing coastal economic activities and the flow of freshwater from rivers into the sea; these problems have received little attention thus far and must be addressed. The combination of several forces is likely to lead to a widespread problem of water salinity, with the ensuing detrimental health effects, in particular, for populations living along the coast and in deltaic areas. The current recommended dietary intake of salt (sodium chloride) has been set at 5 g/day, according to the report of a Joint Expert Consultation of the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations in 2002 [1]. For drinking water, the maximum allowable concentration is 250 mg/L for chloride [2]. In countries where people suffer from iodine deficiency, recommended levels also depend on the iodine status of the concerned populations [1]. While small quantities of salt are essential for regulating the fluid balance of the human body, consumption of salt higher than the recommended levels is associated with adverse health effects [1,3]. In addition to hypertension and stroke, increased salt intake can be responsible for several other health problems, as reports from local populations suggest (discussed below). WHO considers reducing salt intake in the population a public health priority.

The Intergovernmental Panel on Climate Change (IPCC) estimated that marine and coastal ecosystems in South and South-East Asia will be affected by sea-level rise [4] with a grading of “high confidence”. It also stated that future climate change will have severe effects on water security in developing countries, adversely affecting human health in a number of ways (“medium confidence”) [4]. Sea-level rise is a critical factor that makes deltaic regions particularly vulnerable to climate change. Other environmental factors, like tropical cyclones, are likely to interact with higher mean sea-levels and contribute to higher storm surges and increased flooding [5,6]. For example, there is already evidence that salt water from the Bay of Bengal in Bangladesh has penetrated more than 100 km inland along tributary channels during the

dry season [4,7]. This not only increases the potential for economic and infrastructural damage, but also affects livelihoods and increases health risks through contamination of drinking water [3,8]. However, available data are scant and an investigation of the human health impact is urgently required to promote adaptation measures and to avoid long-term consequences, such as an epidemic of hypertension in coastal areas of the world, particularly in low-income countries.

2. Estimates of water salinity

2.1. Bangladesh: a model country

Estimates of sea-level rise were taken from the reports by the Ministry of Environment and Forest (MOEF) in Bangladesh [6] and the United Kingdom Department for Environment Food and Rural Affairs [9], which included assessments of the impacts of climate change and sea-level rise on water resources, land suitability and the health of coastal populations. A hydrodynamic model was used to simulate river systems under present and future conditions [9].

The sea level rose at an average rate of 1.8 (1.3–2.3) mm/year between 1961 and 2003 overall in the world. The rate accelerated from 1993 to 2003 to about 3.1 (2.4–3.8) mm/year [4]. However, for Bangladesh, sea-level rise has been estimated to be higher [9]. Using historical data from three coastal stations (Hiron Point, Char Changa, and Cox’s Bazaar), it was shown that the rate of sea-level rise during the last 22 years in Bangladesh is higher than the global sea-level rise over 100 years (4, 6 and 7.8 mm/year for the three stations, respectively) [9].

In Bangladesh, salinity of surface and groundwater is determined by a combination of factors, including river flow, tidal surges, rainfall and groundwater extraction, as well as the influence of sea-level rise and other climatic variables. The Padma River (Bangladesh branch of the Ganges River) now flows at less than a quarter of its capacity during the dry season (November–May), and the downstream network of rivers struggles to wash the saline water back out to sea. The fresh water stream dropped off significantly in the Padma since

India commissioned the Farakka Barrage in 1975 [10]. The distance of the salinity intrusion inland, and the extent of salinity in the coastal areas, is expected to increase with rising sea levels [6,10].

Another element that contributes to increasing salinity inland is shrimp farming – a rapidly developing business – whereby salt water is deliberately retained in ponds to cultivate shrimp [11]. In the past few decades, large areas of rice fields and cultivable land in the coastal areas have been converted into shrimp farms. This has contributed to increased groundwater salinity, soil degradation, and a lower yield and acreage of rice [6,11]. Finally, in deltaic regions population size tends to increase, thus leading to greater groundwater extraction (a phenomenon not related to climate change).

A study was undertaken to estimate the individual salt intake from river water for a coastal community in Bangladesh [3]. Data included monthly measurements of salinity in the Passur River in Khulna (a coastal area). The average level of river salinity was estimated at 8.21 g/L of water in the dry season. Assuming an average daily consumption of 2 L of water per individual, salt intake from river water was up to 16 g/day. This level of intake may be an underestimation since dietary salt intake was not taken into account.

2.2. Other areas

Though Bangladesh is a model country, indirect estimates of salinity are available for other areas. Documentation in this regard was usually in the form of reports (grey literature): for example, the salinity levels at Pearl River Delta, China [12]; San Joaquin Delta, California [13]; and man-made freshwater lakes in The Netherlands [14] and Australia [15]. Some evidence was also available from Brazil [16]. These reports mainly refer to deltaic regions. It must also be noted that not all data reported here refer to drinking water, which is a direct route of exposure. Clearly, a systematic review is currently not possible. Also, estimates of water salinity would be made possible by remote sensing (satellite data), but, again, the use of such data for river deltas and other sources of drinking water in low-income countries is scanty or unavailable.

2.2.1. The Netherlands

A modelling study estimated the impact of climate change on the chloride concentration and salinization processes in two man-made freshwater lakes in the Netherlands – Lake IJsselmeer and Lake Markermeer – used for drinking purposes [14].

The results from the climate change scenarios show that Lake IJsselmeer is especially vulnerable to climate-induced salinity whereas effects on Lake Markermeer are relatively small. Peak chloride concentrations at the drinking water facility on Lake IJsselmeer are projected to increase to values above 250 mg/L in the most extreme climate change scenario. According to the authors of the paper, climate change impacts the chloride concentrations in a variety of ways, including rises in sea-level that increase seawater intrusion through the dam of Lake IJsselmeer [14].

2.2.2. Sacramento and San Joaquin rivers, California

The amount of water flowing into the Sacramento and San Joaquin river delta is the single most important determinant of salinity at the export pumps, and the amount of inflow has been shown to be largely determined by hydrology. During rainy years, the average salinity at the pumps is low. The average electrical conductivity – a measure of salinity – at the banks pumping plant for the 1983 water year (one of the rainiest on record) was 276 $\mu\text{S}/\text{cm}$, corresponding to 431 mg/L. In the critically dry 1991 water year, electrical conductivity at the same location averaged 589 $\mu\text{S}/\text{cm}$, corresponding to 920 mg/L. Electrical Conductivity can vary from less than 200 $\mu\text{S}/\text{cm}$ to more than 750 $\mu\text{S}/\text{cm}$ in a single water year. The highest salinities occur during the fall and early winter when delta inflow is lowest. Similarities with the case of Bangladesh are obvious, though modifying factors such as shrimp farming are not present.

2.2.3. Australia

In Australia with the removal of the natural vegetation, the amount of water entering the water table (called the recharge) has increased and the rising groundwater level has dissolved the accumulated salt within the soil. Eventually (after many decades), the groundwater level reaches the surface, bringing the salt with it. This results in the death of all but the most salt-tolerant plants with consequent changes to other parts of the ecosystem. Currently, 1.047 million hectares of southwest Western Australia are affected by dryland salinity, and this area may expand up to a further 1.7–3.4 million hectares if trends continue [17]. A comprehensive national assessment of the problem – *The Australian Dryland Salinity Assessment 2000* – has recently been undertaken, and a plan for tackling it has been developed [18].

Salinity and water quality problems are critical: for example, Adelaide's drinking water is likely to

fail World Health Organization salinity standards in two days out of five within 20 years (however, though this was repeated in a number of government bodies, no scientific data are referred to in any of them) [19]. There were no estimates available for other parts of Australia.

2.2.4. Brazil

One study aimed at evaluating differences in rotifer (zooplankton) distribution in three estuarine zones in an estuary located in the Semiarid Region of Brazil [16]. High freshwater precipitation during the rainy season was the major determinant of rotifer composition. Due to higher salinity values during the dry season, very low values of species richness were observed. The study highlights the constraints of salinity and the positive influence of seasonality and river proximity on rotifer species in an estuarine environment.

3. Health impacts

The fact that salinity is increased – particularly in the dry season – in some river deltas obviously does not imply that all coastal populations are exposed via their drinking water. It is likely that in many places treatment of water through desalination plants is used to reduce salt concentrations. However, the effects of higher salinity on health will be seen in low-income countries, those where water is insufficiently treated or not treated at all.

Besides drinking water, there are other routes of exposure to high salinity, e.g. through diet, bathing and occupation (as in the case of shrimp farming in Bangladesh), which also have potential effects on health. The government of Bangladesh and Caritas Development Institute (CDI) reported a range of health problems among coastal populations with potential links to increased salinity exposure through drinking, cooking and bathing, including hypertension and miscarriage among pregnant women, skin diseases, acute respiratory infection and diarrhoeal diseases [6,20,21].

In Western Australia, three key potential impacts on human health resulting from dryland salinity (not via drinking water) were identified: wind-borne dust and respiratory health; altered ecology of the mosquito-borne disease Ross River virus; and mental health consequences of salinity-induced environmental degradation [17]. These adverse outcomes of salinity on human health are likely to be further exacerbated with the increase in extent and severity of dryland salinity over the coming decades [17].

The relevance of salt intake has been mainly considered in the context of diet, while epidemiological studies assessing the health effects resulting from the intake through water have been insufficiently conducted [3]. A prospective study in Massachusetts, USA, looked at two matched cohorts of high-school pupils from towns with a ‘high’ (272 mg/L) and ‘low’ (20 mg/L) salt level in public drinking water, and reported that systolic and diastolic blood pressures in the high-sodium region were significantly higher by 3–5 mmHg after controlling dietary salt intake [22]. A study on similar cohorts in Chicago reported that diastolic blood pressure was 2 mmHg higher in the group with 405 mg/L versus 4 mg/L of sodium in their drinking water ($p = 0.040$ for males and $p = 0.016$ for females) [23]. An investigation carried out after concerns of apparently elevated rates of hypertension in a population living in Arizona with water salt levels of 440 mg/L showed no association when compared with a reference population [24].

Epidemiological studies have shown an association between dietary salt intake and high blood pressure with strong evidence [25,26]. The INTER-SALT epidemiological study showed an association between dietary salt intake and high blood pressure [25] and reported that a sodium intake of higher than 1.8 g/day (approximately 100 mmol/day) caused a rise in systolic blood pressure and diastolic blood pressure of approximately 3–6/0–3 mmHg. According to a review by Macgregor et al. reducing salt intake from 10–12 to 5–6 g/day will have a major effect on blood pressure, thereby preventing cardiovascular mortality [26]. Raised blood pressure throughout the range seen in developed countries is the major cause of cardiovascular disease, responsible for 62% of strokes and 49% of coronary heart disease [26].

4. Exposed populations and overall impact

A few examples of how salinity may affect populations through drinking water as well as other indirect ways have been presented in this research paper. Statistical data on the human impact of sea-level rise are scarce. A study in the April 2007 issue of *Environment and Urbanization* reports that 634 million people live in coastal areas within 30 feet (9.1 m) of sea level [27]. The study also reports that about two thirds of the world’s cities with over 5 million people are located in these low-lying coastal areas.

A large share of the population in coastal Bangladesh may be consuming levels of up to 16 g/day of

salt in the dry season [4] from only 2 L of natural drinking water. Estimates for other populations are not available. While it is unlikely that all populations in vulnerable areas experience this level of exposure, such levels are likely to be widely experienced in low-income countries where natural sources (rivers and tube wells) are used for drinking, and salt-water treatment is likely to be very costly.

High blood pressure is a major cause of disease burden in both developed and developing regions [28]. Using the INTERSALT model, consumption on average of 5 g/day of salt intake among the population in coastal Bangladesh would increase the systolic blood pressure by approximately 9 mmHg. The changes introduced by water salinity would thus lead a large proportion of the population in developing pre-hypertension (systolic BP between 120 and 139 mmHg or diastolic BP between 80 and 89 mmHg) and hypertension (SBP > 140 mmHg or DBP > 90 mmHg), depending on the baseline levels. Given the lack of reliable data on the effects of exposure via drinking water, the INTERSALT model was relied upon since there is no reason why water intake differs substantially from food intake.

5. Discussion: environmental justice

Rather sparse data were available on salinity of fresh waters in proximity to coastal areas, reflecting different and probably not comparable situations. However, there are two common features: the varying levels of salinity according to seasonality, and the likely historical increase expected as an effect of climate change and sea-level rise. The problem of saline intrusion potentially affects 11 Asian mega-deltas, and other large deltas or estuaries, such as the Nile and Mississippi. If salinity on the coasts remains unchecked, a global crisis related to freshwater availability and quality with clear human health implications may be seen. Asia is a particularly vulnerable region; more than 50% of the world's population lives in Asia, and most live in deltaic or estuarine areas.

Rising water salinity is a further potential consequence of climate change and sea-level rise and also raises issues of environmental justice. Not only is the contribution of low-income countries to carbon emissions often negligible (as in the case of Bangladesh), but their burden of negative consequences of climate change is totally disproportionate.

In this paper, one health problem is particularly addressed: hypertension. Several other effects can be attributed to salinity in water, including indirect effects such as stroke and diarrhoeal diseases. But

such an exhaustive ‘‘disease burden’’ estimation is outside the scope of the present paper.

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