

# Hidden Risks of Saline Intrusion: Climate-Driven Sea-Level Rise and Geotechnical Implications for Coastal Stability

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## IAP-25-125

### Introduction and Global Context

Climate change is accelerating global sea-level rise, which threatens coastal regions worldwide. While the visible impacts—such as flooding and shoreline erosion—are widely recognized, a less apparent but equally critical consequence is saline intrusion. This process occurs when seawater infiltrates coastal groundwater systems, compromising freshwater resources essential for drinking water, agriculture, ecosystems, and urban infrastructures such as roads, building foundations, and utility networks. Saline intrusion is not confined to tropical deltas; it affects diverse settings, from East Anglia and the Thames Estuary in the UK to the Mekong Delta in Vietnam, Florida's coastal aquifers, and low-lying areas of Bangladesh amongst many places. Rising seas, combined with groundwater extraction and changing precipitation patterns, amplify this risk, making it a global challenge for water security and infrastructure resilience. By 2100, nearly 77% of global coastal areas below 60°N are expected to experience saltwater intrusion (Adams et al., 2024).

Beyond water quality concerns, saline intrusion can induce geotechnical changes that remain poorly understood. Laboratory studies demonstrate that exposure to saline water accelerates chemical weathering and dissolution of carbonate minerals, weakening cement bonds and altering microstructure. For example, calcarenite samples show short-term debonding when saturated and long-term weakening under persistent saline conditions, reducing compressive strength and increasing compressibility (Ciantia et al., 2015). After repeated wetting–drying cycles and high salinity, these processes not only increase porosity and permeability but also compromise the stability of foundations and underground infrastructure. In coastal zones, such chemical weakening can interact with groundwater withdrawal to exacerbate subsidence, as observed in parts of Italy's Adriatic coast and South Florida. However, despite the growing recognition of saline intrusion's role in coastal geotechnical instability, the complex interplay of saltwater chemistry, groundwater dynamics, and material behaviour remains insufficiently explored.

Bergsaker et al., (2018) results suggest that the ionic composition of saline fluids significantly influences the mechanical behaviour of calcite minerals, with variations in fluid salinity impacting the propagation and healing of subcritical cracks in carbonate rocks, further complicating predictions of long-term stability. Looking at calcite rich rock samples, Pluymakers et al. (2021) have demonstrated that such samples exhibit also greater susceptibility to weakening under saline conditions, emphasizing the need for further research into how these materials interact with fluctuating groundwater salinity. Frame in the context of coastal zones, such, as observed chemical weakening can interact with groundwater withdrawal to exacerbate subsidence in parts of Italy's Adriatic coast and South Florida. Despite these findings, the combined hydro-chemo-mechanical effects of saline intrusion on ground stability remain under-researched, leaving significant uncertainty for long-term adaptation planning.

Non-destructive testing has emerged as a powerful experimental approach for investigating the effects of deformation on the internal structure of geomaterials. X-ray tomography enables the detection of density variations associated with deformation processes, while neutron tomography – owing to its sensitivity to hydrogen – facilitates the visualisation of hydrogen-rich fluids within the material's structure. Both techniques provide spatially and temporally resolved imaging capabilities. Notably, high-speed neutron tomography has been successfully employed to elucidate fluid migration in mechanically deformed sandstones (Tudisco et al., 2019) and carbonates (Madankan, 2021). Cutting-edge research in this domain is supported by large-scale facilities such as synchrotron and neutron sources (Charalampidou et al., 2018), which enable advanced imaging of geomaterials. However, visualising the hydro-chemo-mechanical effects of saline intrusion on carbonates remains relatively unexplored using these experimental tools.

Recent research emphasizes the need for integrated approaches that consider the complex interactions between fluid dynamics, material degradation, and the stability of coastal infrastructure under saline conditions (Hein et al., 2023). While laboratory simulations and computational fluid dynamics (CFD) models have made strides in understanding saline wedge dynamics and their effects on subsurface stress regimes (Chalá et al., 2024), the broader implications for coastal infrastructure stability are still poorly understood. Earth Observation (EO) technologies, including Sentinel-2 and LiDAR, have proven essential in tracking coastal erosion and cliff retreat over both short and long-term periods, offering a means to monitor shifts in shoreline morphology and ground surface dynamics (ESA, 2023). However, existing frameworks need to address the progressive degradation of materials due to repeated saline exposure. Even subtle, long-term changes in the material properties of coastal foundations can amplify risks (properties for processes), accelerating infrastructure failure and undermining resilience. This PhD project will investigate with laboratory experiments how cyclic saline intrusion may initiate feedback mechanisms that exacerbate rock (coastal area underground) fatigue, leading to accelerated damage in critical infrastructure. We will develop a tool that integrates these lab results with Earth Observation (EO)-based risk mapping frameworks, such as the time-series analysis of subsidence in coastal zones by Bateson et al. (2024). By combining experimental degradation studies with spatial risk assessment, this approach will improve predictive models of coastal vulnerability and environmental

resilience. The novelty of this project lies in its ability to merge material-specific degradation analysis with spatial risk mapping, providing more accurate models for assessing both long-term infrastructure resilience and coastal zone vulnerability. Finally, time will be allocated to enable a 3 month internship to further learn on the translation of laboratory results into societal issues, looking at science to policy with a BGS project's partner.

### Motivation and Knowledge Gaps

Despite substantial progress in hydrogeological modelling of saline wedges, three interrelated gaps limit predictive capability for carbonate aquifers:

1. Chemo mechanical weakening under brine exposure: We lack quantitative links between evolving fluid chemistry (ionic strength,  $\text{SO}_4^{2-}/\text{Mg}^{2+}/\text{Cl}^-$  ratios), microstructural change (dissolution/precipitation, ion exchange), and time dependent strength and stiffness loss under relevant stress and saturation states.
2. Cyclic and transient processes: The pore scale dynamics associated with cyclic brine/freshwater saturation (tidal, seasonal, pumping induced) and associated transport–reaction front migration are under characterised, particularly their impact on damage accumulation, permeability anisotropy, and ultrasonic/AE signatures.
3. Mineralogical and textural heterogeneity: Carbonate lithologies (micritic vs. fossiliferous limestones; micro to mesoporous chalk) show markedly different reactive and mechanical behaviours, yet systematic, comparative datasets that resolve mineralogy–texture–fluid chemistry controls are rare. This heterogeneity undermines transferable risk metrics for vulnerability mapping.

Addressing these gaps will enable clearer assessments of progressive degradation trajectories in coastal aquifers, allowing for more accurate properties-to-process correlations. These insights will be crucial for developing predictive models of material vulnerability and damage evolution, thereby improving the precision of spatial risk mapping for infrastructure resilience in coastal regions.

The Phd project will aim to answer the following questions:

1. How does brine composition and exposure history govern the coupled chemical, hydrological, and mechanical evolution of carbonate rocks?
2. What pore scale mechanisms (e.g., localized dissolution, cement recrystallization, fabric realignment) control progressive damage during cyclic salinity changes, and how do these manifest in petrophysical and acoustic properties?
3. How do mineralogical–textural variations across representative carbonate types modulate degradation pathways and rates?
4. Can we build predictive models that integrate time dependent rock properties evolution from mineralogy, texture, and fluid chemistry to support vulnerability and risk mapping at regional scale?

These questions are framed assuming that saline intrusion induces time dependent chemo mechanical weakening whose rate and extent scale with ionic strength and specific ion effects (e.g., Mg driven stabilization vs.  $\text{SO}_4$  mediated alteration) under stress and saturation representative of site conditions. The second hypothesis is that cyclic brine–freshwater saturation amplifies damage through hysteretic transport–reaction fronts

and microcrack opening–healing asymmetry, producing distinctive petrophysical and ultrasonic signatures that can be used as diagnostics. Finally, mineralogy and fabric (e.g., micrite content, bioclast distribution, chalk platelet arrangement) are thought to exert first order control on degradation trajectories; these controls can be parameterised to enable material specific vulnerability indices.

### Objectives

1. Quantify chemo mechanical evolution (strength, stiffness, permeability, acoustic velocity/attenuation) of limestones and chalk under controlled brine exposure and THCM boundary conditions.
2. Resolve pore scale processes during cyclic saturation using non-destructive time-resolved imaging (e.g., neutron tomography and X-ray tomography) to link microstructural changes to macroscopic behaviour.
3. Compare lithologies (e.g. micritic, fossiliferous, chalk...) to establish mineralogy–texture–chemistry controls on degradation and derive material specific parameters for models.
4. Produce dynamic risk maps/heat maps for UK coastal carbonate aquifers by fusing laboratory derived degradation rates (for different lithologies) with EO indicators (InSAR, LiDAR/Sentinel derived coastal change), hydrogeological salinity fields, and optional socio economic overlays (e.g., infrastructure, abstraction points).
5. Translate findings to practice via an embedded 3 month internship with an end user (e.g., CASE partner Environment Agency), developing a policy brief and a prototype decision support tool for saline intrusion risk.

### Expected Outcomes and Impact

- A mechanistic framework linking saline chemistry and cyclic exposure to time dependent weakening and transport evolution in carbonates, with diagnostic acoustic/petrophysical indicators.
- Comparative datasets and constitutive relationships that capture mineralogy–texture controls for limestones and chalk, enabling material specific parameterisation in coupled models.
- Validated predictive models that upscale lab calibrated processes to aquifer scales and quantify uncertainty arising from lithological heterogeneity and transient forcing. This includes the usage of the lab data as a calibration tool for field-based self-potential measurements (MacAllister et al., 2018).
- Dynamic vulnerability/risk heat maps for selected UK coastal carbonate aquifers integrating lab derived degradation rates, EO based stability indicators, and hydrogeological salinity fields.

### Training and IAPETUS alignment

The student will acquire an interdisciplinary skillset spanning experimental geomechanics, geochemistry, neutron beam imaging, Earth Observation and GIS data fusion, and science policy translation. The project's integrated lab–model–EO–policy pathway, risk mapping deliverables, and internship directly reflect IAPETUS priorities on skills development, interdisciplinarity, and societal impact.

## Image Captions

Modified after ScienceSource.com.

## Methodology

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**Materials & Fluids.** Representative UK carbonates (e.g., Chalk, Lincolnshire limestones) and selected analogues; synthetic brines spanning salinity and ion chemistries relevant to coastal settings. Mineralogical characterisation will ensure that chalk specific fabric/mineralogical features are captured for robust inter comparisons.

**Chemo-hydro mechanical testing.** Synthetic brines and freshwater solutions.

Uniaxial/triaxial and hydrostatic creep tests under in situ saturation, pore pressure, and temperature, with controlled static/cyclic salinity histories. Concurrent permeability/porosity tracking, ultrasonic monitoring, and acoustic emission will quantify time dependent damage and transport changes.

**Imaging & petrophysics.** Time-resolved and/or where appropriate only spatially resolved imaging (non-destructive) will provide the understanding of the occurring processes. This will include neutron tomography to capture preferential flow pathways, which will be affected by the textural changes (chemo-mechanical coupling) as well as x-ray tomography with accompanied digital image correlation (using open access software) to visualise the occurring textural changes.

**EO and data fusion.** Integrate InSAR derived ground motion, coastal morphology change (Sentinel/LiDAR), and available hydrogeological salinity fields to contextualise degradation forecasts. The new tool will combine GIS based info with lab data to produce dynamic risk maps and an interactive dashboard for stakeholders.

**Science to policy pathway.** A structured internship will support co design of the risk products (maps/briefs/tooling) with practitioners, ensuring alignment with regulatory workflows (e.g., groundwater status assessments, coastal zone planning) and real world uptake.

## Project Timeline

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Year 1

Training

- Systematic literature review methods and time management
- Sample preparation methods, and sample characterisation techniques involving

acquisition, processing and analysis for x-ray tomography, ultrasonic velocity, SEM, neutron tomography, and XRF data

- Heriot-Watt training sessions for PhD students will be offered via the Research Futures Academy. All our courses can be booked via online booking system LibCal
- International Summer School on geomechanics

#### Literature review

- Literature review on saline intrusion, geotechnical methodologies, geomechanics, rock physics, carbonate rocks, coastal aquifers

#### Sample collection, preparation, characterisation

- Fieldwork to collect material to sample (BGS)
- Prepare samples for testing (BGS)
- Perform x-ray tomography, SEM, XRF and run analysis to characterise samples (Heriot-Watt)
- Synchrotron and Neutron Facilities to be accessed after successful beam line proposals (e.g., Diamond Light Source).

#### Internship

- One month internship at the end of the first year

#### Communication

- One national conference
- One review paper

#### Year 2

##### Training

- Chemo-mechanical experimental testing (BGS)
- Neutron beamline safety and processes (Institute Laue–Langevin (NeXT instrument), or ISIS Neutron and Muon Source (IMAT instrument)).
- Project management and proposal writing (BGS)
- Heriot-Watt training sessions for PhD students (see Y1)
- Workshop: e.g. ALERT Geomaterials Doctoral School

##### Experimental campaigns

- Chemo-hydro-mechanical experiments (BGS) on samples representative of selected aquifers in the UK. The experimental conditions will be designed to simulate in-situ environments (saturation, pressure, fluid chemistry) and facilitate knowledge transfer from the laboratory- to the field-scale.
- Neutron proposal and subsequent campaign for targeted cyclic injection experiments with time-resolved in-situ imaging to visualise changes in the microstructure and benchmark previously inferred geomechanical behaviour (ILL or ISIS).

#### Internship

- One month internship at the end of the first year

#### Communication

- One international conference, e.g., EGU (academia-led) or EAGE/GET (industry-led)
- One “progressive damage in the laboratory” paper

### Year 3

#### Training

- GIS software
- Databases: CoastalMe, GeoSure, EGD
- Geomechanical modelling methods
- Heriot-Watt training sessions for PhD students (see Y1)

#### Data integration and evaluation

- Data management and processing
- Data analysis to characterise fluid-rock behaviour under in-situ conditions relevant for saline intrusion
- Develop predictive models
- Hypothesis testing
- Heat map for risk communication

#### Internship

- One month internship at the end of the first year

#### Communication

- One international conference, e.g., EGU (academia-led) or EAGE (industry-led)

### Year 3.5

#### Communication

- Thesis completion
- One hypothesis-testing paper including modelling results (“properties for processes”)

## **Training & Skills**

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In addition to the IAPETUS training, a comprehensive training programme will be provided comprising both specialist scientific training and generic transferable and professional skills.

Key project-specific training will be given in experimental techniques, managing and analysing mechanical, micro-seismic and large x-ray datasets, and methods for geomechanical and analytical modelling. This will be provided by the supervisory team and technical staff at HWU and BGS and external collaborators where appropriate. This specialist training will be complemented by attendance at external workshops and conferences. Attendance at two to three doctoral training schools and two to three international conferences over the course of the project will be encouraged. This attendance will supplement project-specific training, provide exposure to a broad scientific network and audience, and enabling the application of transferable and professional skills developed through relevant University-level and School courses.

The Research Futures Academy (RFA) at Heriot-Watt provides transferable skills / career development workshops to facilitate the doctorate and future research career of PhD students. The student will be able to attend workshops focusing on:

- basic skills for successful research
- research data management
- communication and dissemination skills
- strategy for publishing
- citation and impact

In addition to supporting doctoral students to develop such competencies, the RFA provides valuable networking and collaboration opportunities between researchers across diverse disciplines. Heriot-Watt subscribes to LinkedIn Learning which provides courses in a variety of common software packages, coding languages and other transferable skills that doctoral students have access to for online learning at their own pace. At BGS the student will attend training sessions on scientific paper and proposal writing and project management.

The student will belong a diverse, inclusive and international community with a strong research culture that celebrates effort and achievement. As part of the IAPETUS DTP cohort, the student will receive a multidisciplinary package of training focused around meeting the specific needs and requirements of each student, benefitting from the combined strength and expertise that is available across the partner organisations.

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