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Climate Change and Coastal Development in Kuwait: Key Challenges and Insights

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KUWAIT PORTS AUTHORITY

inspiring change

MOTIVATION

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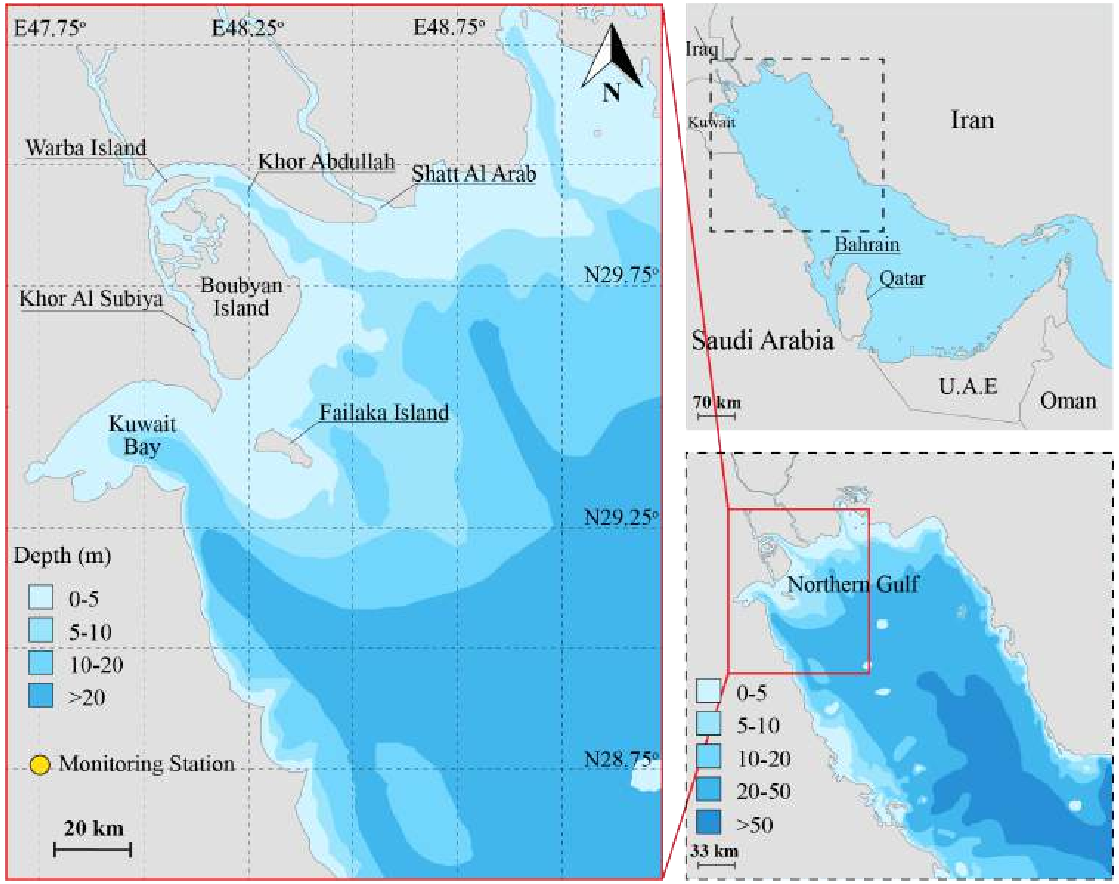
Kuwait's coastal regions are experiencing rapid development, yet climate resilience remains inadequately addressed. This gap is driven by the inherent uncertainties and cost challenges associated with predictive climate models and the unpredictable human responses to emerging climate risks. The reluctance to base designs on uncertain projections exposes waterfront infrastructure to risks such as rising sea levels, extreme weather events, and changing coastal dynamics.

CONTENT

- Motivations
- General physical characteristics of the Gulf and Kuwait waters
- General Circulations in the Gulf
- Key developments in Kuwait
- Environmental challenges associated with climate change
  - *Implications of extreme heat waves*
  - *Flash floods and runoffs*
  - *Desertification and dust storm impacts*
- Conclusion and remarks

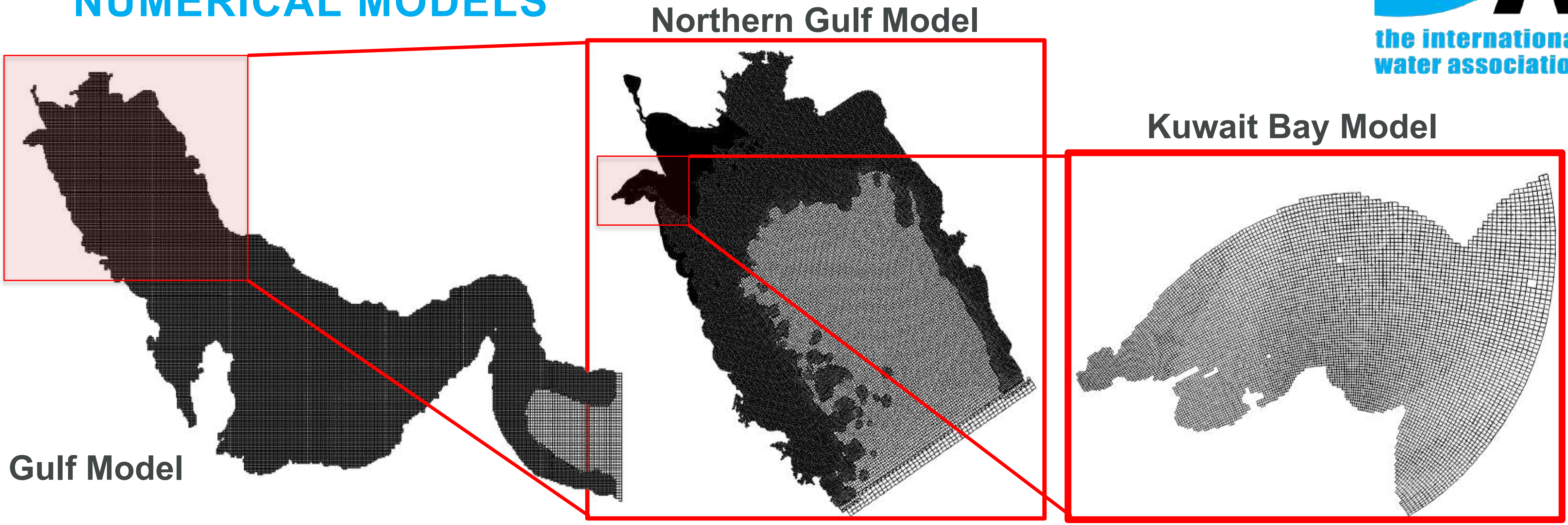
GENERAL GULF CHARACTERISTICS

- Weak estuary (**limited freshwater discharge**)
- **Limited exchange** with the open ocean through the **Strait of Hormuz.**
- The Gulf has an average depth of approximately **35 meters**
- Tides in the Gulf are mixed semi-diurnal, with tidal ranges varying from less than **1 m** in the southern part to **over 2 m** in the northern areas.
- The Gulf experiences high salinity levels, with an average of around **40–42 PPT** in summer due to **high evaporation** rates and **minimal freshwater influx**, increasing further in shallow areas
- The region is dominated by a seasonal wind regime, with northwesterly **“Shamal" winds** prevailing during summer and winter.
- Summer Temperatures: Surface water temperatures in the Gulf can exceed **35°C** in shallow regions and drop to **15 °C** in winter.



•Emery, K. O. (1956). *Sediments and water of the Persian Gulf.* AAPG Bulletin, 40(10), 2354-2383.
•Sheppard, C., Price, A., & Roberts, C. (1992). *Marine Ecology of the Arabian Region: Patterns and Processes in Extreme Tropical Environments.* Academic Press.
•Reynolds, R. M. (1993). Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman—Results from the Mt Mitchell expedition. *Marine Pollution Bulletin*, 27, 35-59.

NUMERICAL MODELS



- Hydrodynamics (Delft3D, Delft-FM)
- Water Quality (D-WAQ)
- Sediment Transport
- Particle tracking (oil spills, solid waste, .. etc

- 2D and 3D models
- Hydrostatic and Non-Hydrostatic
- Regular, curvilinear, and flexible mesh
- Normal and Parallel computing

FIELD MEASUREMENTS FOR MODEL VALIDATION

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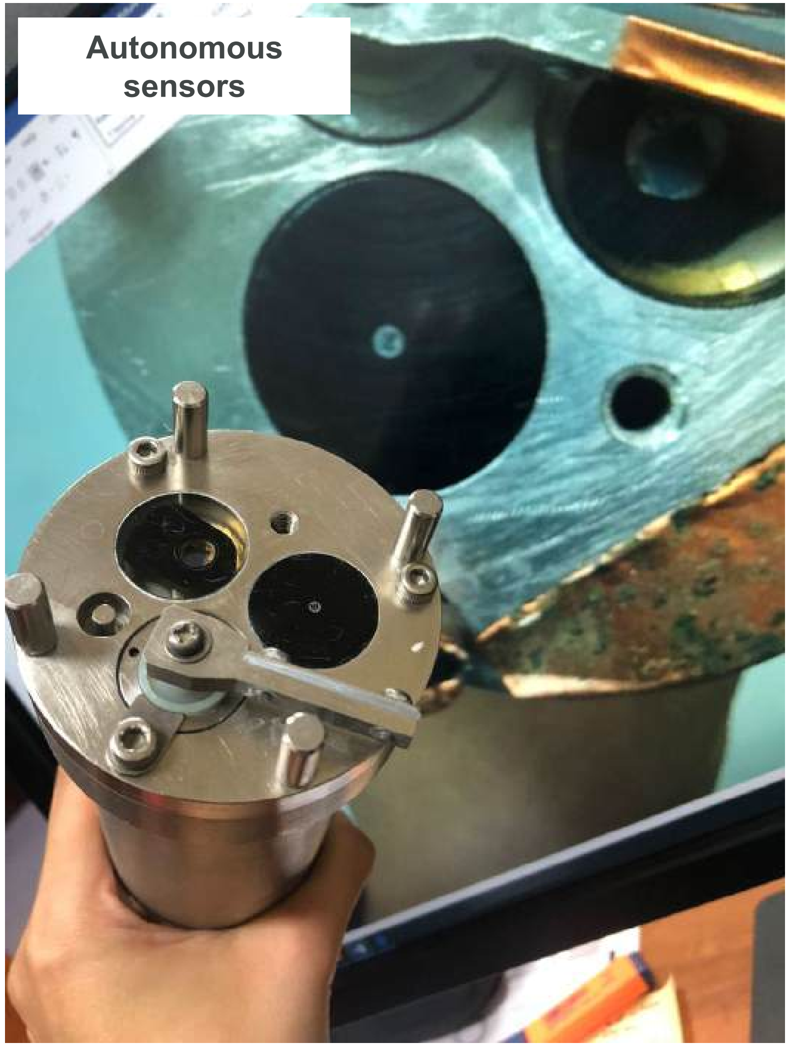
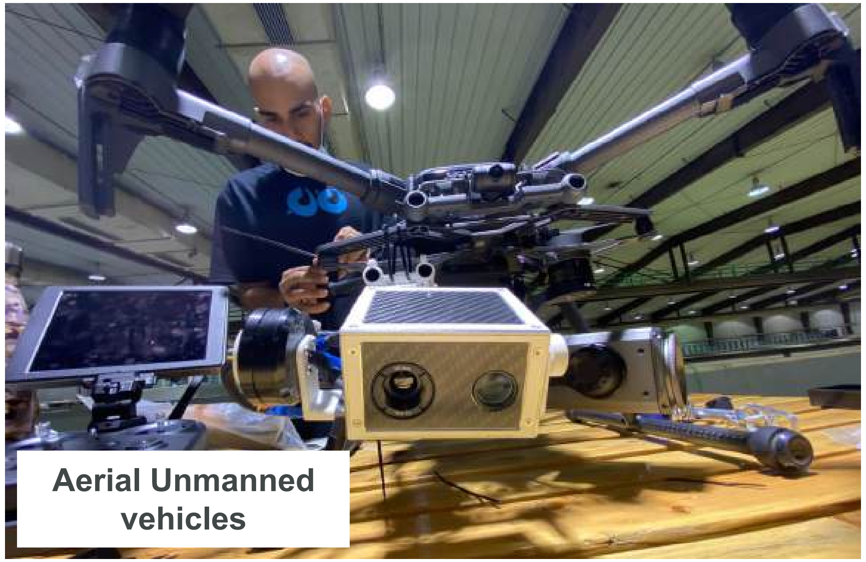
Surface unmanned vehicles

Real-time monitoring system

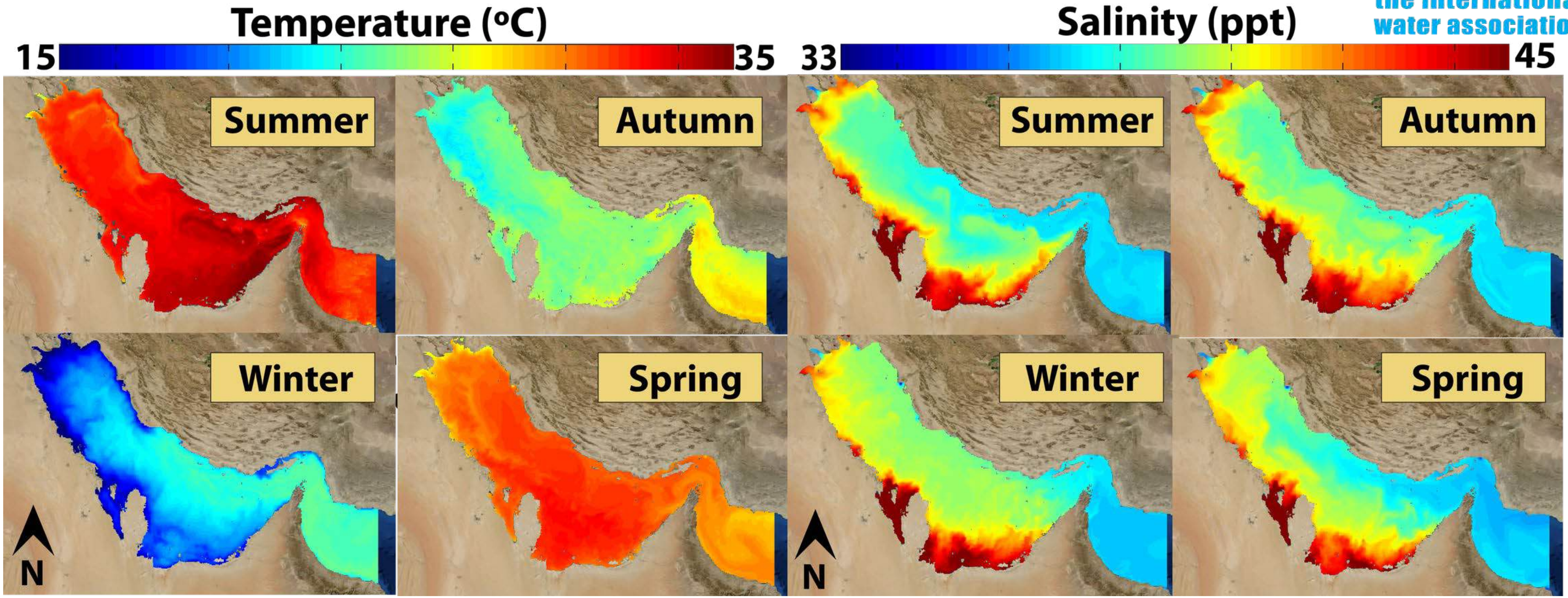


Autonomous sensors



Aerial Unmanned vehicles

SEASONAL MODELLING (TEMPERATURE AND SALINITY)



- The residence time of water in the Gulf is estimated to be approximately **3 to 5 years**
- The Gulf's shallow depth and semi-enclosed nature also contribute to a **slower turnover rate**, which affects the dispersal of pollutants and other contaminants, making it particularly vulnerable to environmental stress.

Alosairi, Y., Imberger, J., & Falconer, R. A. (2011). Mixing and flushing in the Persian Gulf (Arabian Gulf). *Journal of Geophysical Research: Oceans*, 116(C3).

TEMPERATURE AND SALINITY FIELDS IN NORTHWEST OF THE GULF-KUWAIT

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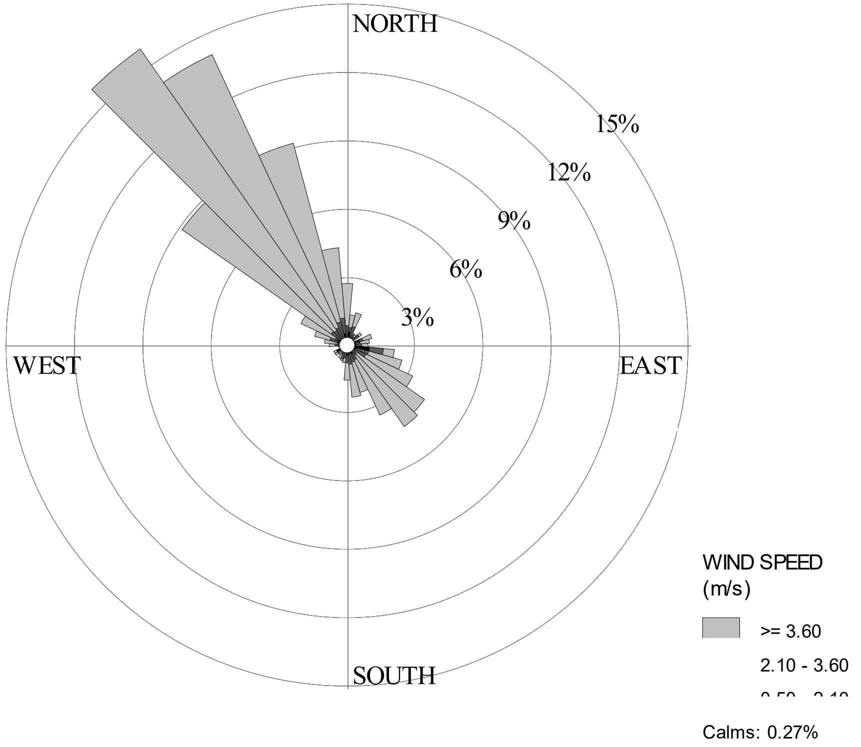
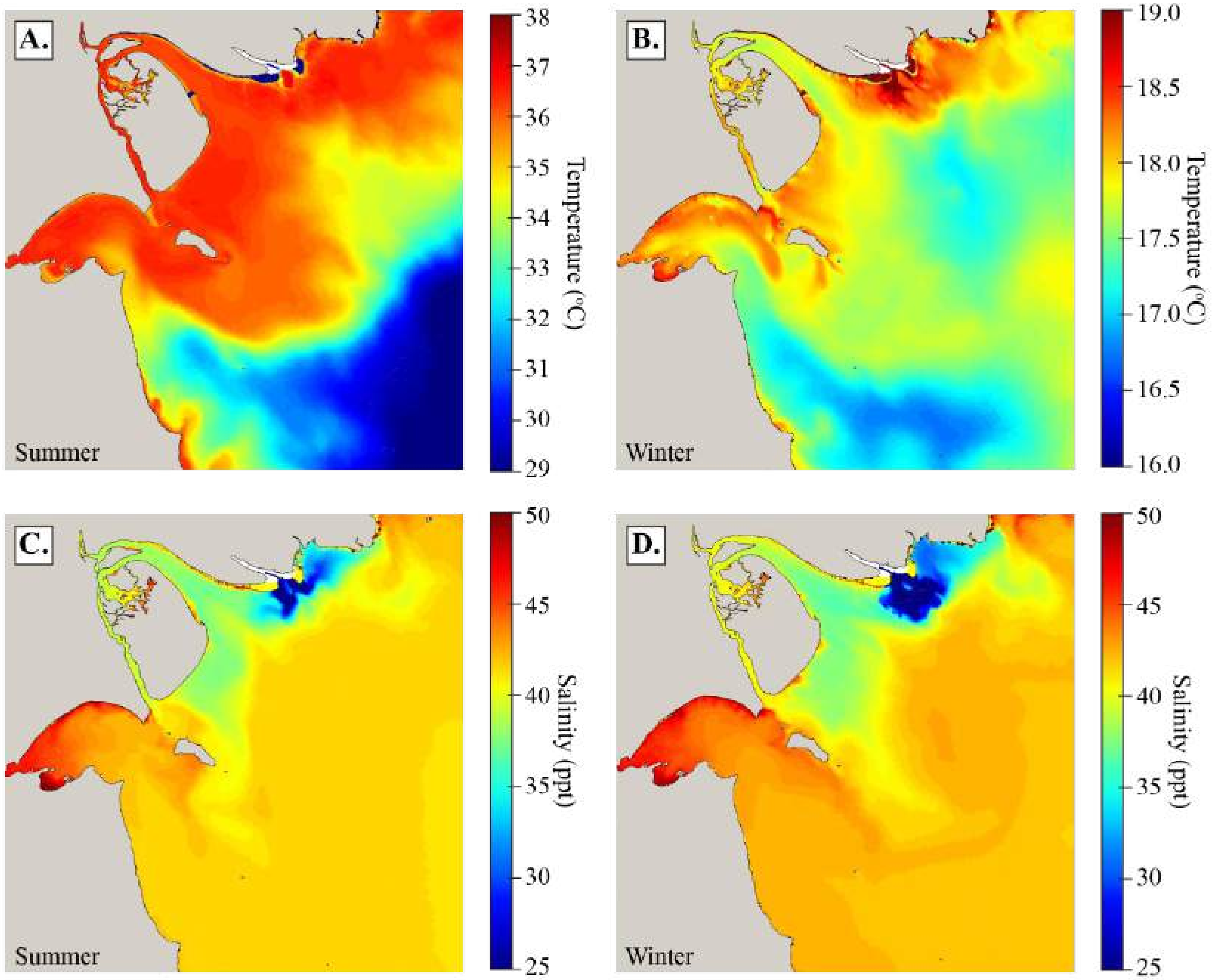


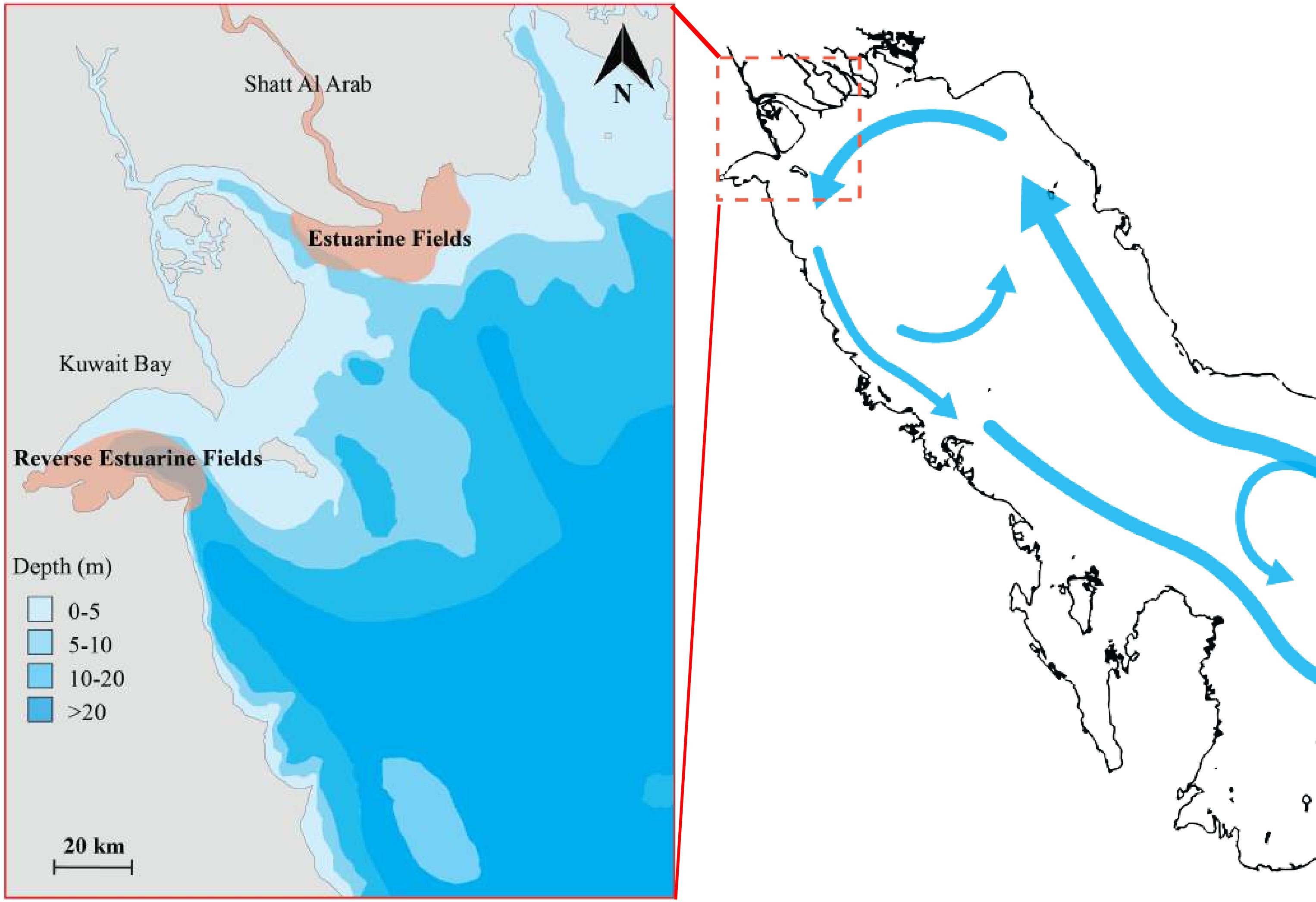


- Hypersaline and high-temperature waters in Kuwait Bay, impose horizontal density gradients gradients

Alosairi, Y., van Maren, D. S., Scheel, F., Smits, B. P., & Al-Khaldi, M. S. (2024). Aeolian desert dust as a primary estuarine sediment source: Fine sediment transport and dynamics in the northern Arabian/Persian gulf. *Estuarine, Coastal and Shelf Science*, *302*, 108771

KUWAIT SEASONAL CIRCULATIONS

- Localised **estuarine and reverse estuarine circulations** near Kuwait.
- Regionally, Kuwait's water is affected by the counter-clockwise circulations of the northern Gulf; these circulations vary seasonally (same direction but different strength).
- Dominant **along-shore** currents at the southern coast of Kuwait.
- Some recent findings indicate that the dominant circulations have been affected due to **short and long term factors**.



RELEVANCE OF CLIMATE CHANGE TO KUWAITS WATER

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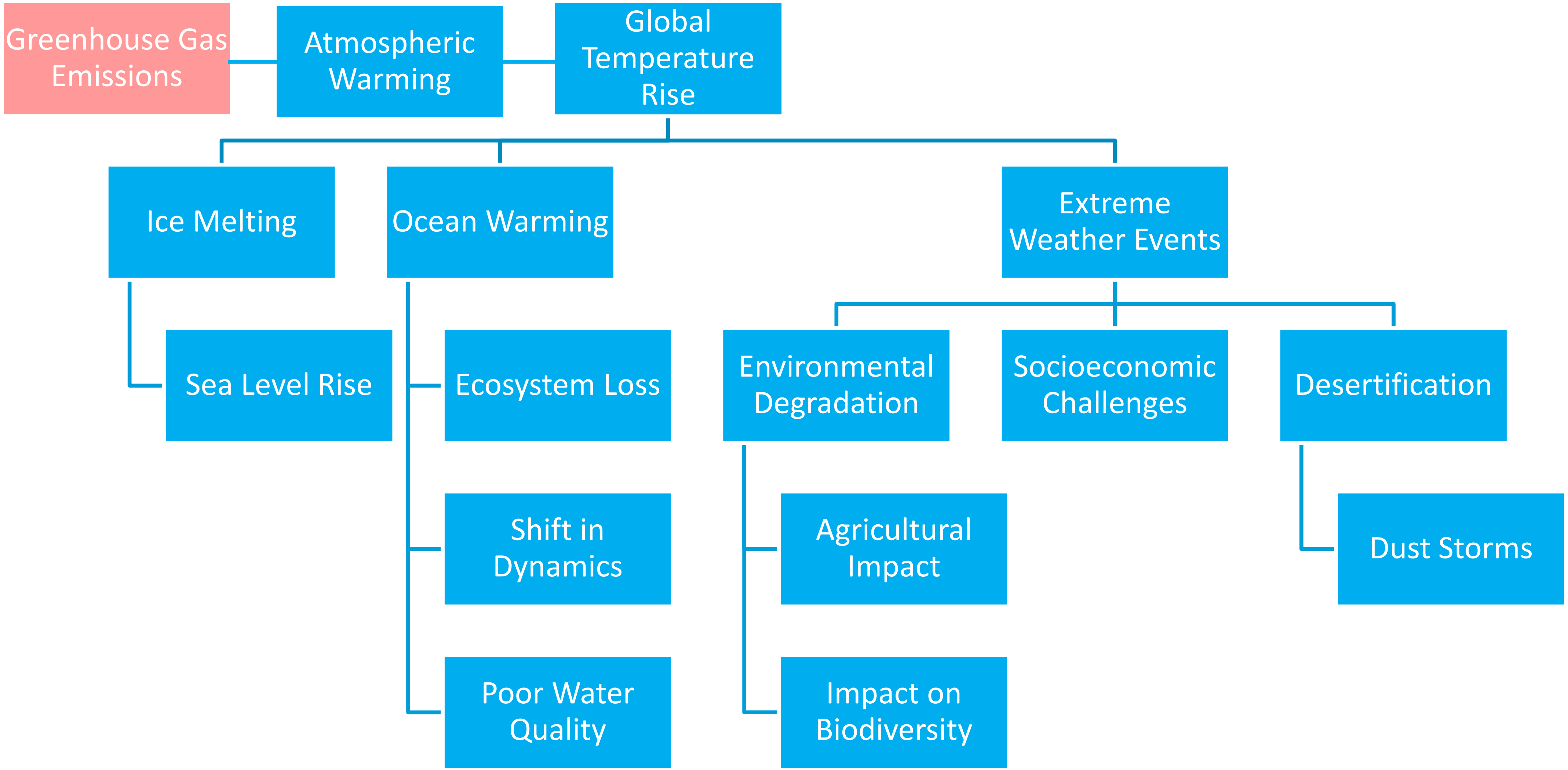

CHALLENGES ASSOCIATED WITH CLIMATE CHANGE

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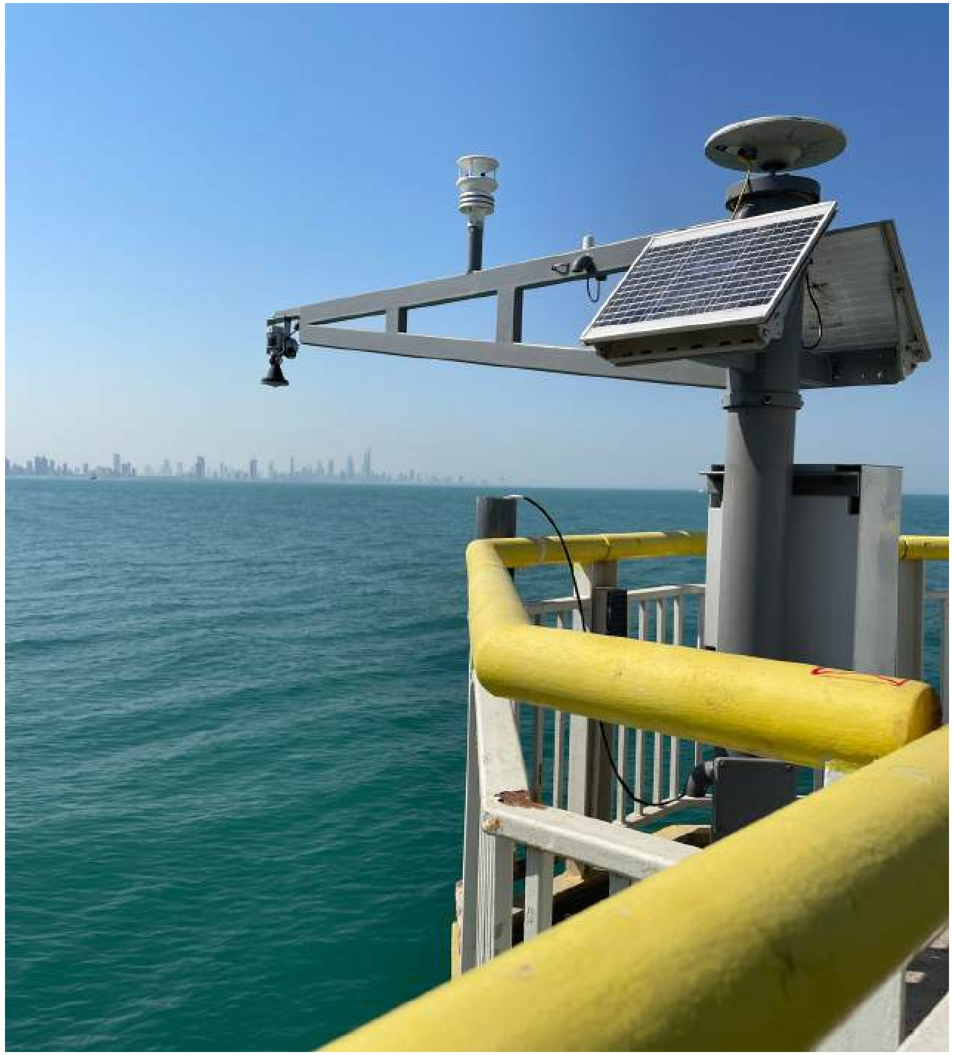
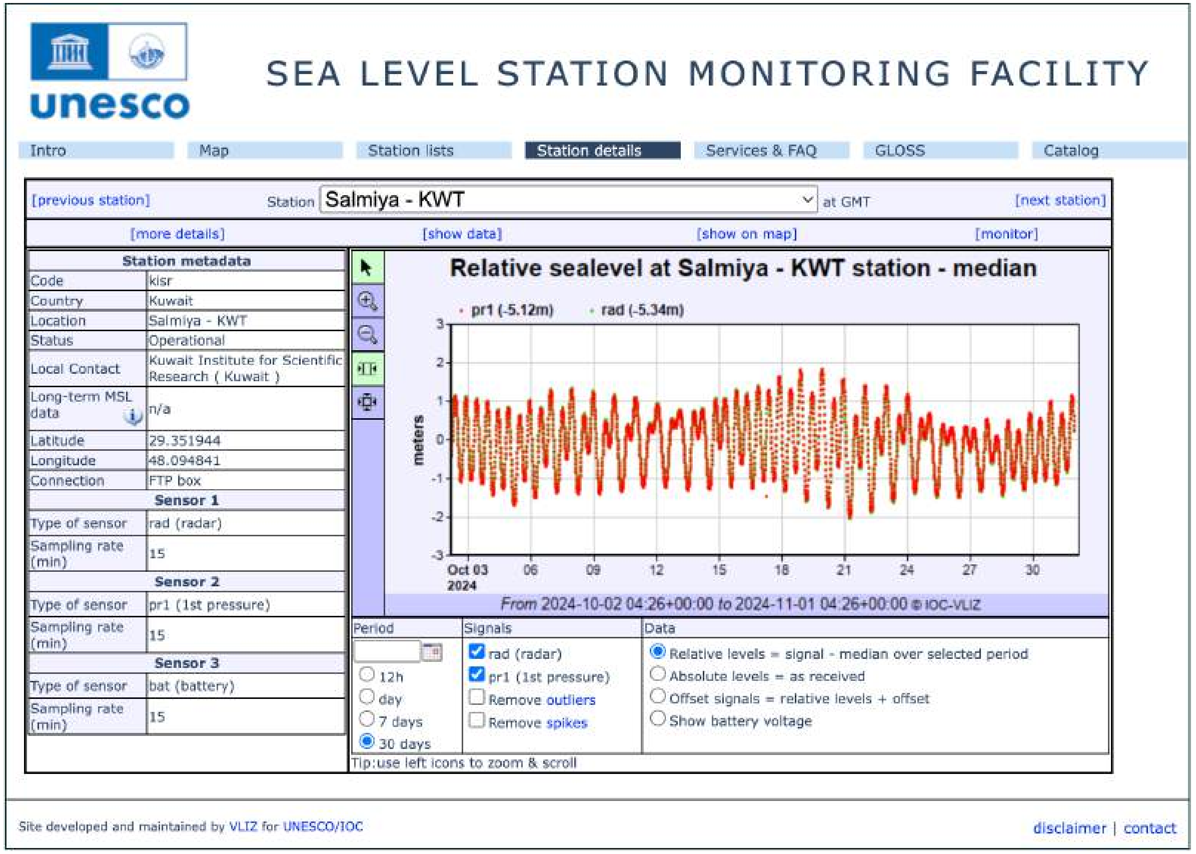
- **Complex Causality**: Climate change impacts are rarely caused by a single factor. They are often the result of complex interactions between climate change itself and other existing stressors like pollution, habitat loss, natural climate variability, and human activities.
- **Long Time Scales**: Many climate change impacts, such as sea-level rise or shifts in ecosystems, occur gradually over extended periods. This makes it difficult to establish a direct causal link between current emissions and observed changes, as opposed to natural fluctuations that occur over similar timescales.
- **Uncertainty in Projections**: While climate models are constantly improving, there is still uncertainty associated with future climate projections, particularly at regional and local scales. This uncertainty can make it difficult to predict the precise impacts of climate change on specific systems or locations.
- **Data Availability and Quality**: Historical data on climate and environmental variables is not always readily available, especially in some regions like the Gulf. Additionally, the quality and resolution of data can vary, making it difficult to draw definitive conclusions about long-term trends and attribute them to climate change.

KUWAIT SEA LEVEL RISE STATION





https://www.ioc-sealevelmonitoring.org/station.php?code=kisr

Since 2022

SEA LEVEL RISE STATION IN THE GULF

https://www.ioc-sealevelmonitoring.org/station.php?code=kisr

MAJOR WATERFRONT DEVELOPMENTS IN KUWAIT

MAIN ACTIVITIES IN KUWAIT COASTAL WATERS

- The project spans approximately **6,500** hectares
- The development includes **11,252** residential plots, with **3,000 plots** featuring direct sea access

Al-Khairan Pearl City Project

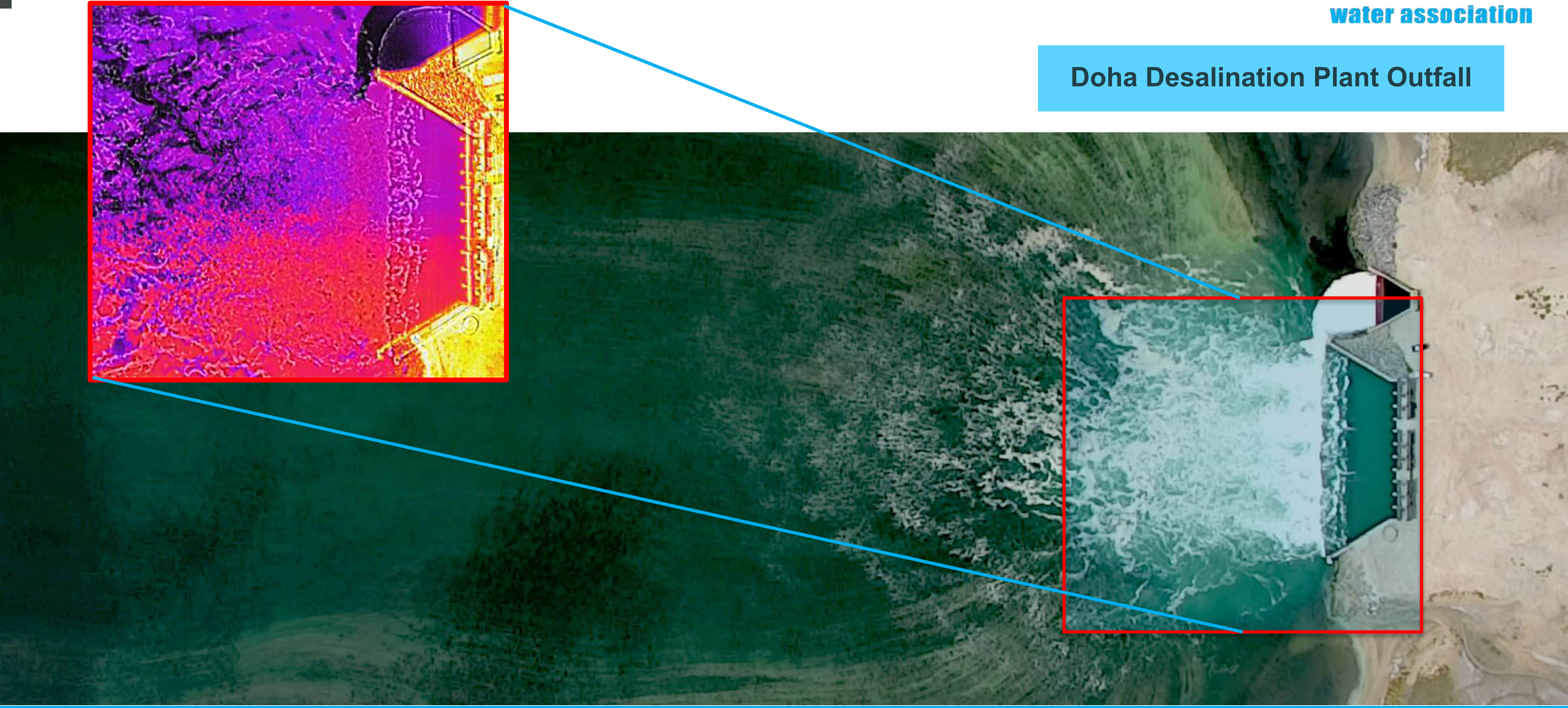
CONTINUED

- In 2021, Kuwait's net production of potable water was approximately **756 million m^3**.
- Desalination plants are the **primary source of fresh water**, providing around 92% of water for domestic and industrial needs.
- In the same year, Kuwait generated 71.22 (TWh) of electricity.

Al Zour Desalination & Power Plant

Statista. (2024). Desalinated water production in Kuwait 2012-2021. Retrieved from https://www.statista.com/statistics/1388517/kuwait-desalinated-water-production/
Fanack Water. (2020). Water Use in Kuwait. Retrieved from https://water.fanack.com/kuwait/water-use-in-kuwait/
Database.Earth. (2021). Electricity Generation of Kuwait 2000-2021. Retrieved from https://database.earth/energy/electricity-generation/kuwait

THERMAL/SALINE PLUMES



CONTINUED

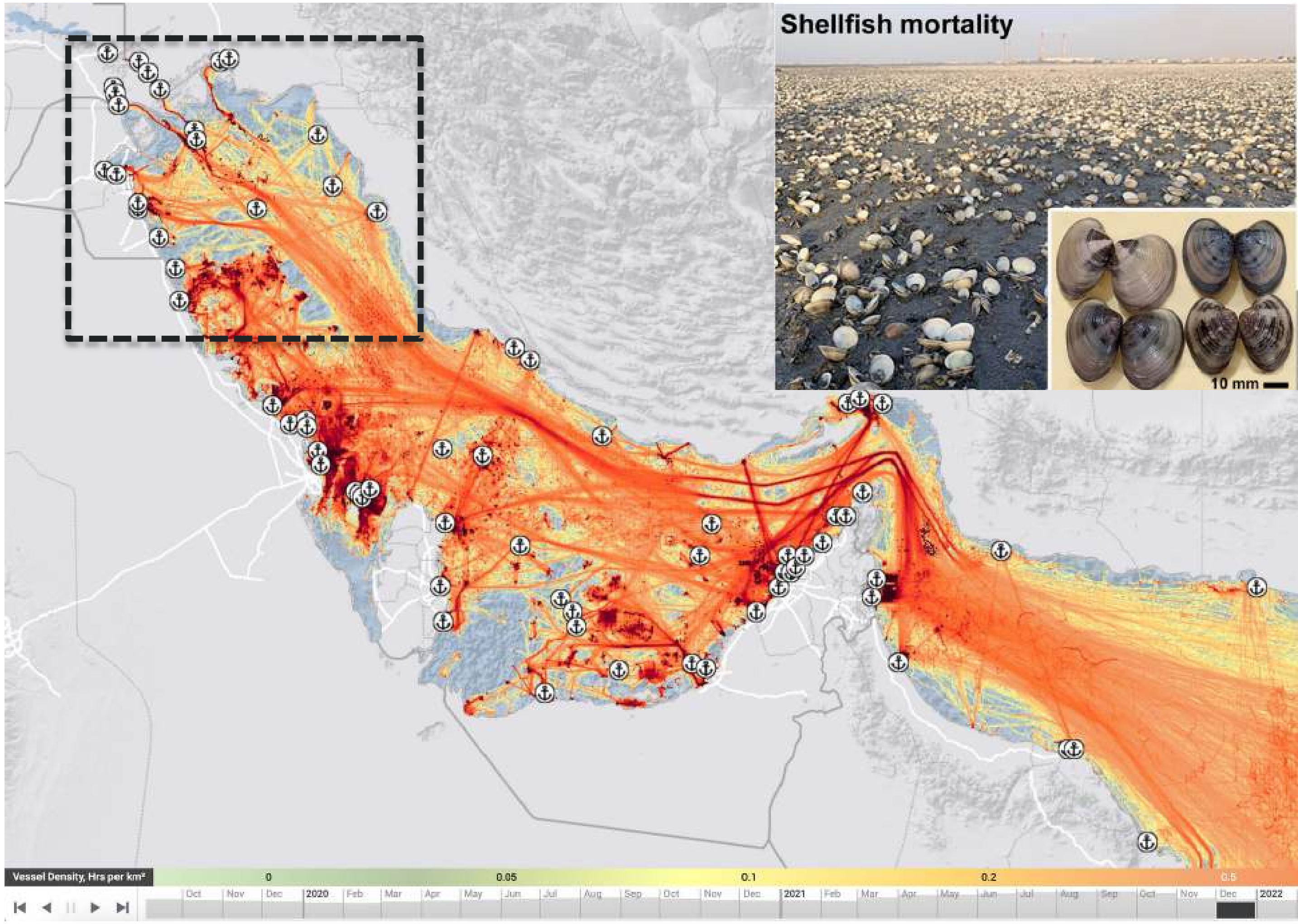
- The combined length of the causeway is approximately **48.5 km**, making it one of the longest sea bridges globally.
- Two artificial islands, each spanning **30 hectares**, were constructed to support the bridge and provide facilities for maintenance and emergency services.
- The main link includes **1,190 piers**.

Jaber Al Ahmad Causeway


Sediment Transport Issues
Kuwait Bay
Tidal currents

VESSEL DENSITY (2019-2021)

- Significant vessel density is concentrated around major ports in Kuwait, Iraq, and Iran, indicating heavy maritime **traffic related to trade and oil transport**.
- **High-density shipping** lanes leading in and out of the northern Gulf, connecting it to the Strait of Hormuz.
- The high vessel density in specific areas could lead to environmental stress, including potential **oil spills, air pollution, and impacts on marine ecosystems** due to frequent vessel movement.
- **Invasive species** introduced through ballast water discharge have been identified as a contributing factor to oyster mortality in Kuwait



https://globalmaritimetraffic.org/

ALGAL BLOOMS/FISHKILL EVENTS

ALGAL BLOOM EVENTS IN KUWAIT'S MARINE WATER

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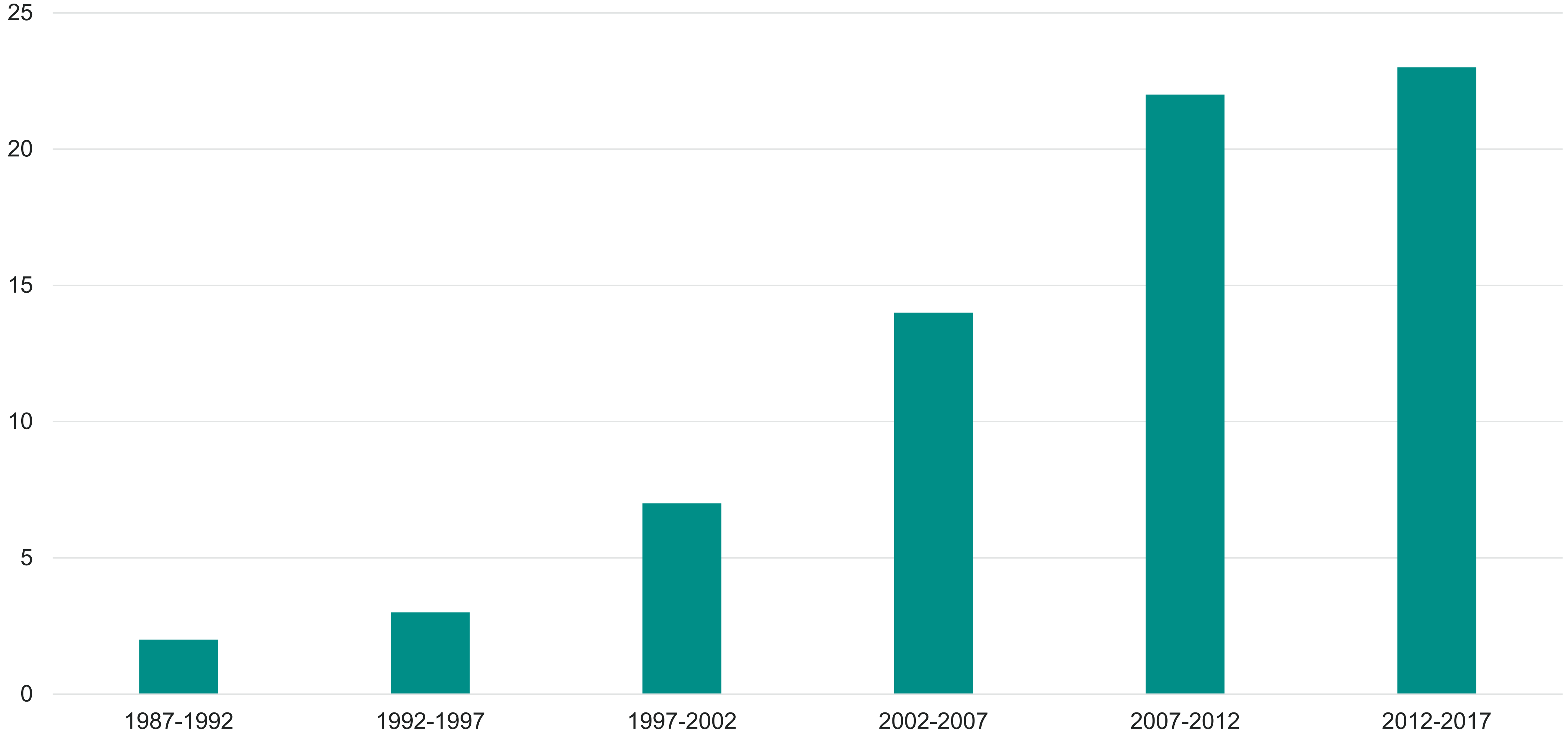

Al-Yamani, F., Saburova, M., 2019. Harmful algal blooms in Kuwait's waters. In: Marine Phytoplankton of Kuwait's Waters. Vol. I. Cyanobacteria, Dinoflagellates, Flagellates, pp. 412-431. Kuwait Institute for Scientific Research, Kuwait, ISBN 978-99966-37-20-9.

KEY ENVIRONMENTAL ISSUES ASSOCIATED WITH CLIMATE CHANGE

OBSERVED TRENDS: EXTREME HEAT, PRECIPITATION, AND DUST STORM

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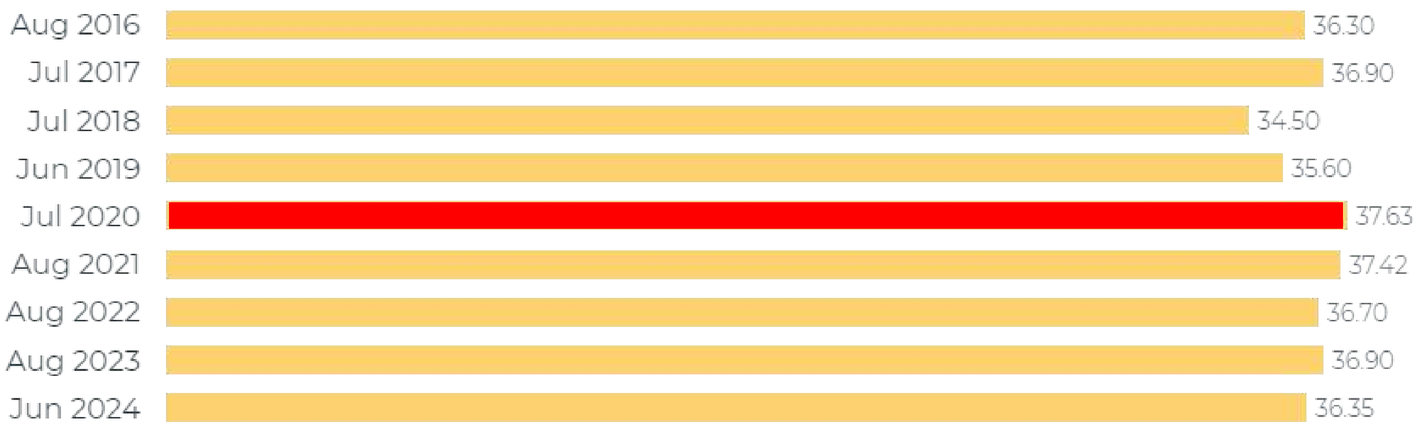
Extreme Heat waves

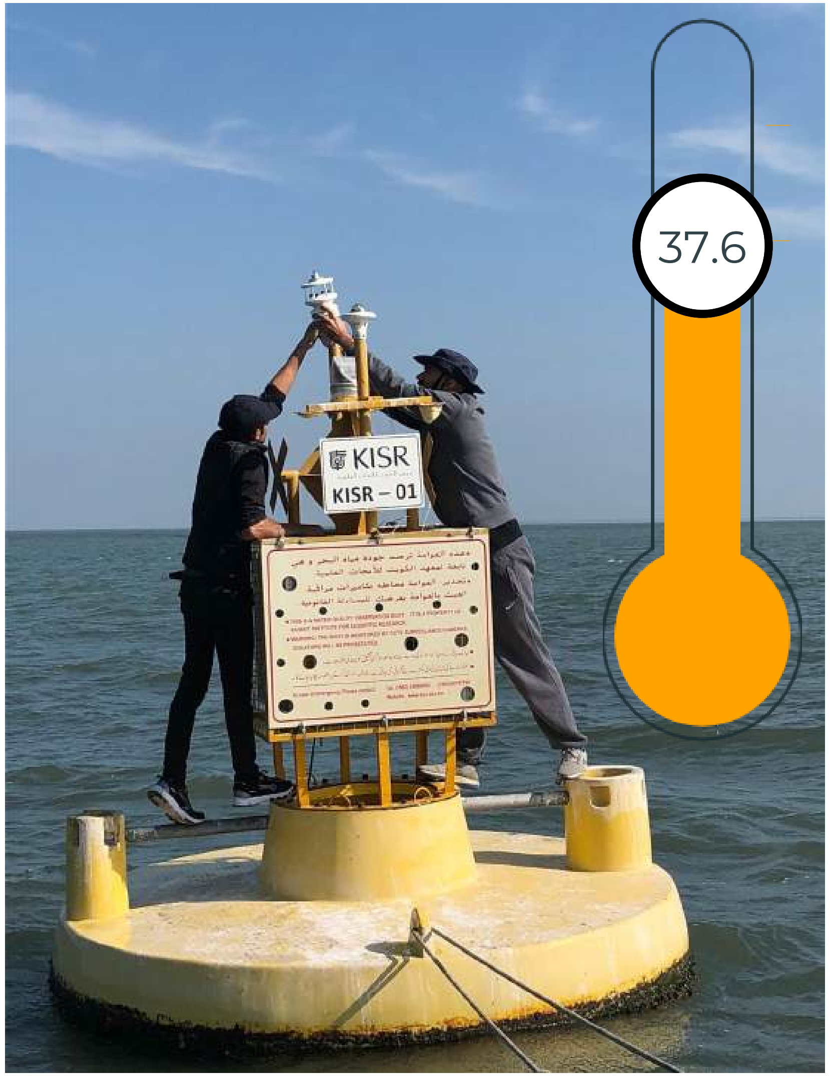
Precipitation

Desert Dust

SEA SURFACE TEMPERATURE

- **Record Temperature**: Sea surface temperature (SST) in Kuwait Bay reached a record **37.6°C on July 30, 2020**.
- **Contributing Factors**: This extreme temperature coincided with a prolonged heatwave, low wind speeds, high humidity, and neap tide conditions.
- **Ecological Impact:** The event led to significant fish kills and coral bleaching, indicating heightened ecological stress due to elevated temperatures in the region





Alosairi, Y., Alsulaiman, N., Rashed, A., & Al-Houti, D. (2020). World record extreme sea surface temperatures in the northwestern Arabian/Persian Gulf verified by in situ measurements. *Marine Pollution Bulletin, 161*, 111766.

IMPLICATIONS OF INCREASED SEA SURFACE TEMPERATURE

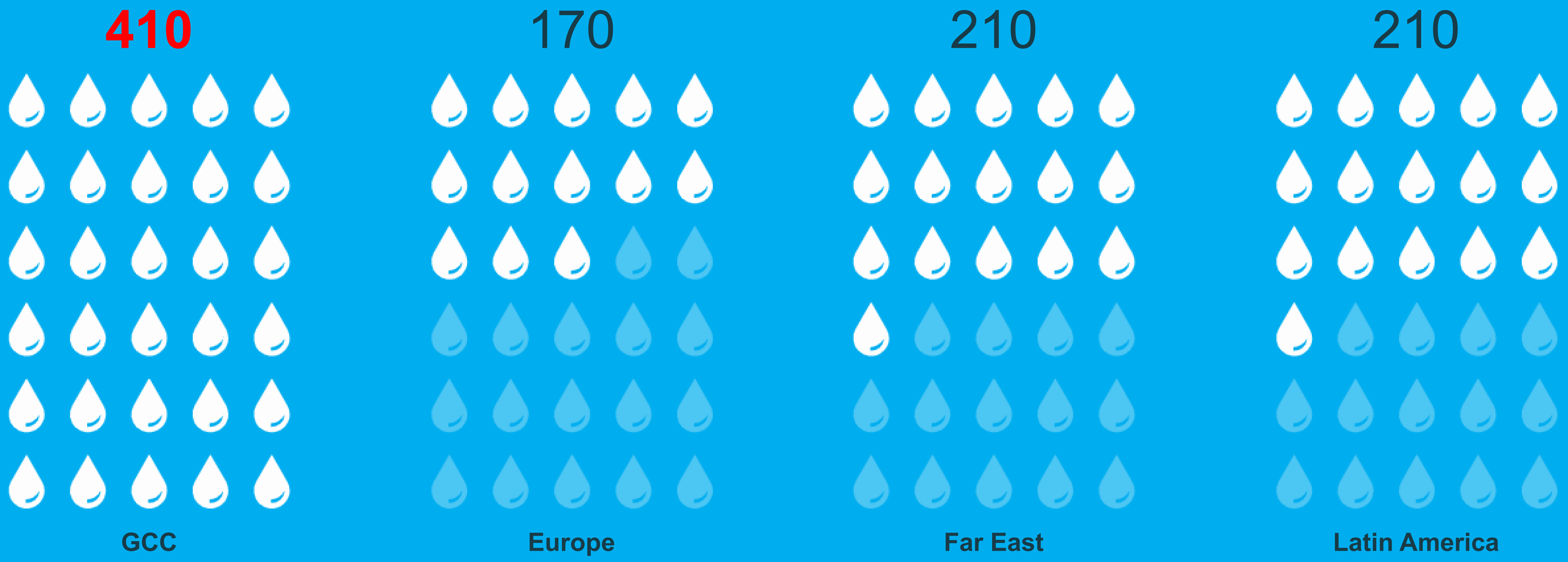
- According to the Intergovernmental Panel on Climate Change (IPCC), if greenhouse gas emissions remain constant, the global average temperature is projected to increase by about **0.26°C per decade**, potentially leading to a total increase **of 2.6°C by 2100** (IPCC, 2021).
- After validating the model for the summer seasons using field measurements the model was used to provide 2100 sea surface currents projections.
- An **increase of 2-4%** in the sea surface current has been computed for the dominant circulations, and increased turbulent fields (Alosairi et al., 2025 in preparation).
- This would lead to shift in the transport regime (suspended material, nutrients, trace metals … etc.)

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

WATER CONSUMPTION

Extreme hot climates often leads to high demand **(requires high production)**

Liters per capita per day (average)



World Bank Water Data Reports, European Environment Agency (EEA)National Statistics and Water Agencies in respective countries Gulf Cooperation Council Secretariat ReportsAsian Development Bank (ADB) Publications

PRESSURE ON DESALINATION/POWER PLANT INTAKE

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ISSUES

- **Increased Energy Consumption:** Warmer water can reduce the efficiency of cooling systems in the plant
- **Reduced Membrane Efficiency:** In RO systems, higher temperatures can lead to reduced membrane lifespan and efficiency. The solubility of salts increases with temperature
- **Higher Scaling and Fouling Risks:** Warm water can promote scaling and biofouling, which can obstruct desalination processes

SOLUTIONS

- **Cooling Systems:** Using heat exchangers or cooling towers
- **Anti-Fouling Treatments:** Pre-treatment using chemical dosing or filtration
- **Membrane Adaptation:** Using membranes that are more resilient to higher temperatures
- **Increase intake length/depth: To allow cooler water intake**

EFFICIENCY OF ELECTRICITY/DESALINATION PLANT: INTAKE EXTENSION

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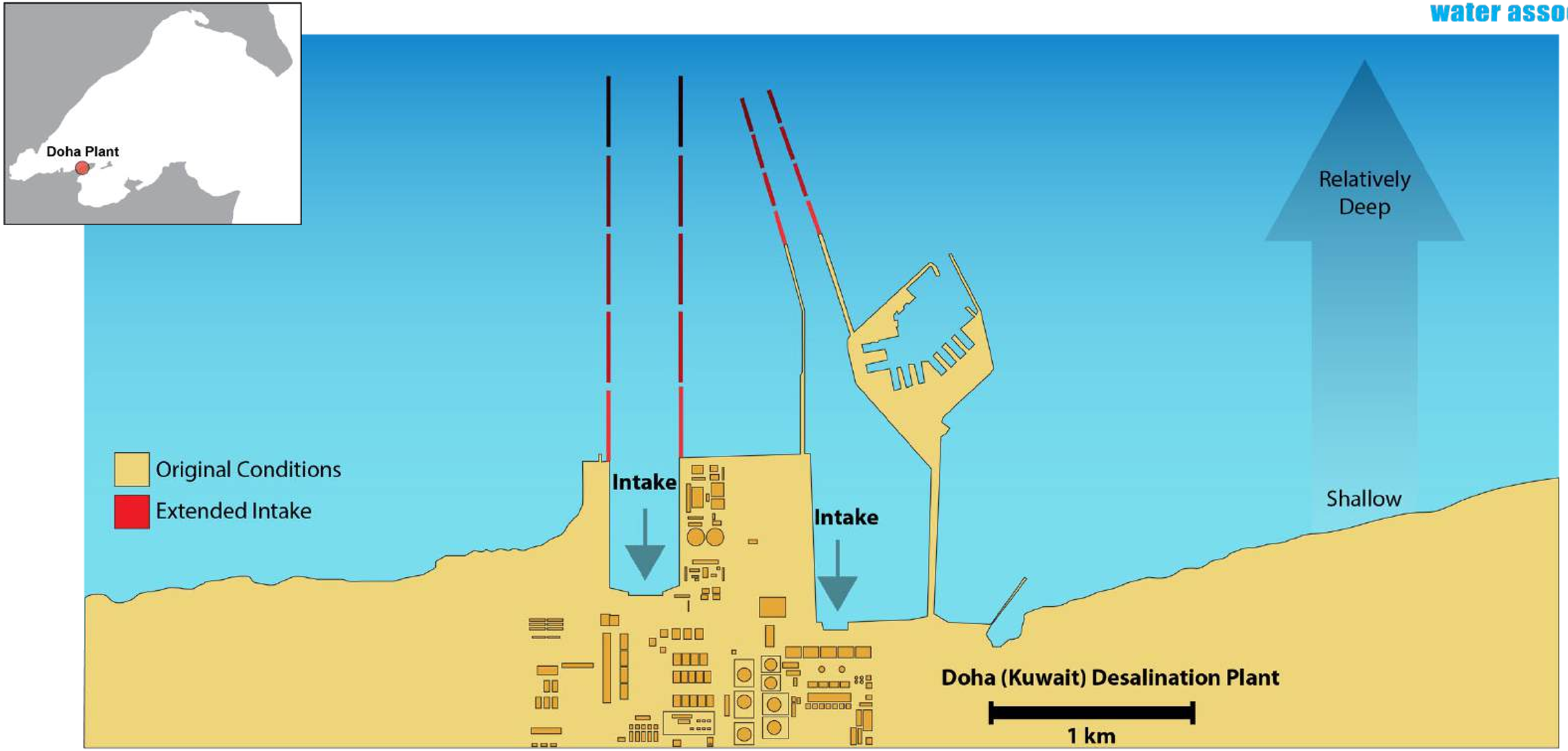
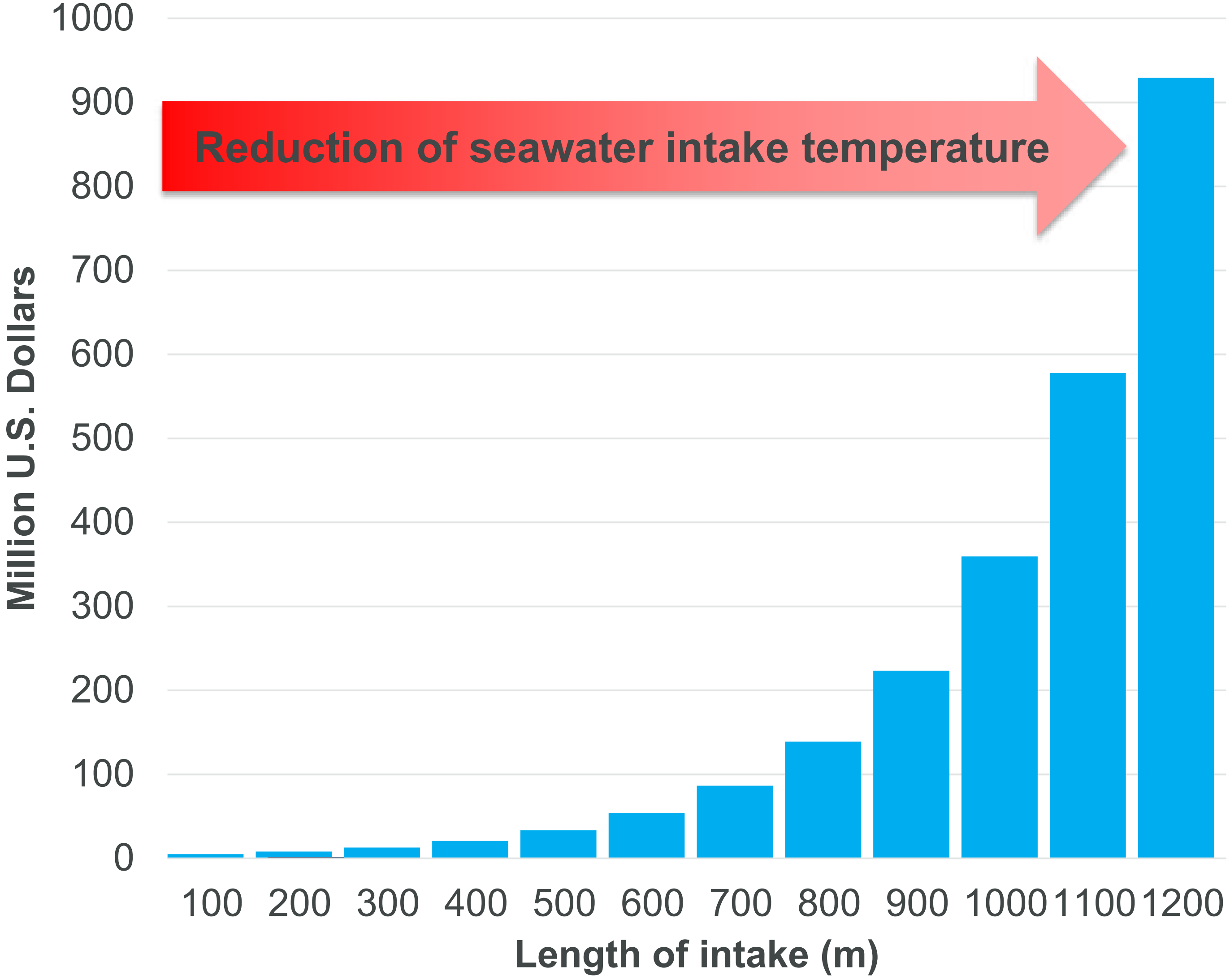


INTAKE LENGTH VS COST



- **Numerical Modeling**: Assessed seawater depth and temperature impacts on intake water quality for the Doha desalination plant.
- **Exponential Cost Increase:** Construction expenses rise exponentially with greater intake depths due to increased engineering complexities
- **Temperature Impact on Efficiency:** Each 1°C increase in intake water temperature leads to higher operational costs and reduced plant efficiency.
- **Optimal Intake Design:** Balancing intake depth and temperature is crucial to minimize costs and maximize desalination efficiency.
- **Strategic Planning:** Informed decisions on intake parameters are essential for the plant's economic and operational success.

REDUCTION IN DISSOLVE OXYGEN: HYPOXIA IN KUWAIT BAY

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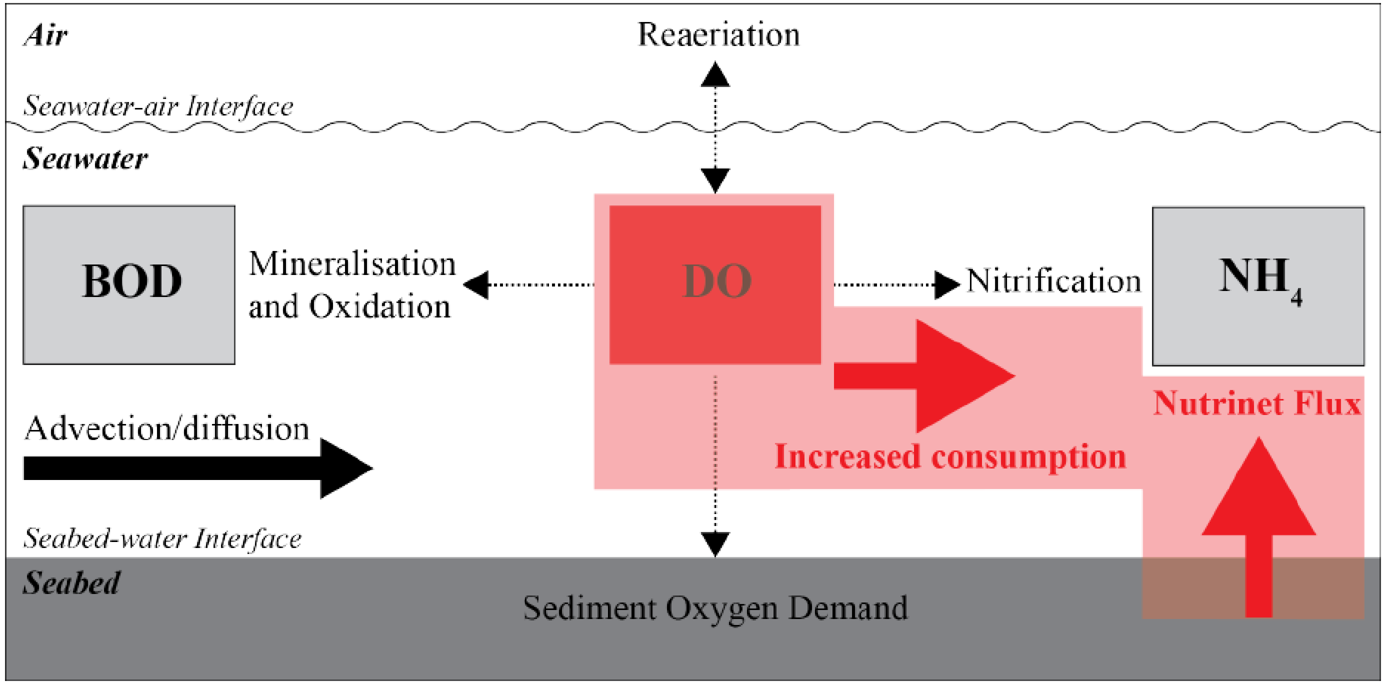
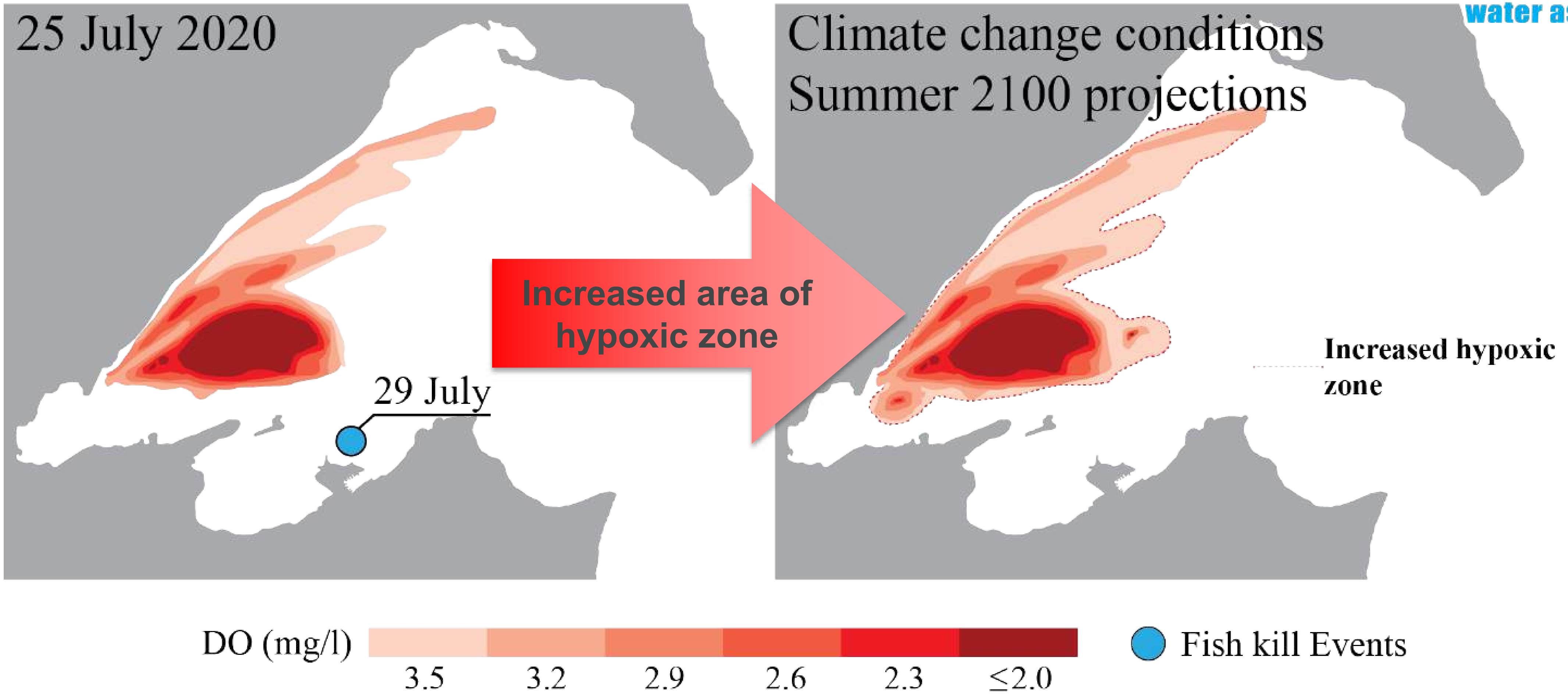
- **Fish kill** events correlate with hypoxic conditions, with critical DO thresholds primarily reached near the bed during calm, low-mixing periods.
- Extreme water temperature promotes high DO demands and bed sediment interactions.



- Key processes associated with DO consumption in Kuwait Bay are **sediment nutrient fluxes** from muddy areas and ecological consumption through **respiration**.

Alosairi, Y., & Alsulaiman, N. (2019). Hydro-environmental processes governing the formation of hypoxic parcels in an inverse estuarine water body: Model validation and discussion. *Marine Pollution Bulletin, 144*, 92-104.

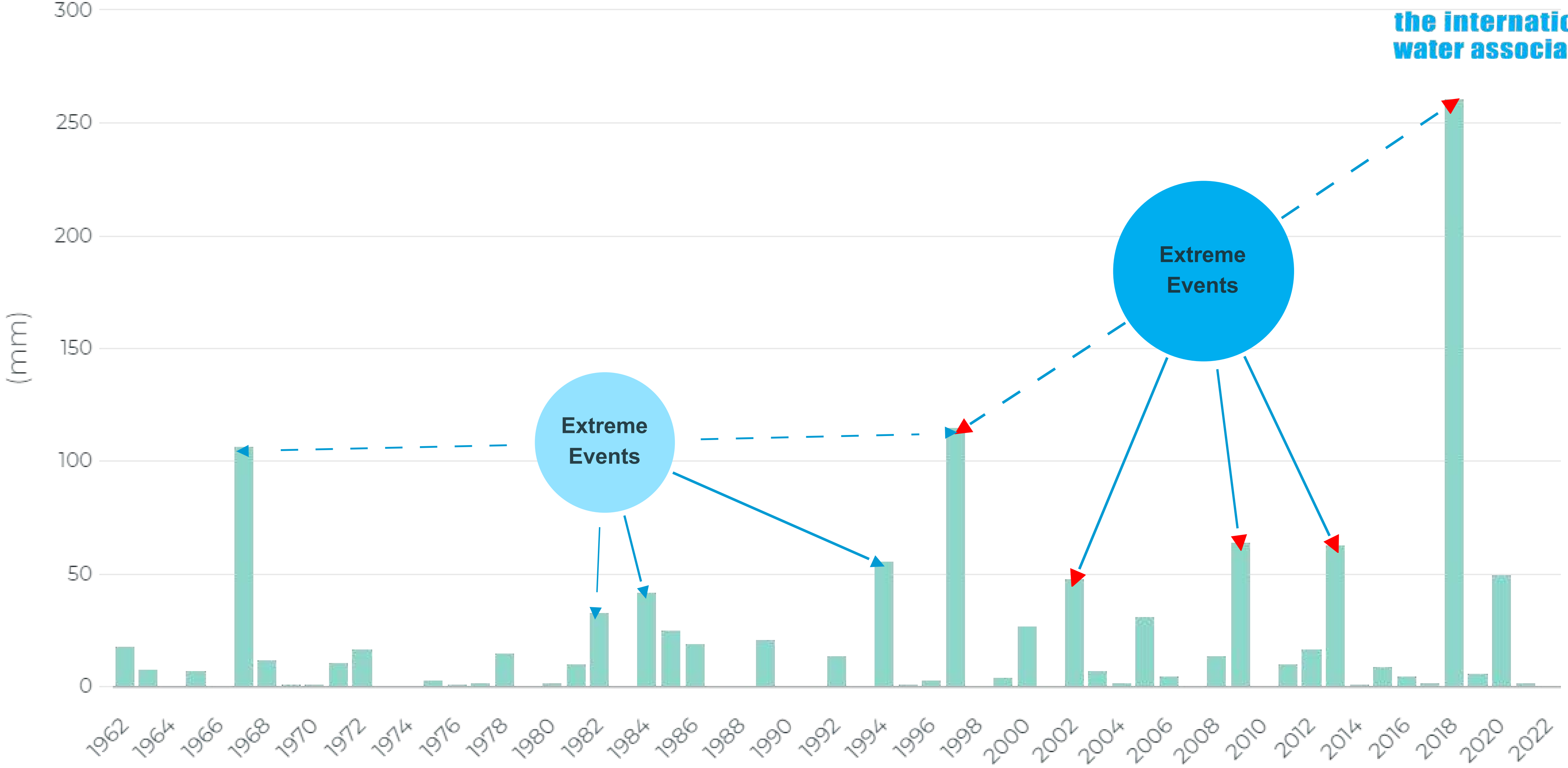
HYPOXIA IN KUWAIT BAY



Increased hypoxic area from **9.7 km^2** to **13.2 km^2** (i.e. increased by **≈ 36% in 2100)** (Alosairi et al., 2025 in preparation)

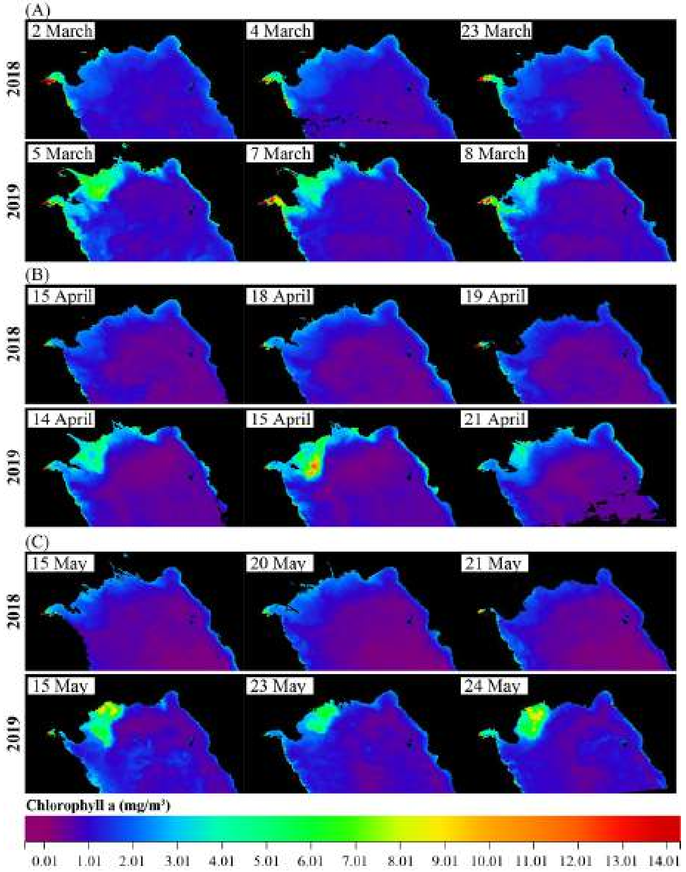
Alosairi, Y., & Alsulaiman, N. (2019). Hydro-environmental processes governing the formation of hypoxic parcels in an inverse estuarine water body: Model validation and discussion. *Marine Pollution Bulletin, 144*, 92-104.

ANNUAL RAIN LEVELS IN KUWAIT



Hassan, A., Albanay, J. A., Al-Ali, J., Fayad, M., Atalla, M. A., Abdelkarim, A., & Badawy, H. D. (2024). Assessment of flash flood risks in the desert cities: A case study on Sabah Al-Ahmad City, Kuwait. *Journal of Water and Climate Change*. https://doi.org/10.2166/wcc.2024.191

SHATT AL ARAB RUNOFFS



- Numerical models show the extent of the **estuarine fields** (effects of the freshwater discharges from Shatt Al Arab)
- **Extreme shifts** in salinity levels impact marine biodiversity, with some species **affected in the short term** and others over the long term

Al-Yamani, F., Bishop, J. M., Al-Rifaie, K., & Ismail, W. (2007). The effects of river diversion, Mesopotamian marsh drainage and restoration, and river damming on the marine environment of the northwestern Arabian Gulf. *Aquatic Ecosystem Health & Management, 10*(3), 277–289. https://doi.org/10.1080/14634980701512339

IMPACT OF FLASHFLOODS AND EXTREME RUNOFFS

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Vast quantities of nutrients/blooms

- **Shift** in the composition and distribution of macroalgal assemblages, which play a crucial role in the overall ecological productivity of the system.
- **Altering** the balance between different primary producers.

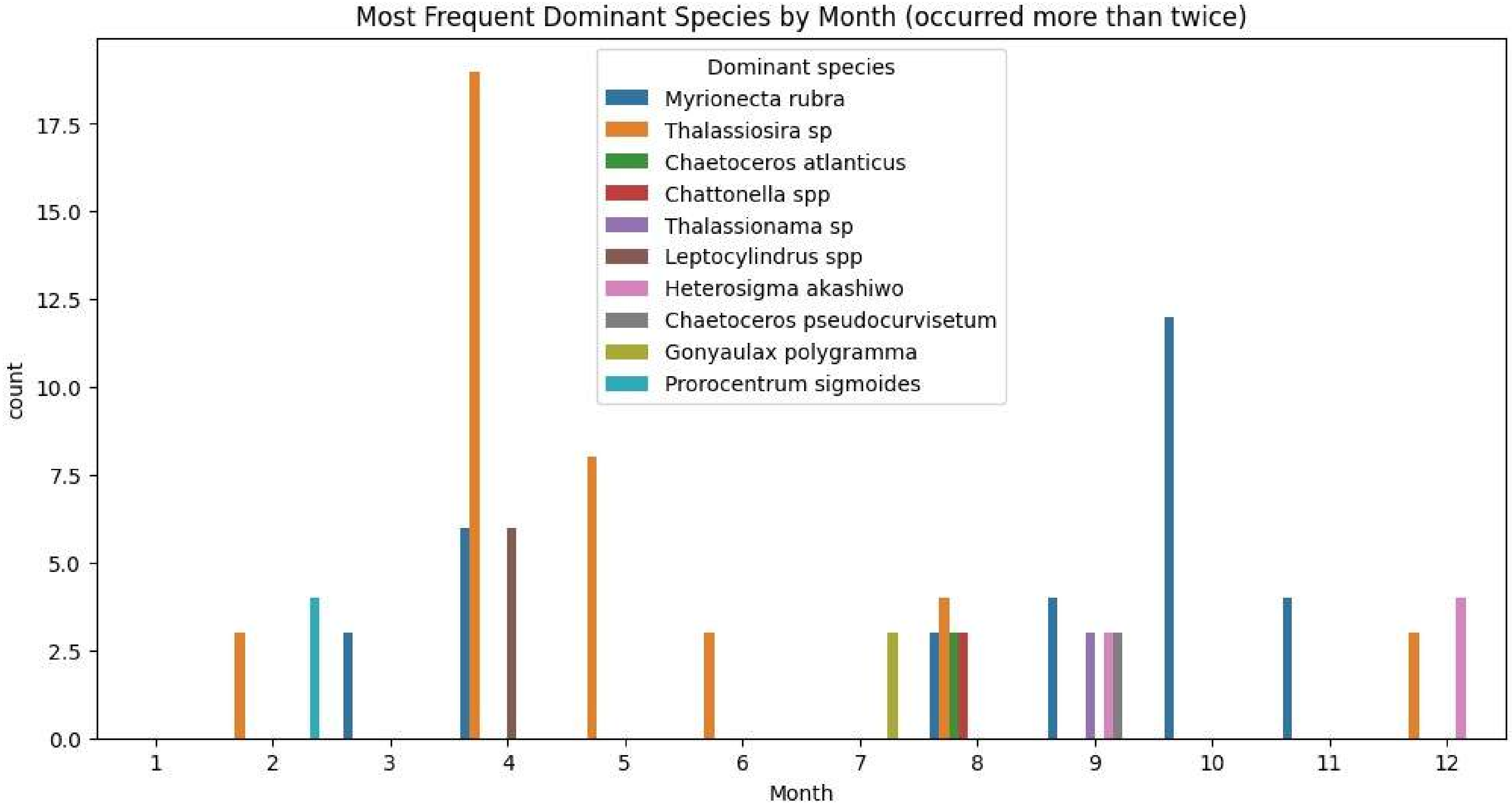
Extended estuarine circulation

- **Alter** the sediment dynamics and horizontal transport processes within shallow estuaries.
- These events can lead to **increased erosion, sediment resuspension, and the redistribution** of particulate matter throughout the system.
- The influx of sediment and the associated changes in turbidity can impact **light availability**, **primary productivity, and the suitability of habitats** for various organisms.

Shift in bed sediment

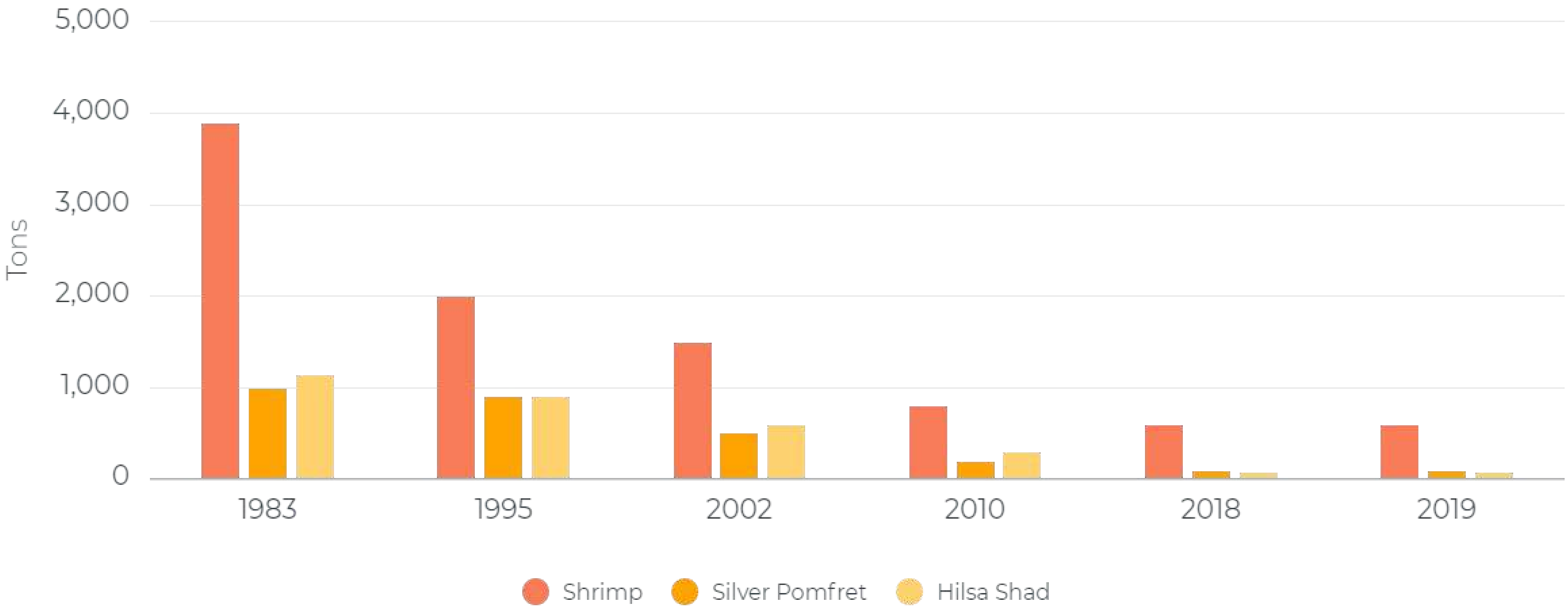
- The distribution of the bed sediment is quite significant for the overall health of the system, as it can **impact the availability of nutrients**, the suitability of habitats for various organisms, and the overall functioning of the food web.

ALGAL BLOOM VARIATIONS



Karam, Q., Al-Osairi, Y., Al-Anzi, A., Al-Saleh, A., Al-Senafi, A., Al-Saraf, M., Dashti, A., Ali, M., Al-Awadhi, M., Al-Sarawi, A., A-Bolouchi, F., Al-Oqab, W., & Al-Mutairi, M. (2023). *Development of early warning system for harmful algal blooms, red tide, and fish kills incidents in Kuwait territorial waters (EC140C)*. Crisis Decision Support Program, Environment and Life Sciences Research Center, Kuwait Institute for Scientific Research. Restricted.

FISH STOCK IN KUWAIT



CSB (2021); Alqattan & Gray (2021), PAAFR (2017); Al-Baz et al. (2018), KISR Annual Report (2010), Kuwaiti Environmental Report (2018), CSB (2021); Alqattan & Gray (2021), CSB (2021); Edmonds et al. (2021)

IMPACT OF DUST/DUST STORM

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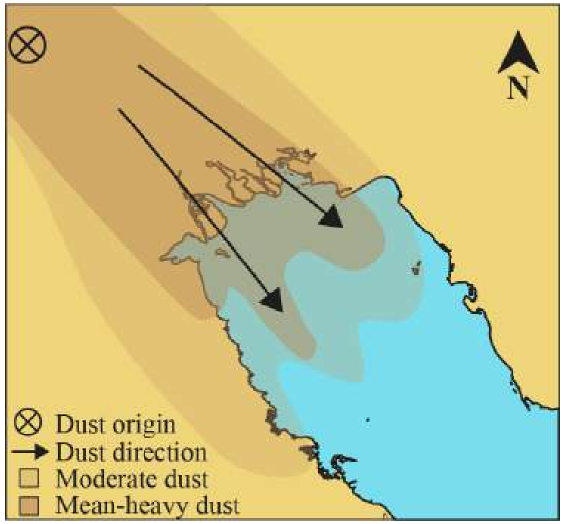
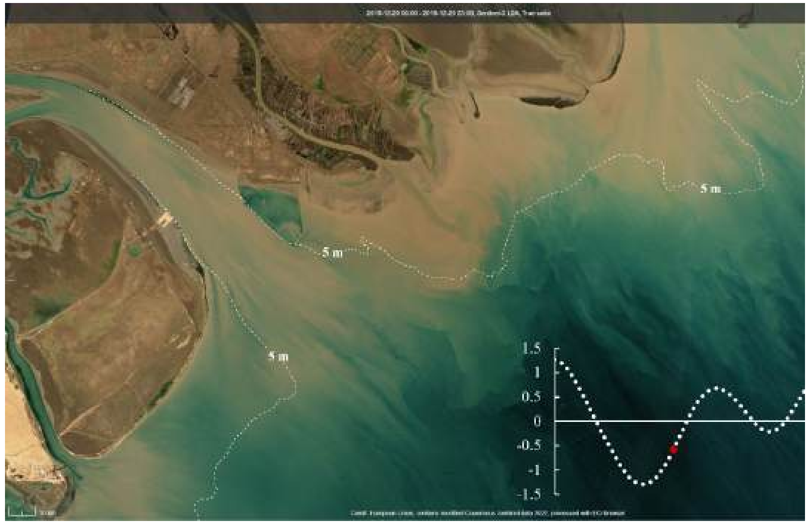




Sever Dust Storm (Iraq-Syria)

- The Gulf is surrounded by **arid regions** with substantial loose sediment vulnerable to wind erosion.
- **Dust storms** in the region, often driven by strong northwesterly "Shamal" winds, transport significant quantities of fine sediment into the Gulf.
- The impact of **aeolian sedimentation extends to the marine** ecosystem. The dust can carry contaminants and potentially toxic elements, posing a risk to marine organisms and their habitats.
- Due to **shift in rain patterns**, and **extended desertification**, new dust sources are emerging.

Alosairi, Y., van Maren, D. S., Scheel, F., Smits, B. P., & Al-Khaldi, M. S. (2024). Aeolian desert dust as a primary estuarine sediment source: Fine sediment transport and dynamics in the northern Arabian/Persian gulf. *Estuarine, Coastal and Shelf Science*, *302*, 108771

SEDIMENT TRANSPORT MODELLING

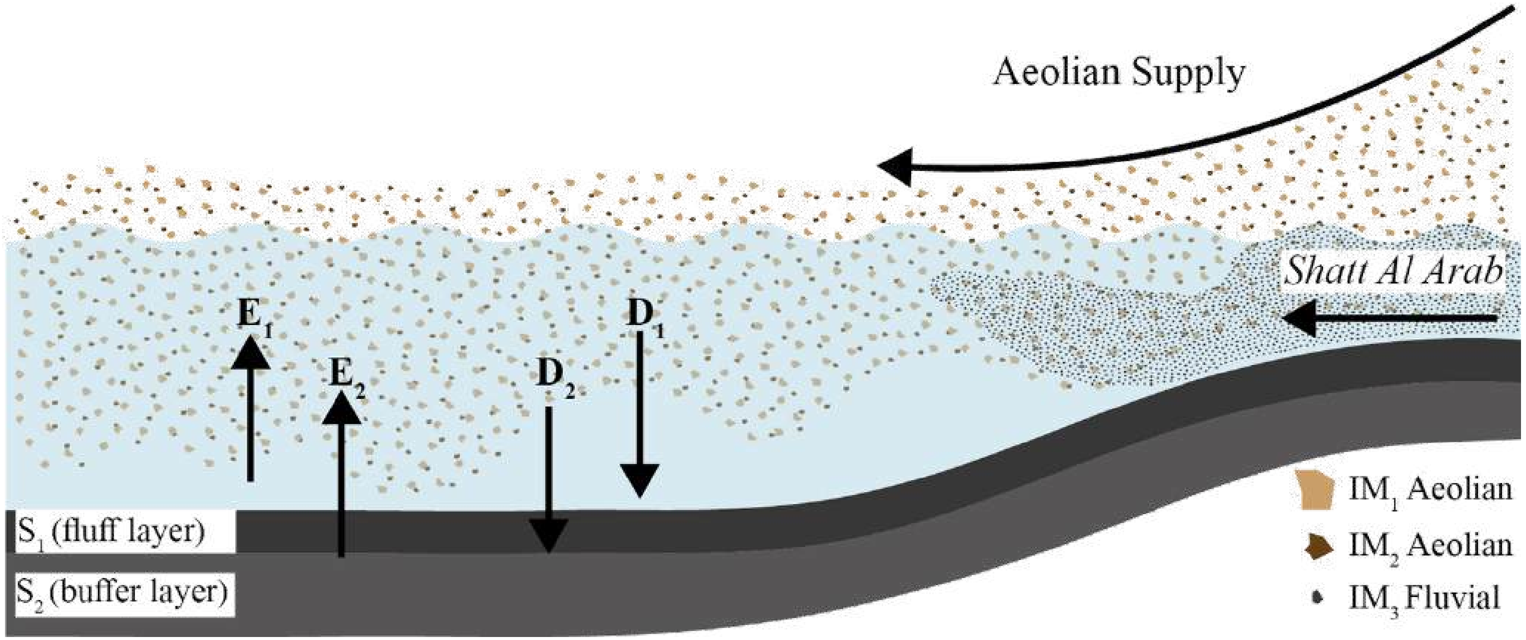
Aeolian Supply

Referring to Foda et al., (1985), it is reasonable to assume that the **0.8 mm/yr sedimentation rate** of the first **200 km** occurred over the entire width of the Northern Gulf. This assumption results in **32 million m^3** annual deposition of aeolian sediments. With a typical density of **1,600 kg/m^3**, this is equivalent to **51 million ton/yr.**

This rate is substantially higher, by several orders of magnitude than the average rate of dust deposition in the world's estuaries.

Fluvial Supply

One to several million ton/yr is the best estimate for the present-day annual discharge of fine sediments to the Northern Gulf via Shatt Al Arab



Alosairi, Y., van Maren, D. S., Scheel, F., Smits, B. P., & Al-Khaldi, M. S. (2024). Aeolian desert dust as a primary estuarine sediment source: Fine sediment transport and dynamics in the northern Arabian/Persian gulf. *Estuarine, Coastal and Shelf Science*, *302*, 108771

VALIDATION OF NUMERICAL MODEL FOR SUSPENDED SEDIMENT CONCENTRATION

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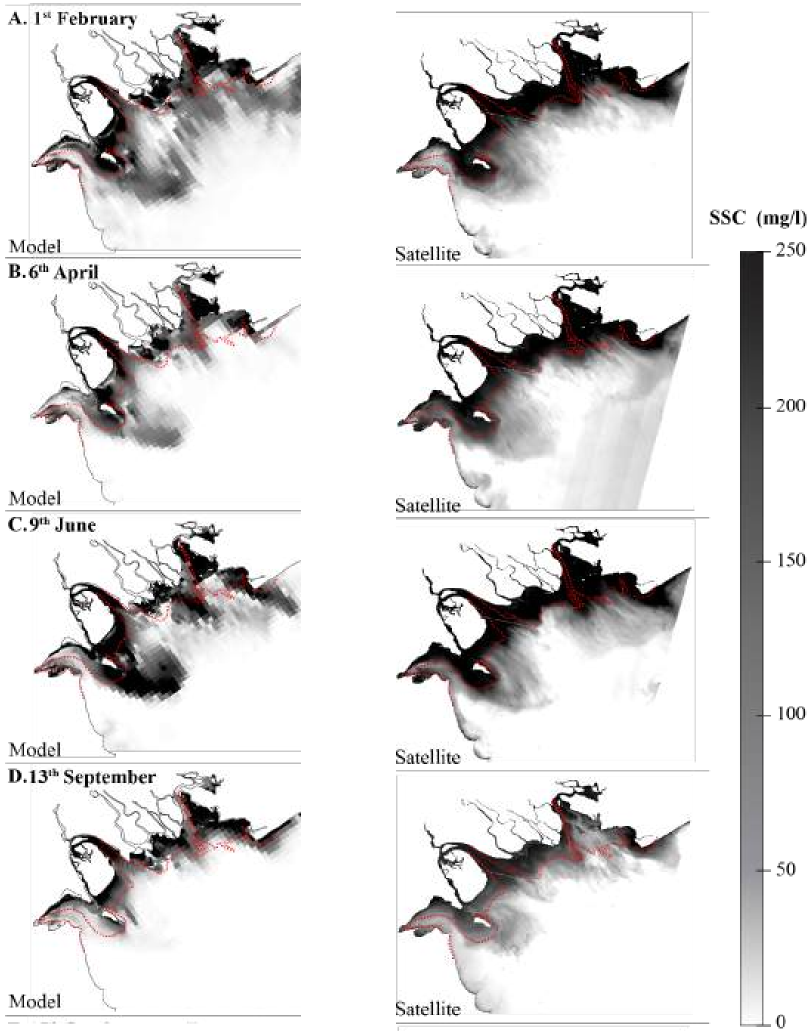
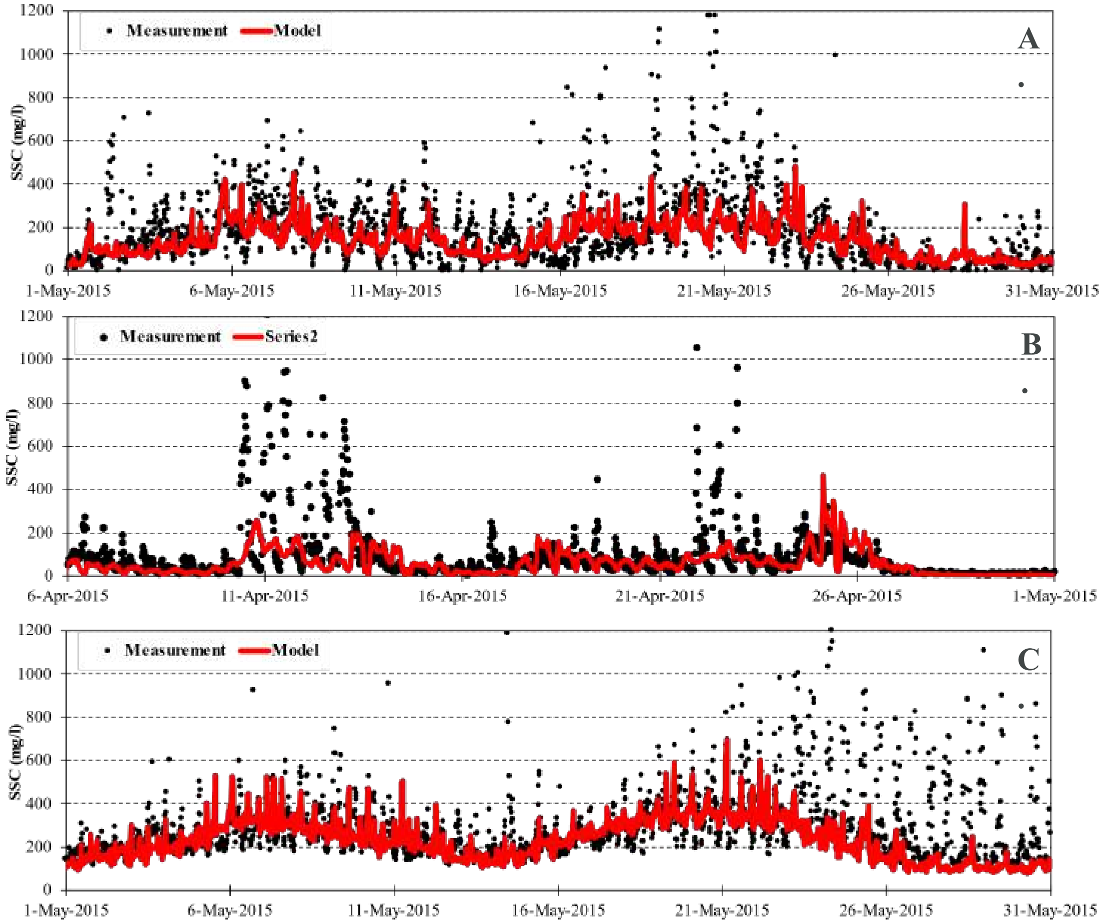
Model **Remotely Sensed Data** **Time Series (3 locations)**





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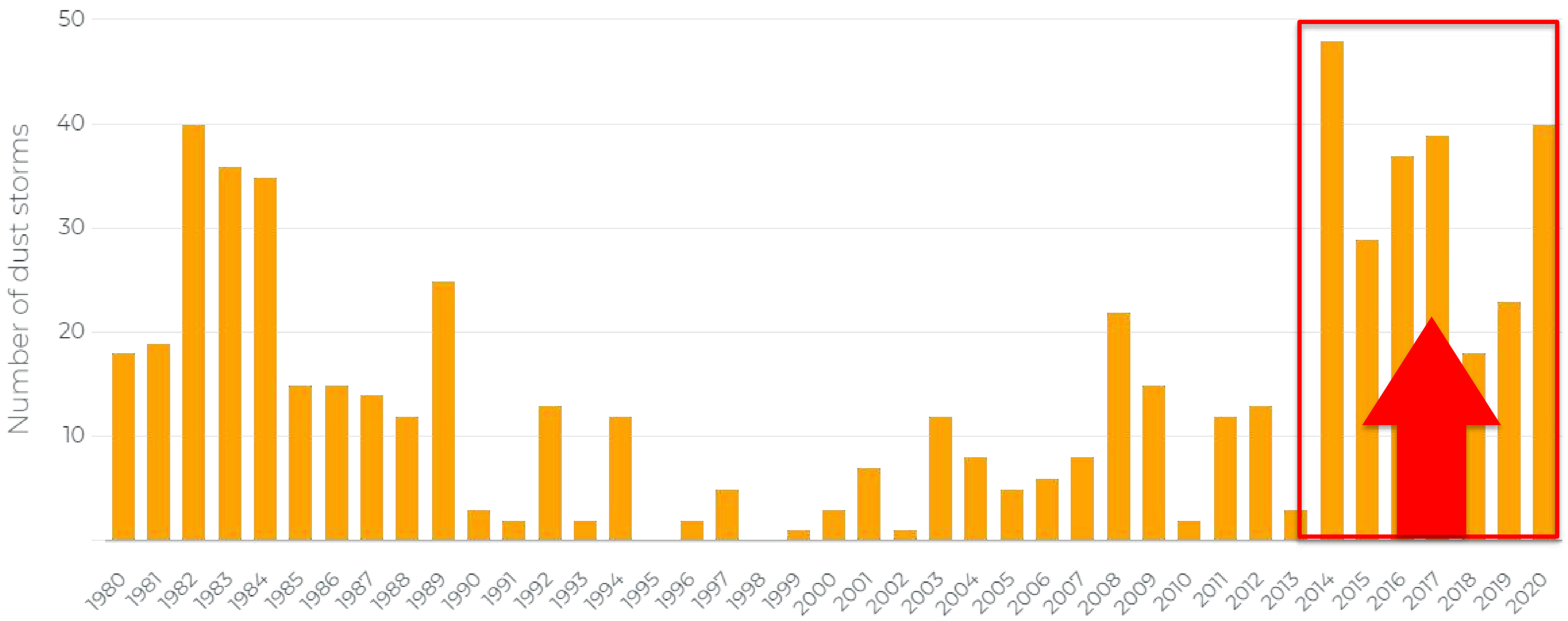
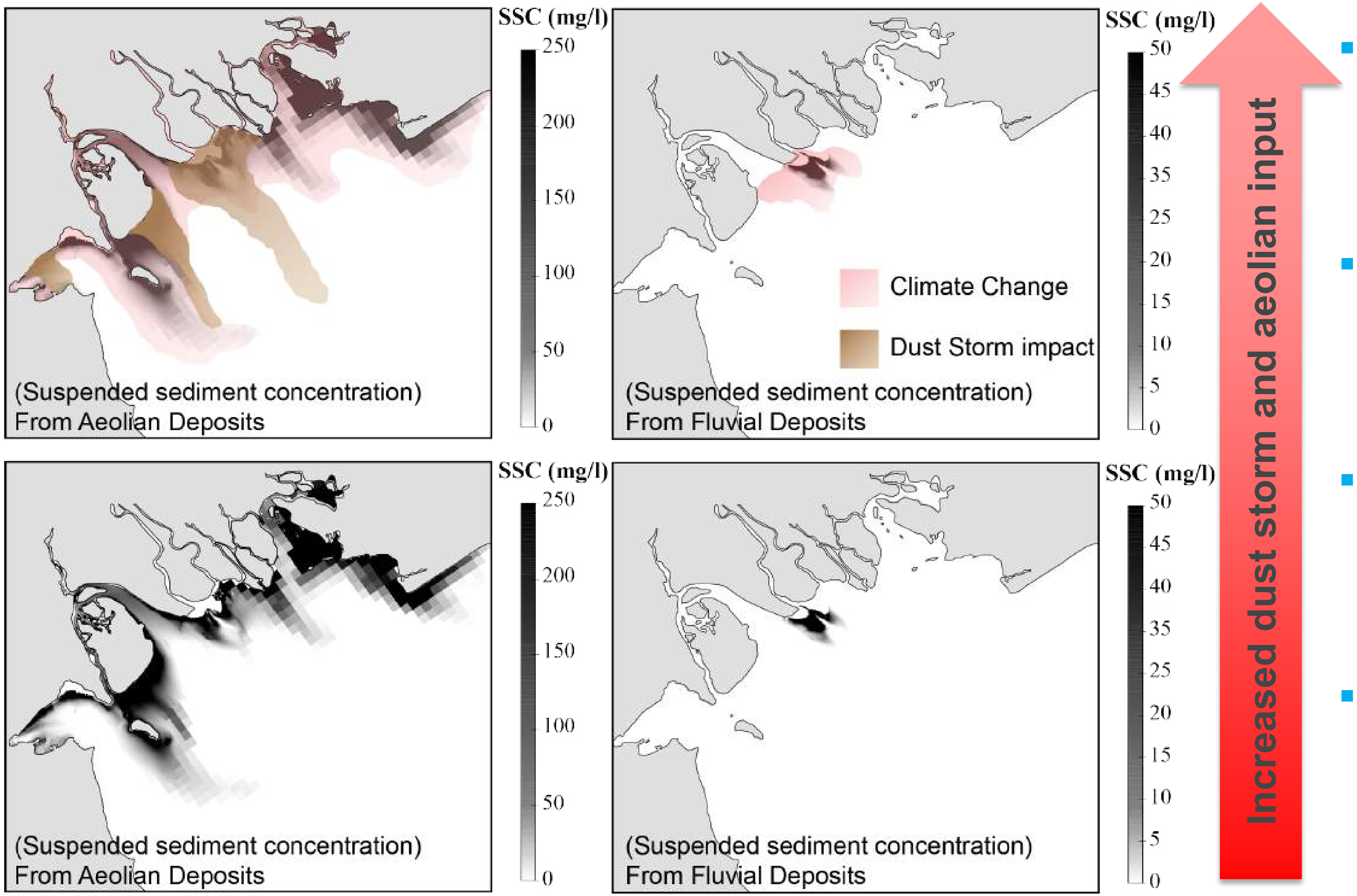
ANNUAL DUST STORM COUNTS



- **Climate change:** Rising temperatures and altered precipitation patterns and introduced new dry zones.
- **Land degradation:** Human activities such as deforestation, overgrazing, and unsustainable agricultural practices

A. Al-Saleh, (2020), Dust storms in Kuwait, Crisis and decision support program, Kuwait Institute for Scientific Research. Poster.

PROJECTION ON CLIMATE CHANGE

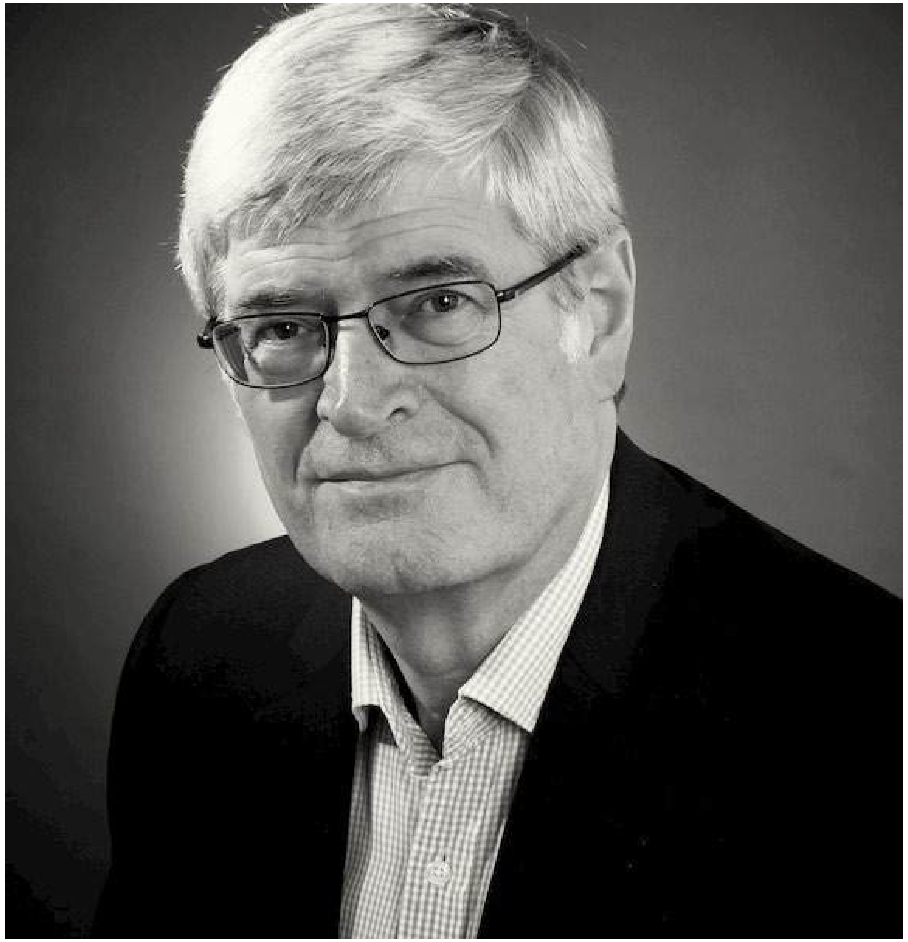


- Suspended sediment concentration is expected to increase by **17% in 2100** in the Northern Gulf (Alosairi et al., 2025, in preparation).
- **Increased sediment loading** would lead to redistribution of sediments in the vicinity of mega infrastructure like the causeway.
- Increased sediment would lead to **less light penetration**, therefore disturbance to the ecological productivity.
- Higher cost is anticipated to maintain depths of intake channels of desalination/power plants as well as the navigational channels of the ports.

CONCLUSIONS AND REMARKS

- **Long-term monitoring programs** and networks are crucial for accurately assessing and understanding the ongoing and cumulative effects of climate change, enabling informed decision-making and adaptive strategies.
- **Biodiversity recovery** near estuaries is a prolonged process, as significant salinity fluctuations disrupt ecological stability, making it difficult for species to adapt and ecosystems to reestablish balance.
- **Numerical models** are effective in understanding the implications of extreme events and could aid the strategic planning of waterfront developments in Kuwait and other locations with similar conditions.
- **Hard engineering** solutions can be costly and inefficient. This highlights the importance of adopting sustainable, nature-based approaches that are more adaptable and cost-effective in the long run.
- **Designing sustainable waterfront infrastructure** that effectively addresses the complex challenges of climate change requires adaptive and innovative approaches grounded in science.

PEOPLE THAT UNDERPINNED MY CAREER



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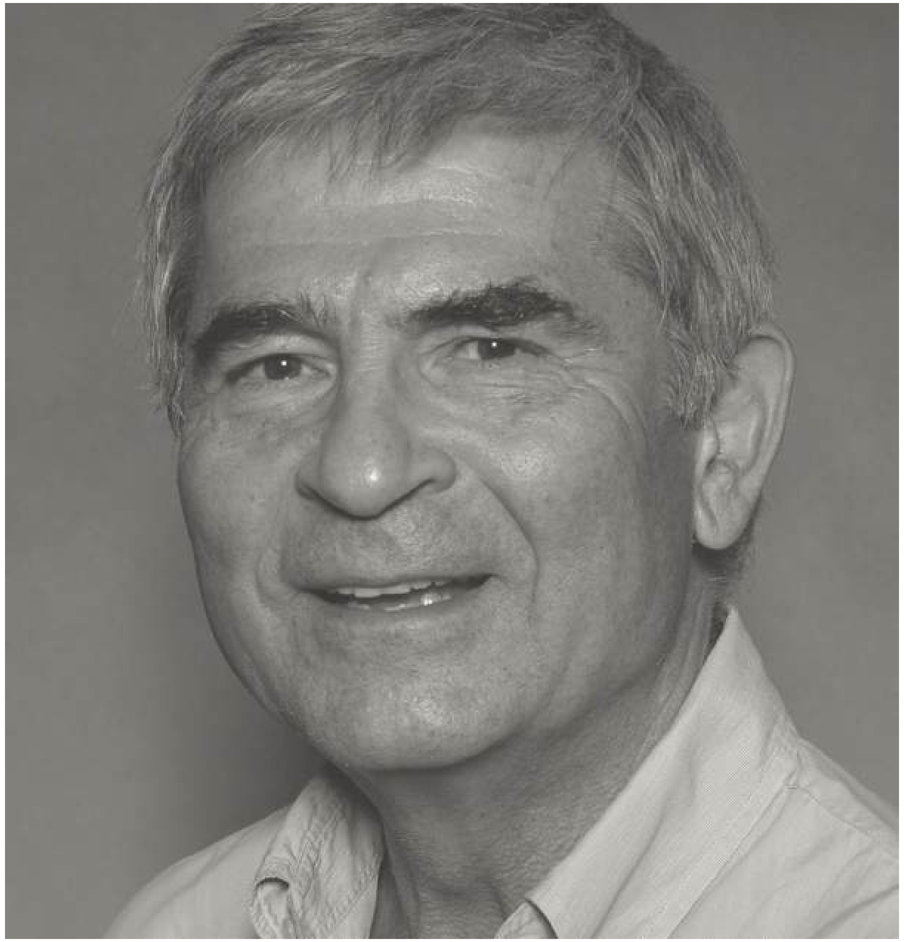

Prof. Jorg Imberger

THANK YOU