FORESIGHT STUDY: FUTURE DEVELOPMENTS IN PHYSICAL MODELLING OF CLIMATE CHANGE IMPACTS

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The HYDRALAB+ Project is an advanced network of European research organisations that focus on physical modelling of environmental hydraulics. The aim is to develop and improve the experimental facilities for the investigation of expected climate change impacts to ensure that future management and adaptation measures are effective. An important aspect of this work is to identify new or alternative experimental methods and resources to better support future work in modelling climate change impacts and adaptation strategies.

The estimated rise of mean sea water level and increased occurrence of storms in the coming decades prompts our societies to rethink exploitation of the coastal, riverine and polar regions worldwide. The coastal and riparian zones are often heavily urbanized and are therefore very important for industrial development, commerce and tourism. Facilities, infrastructure and protective structures, along the margins of water bodies, have been constructed based on design life expectations, which are typically derived from extrapolations of historical design parameters, but do not necessarily account for inevitable climate change impacts in the design process.

Conflict is almost inevitable with the continued development of areas where there is interaction with coastal, fluvial, and ice processes. Development and exploitation of resources requires stability, whilst it is evident that natural processes are subject to constant change.

In this context, the Foresight Studies, a networking activity of HYDRALAB+ project [1], have been employed to identify and highlight areas of recent novel developments and to define the combined requirements for morphological, ecological and structural methods in experimental modelling to improve our understanding and response to climate change issues through adaptation in rivers, coastal and offshore regions such as that shown in Figure 1.

This work is focused on the variables and forcing to be represented in the experimental domain, the measuring equipment and technologies, as well as the experimental procedures, methodologies and facilities for analysing processes in dynamic coastal, fluvial and polar regions.

Figure 1. Climate change in coastal environments (Source: hydralab.eu)

Climate change impacts will alter many important boundary conditions (e.g. rise of mean sea water level, increased storm events – both in terms of intensity and frequency of occurrence, etc.). The related development of management approaches to adapt to these new boundary conditions brings new and significant challenges to experimental facilities worldwide, at different temporal and spatial scales across climate change related topics.

Current limitations for experimental modelling

Most experimental facilities have the capability to simulate typical forcing to represent the system being modelled (e.g. waves, unidirectional or bidirectional currents and ice) however there are limitations. In many cases only a single forcing can be represented or there are compromises in the simultaneous action of multiple forcing (e.g. wave paddles interact with flow currents). Technical limitations may also be an issue, for example, traditional wave basins and flumes have conservative limits in terms of wave steepness compared to wind-generated waves in the natural environment. On the other hand, discharge hydrographs in fluvial models are often represented by step changes rather than being continuously variable. In addition, the modelling of climate change scenarios requires changes in forcing to be more intense, frequent and unsteady (e.g. seasonal or inter-annual variability, in conjunction with the slowly varying system change). Climate change effects are also expected to lead to more frequent storm events with steeper waves (i.e., with a higher wave height to length ratio) and potentially more frequent, intense and/or localised rainfall events driving flood events.

Since there are significant uncertainties in predicting the effects of climate change in the variables driving the design of coastal and hydraulic structures (i.e., establishing the sea level rise or predicting extreme flood events), the use of multiple scenarios to predict possible future realities (in the medium- to long-term) is of paramount importance. However, modelling multiple scenarios is time-consuming and therefore expensive. Thus, the key question is, how to correctly select representative conditions to be considered in any test programme. This requires the merger of probabilistic approaches like joint probability analysis with experimental programme design to improve the operational effectiveness of physical modelling studies.
In addition, the relevance of reproducing sequences of extreme events over the life span of a structure, including their cumulative effects, needs to be highlighted [2; 3; 4]. Cumulative effects due to storm sequences may, for example,

produce progressive failures in coastal defence structures due to armour instability and related overtopping of structures. Therefore, in this example, an appropriate description of storm evolution is critical for simulating damage progression and its impact on wave overtopping. Similarly, the morphological evolution of natural features like beaches and river channels depends not only on the erosive impacts of storm events themselves, but also on the antecedent conditions which dictate the state of the system prior to a storm event. Hence, the modelling of extreme events depends on the chronology and sequencing of both energetic and quiescent events.

Global warming has also significantly reduced sea ice extent in the Arctic and, with ice cover retreating, Arctic sea ice is surrounded by more open ocean than land. The marginal ice zone (MIZ) is the transitional area between the open ocean and pack ice cover. It consists of individual ice floes of varying size often formed by ocean waves penetrating a solid ice field. Both winter navigation and offshore structures may be impacted by MIZ conditions for at least part of the ice season. However, there is insufficient understanding of the air-ice-ocean system to operate effectively in this region. In particular, the increased area of open water in the Arctic has amplified wave intensity. Hence, wave propagation through dynamically changing ice cover in the MIZ has become an important topic for maritime operations in the Arctic [5]. Therefore, predicting the wave climate and its effect on structures in the MIZ is of practical importance since waves affect the ice breakage, while the ice contributes to the attenuation and dissipation of waves [6].

Despite its importance, limited data are available for wave propagation in the MIZ. Field measurements [7] and remote sensing [8] data have been gathered and laboratory experiments have been conducted [9]. However, these studies have only scratched the surface of the complex wave-ice interaction problem and a systematic study is urgently required to develop a better understanding for Arctic engineering in the MIZ.

For many facilities it is often difficult to work with living organisms because the local environmental conditions such as light, water quality, temperature, etc. cannot be controlled or maintained to ensure survival for the duration of the experiment. Although there are some facilities that can support the growth of organisms, such as mussels or eelgrass, they are often not equipped to create the full range of waves or flows over representative length and time scales in relation to the size and growth or reproduction cycles of the organisms. In addition, the time required for such experimentation would make such work prohibitively expensive.

Another serious problem is that plants require time to grow. Changes in the density and biomechanics occurring on seasonally (winter die-off) as well as on inter-annual scales result in experiments that are unrealistically long. To solve this issue, the use of surrogates has been investigated intensively in HYDRALAB research, but numerous issues still remain unresolved and organism response to climate change is only one of those. Furthermore, the inherent variability of organism response to the same environmental conditions requires numerous repetitions of experiments to satisfy statistical significance tests, which are necessary to distinguish random variability in organism response from the causal response due to changes in environmental variables.

To improve the understanding of fluvial processes, a better knowledge of the uncertainties in the required inputs (climate change model predictions) is needed. One approach to improving the representation of these uncertainties would be the development of probabilistic approaches (like those used for simulating coastal processes) to help reduce and characterise uncertainties. Improved methodologies are also required to better represent the unsteadiness and variability of flow processes.

Interdisciplinary collaboration is generally underdeveloped, and there is the need for a more integrated approach to experimentation. For example, in some fluvial/coastal environments, the study of climate change effects and adaptive measures might involve the unusual combinations of physical processes. For example, the modelling of soft cliffs, may require the reproduction of extreme rainfall events which necessitates the accurate modelling of rain intensity and its spatial distribution in time which in turn requires different scaling effects to be resolved (e.g. tension effect in water drops). In addition, integrated management approaches are likely to be adopted when addressing climate change impacts therefore fluvial and coastal systems cannot be considered (or modelled) in isolation and similarly the role of biota in the environment cannot be ignored. Therefore, it is expected that ecohydraulic modelling will become increasingly important.

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Foresight studies

The representation of climate change impacts in physical models still presents significant challenges. The HYDRALAB foresight studies aim to identify the requirements in terms of experimental facilities, equipment, methodologies, datasets and model/field experiments to make a step-change in modelling climate change impacts and the managed adaptation to climate changes, for coastal, ice, and fluvial processes.

In terms of experimental facilities, equipment, methodologies and datasets, the main needs are:

- Development of laboratories and simulators in the natural environment to enable unscaled experiments to investigate critical properties of the prototype that cannot be scaled (e.g. behaviour of animals such as burrowing);
- Improve landscape scale observation capability to better capture validation data and ensure that the entire system is properly represented in experimental models (e.g. remote sensing surveys such as LIDAR);
- Improve the operational range of existing laboratory equipment process interactions (e.g. wind, wave, current and tide);
- Improve experimental facilities and methodologies to better reproduce the (sometimes complex) characteristics of the natural environment (including its ecological components) with respect to water (temperature and chemistry), sediments (size distributions), ice (physical properties) and biota (effective surrogates or real vegetation);
- Improve wave generation hardware and software to correctly generate new, less common (more extreme), sea states;
- Improve current simulation for better representations of hydrographic changes in fluvial systems (e.g. simultaneous depth and velocity variations);
- Develop new techniques for measurement and analysis of flow and sediment behaviour, particularly in shallow flows, subsurface flows and aerated flows with high spatial and temporal resolution (e.g. run-up/overtopping, forces/pressure, flows with bed materials, morphology, etc.);
- Enhance the assessment of uncertainties through new methodologies and the provision of more extensive and detailed datasets;
- Exploit further advanced probabilistic methods for the modelling of long-term trends and extreme events;
- Develop reduced scale or miniaturised measurement equipment for both laboratories and the field;
- Continuously update predicted climate conditions using freely available data gathered at high resolution.

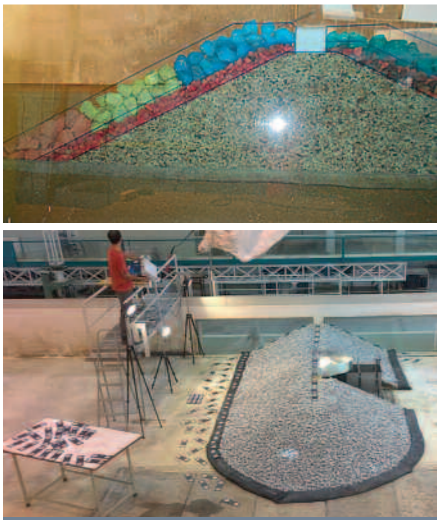

Figure 2. Upper panel: Model setup in LNEC's (Laboratório Nacional de Engenharia Civil) flume. Lower panel: Model setup in FEUP's (Faculdade de Engenharia da Universidade do Porto) basin

The main approaches to experiments that should be developed are as follows:

a) For the study of **coastal processes**:

- Long-term tests incorporating extreme events, storm event sequences and sea level rise;
- Tests on long-term behaviour of maritime and coastal structures affected by dynamic changes in forcing;
- Tests that incorporate mixed sediments and interactions of biota with sediment (scale 1:1);

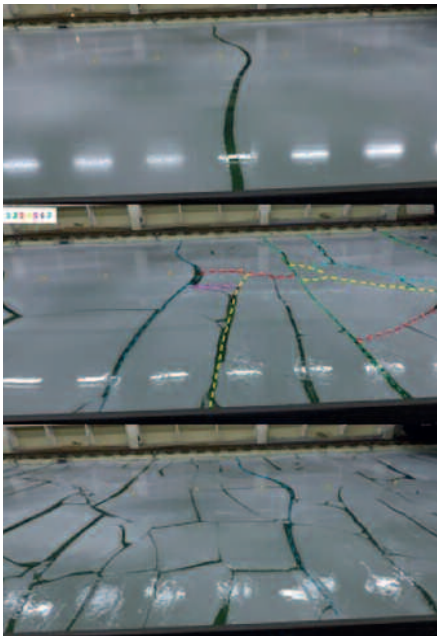

Figure 3. Snapshots of the crack formation in ice sheets [10]

- Tests with natural and nature-based solutions;
- Experiments on flooding (storm-induced and/or surge-related) in cities and urban areas near the coastal zone by downscaling;
- Test series on beach recovery in climate change scenarios, including "soft" and "hard" coastal defence structures;
- Cost effective and manageable physical models to assess response to extreme events,
- Study of medium to long-term processes and climate change adaptation measures (Figure 2);
- Flooding and morphological risks in both mud-dominated and sandy estuarine environments with sea-level change;

b) For the study of **ice processes**:

- Increased wave dispersion and attenuation in the marginal ice zone;
- Permafrost-flux interactions and shore erosion due to permafrost thawing processes;
- Internal stresses in ice sheets and ice scouring due to ice ridges in shallow waters;
- Sediment transport by ice;
- Behaviour of structures frozen in an intact ice sheet which is subsequently broken by waves (Figure 3);
- Impact of reduced ice cover on coastal erosion;
- Modelling ice jams near river estuaries at the end of severe winter and start of very warm spring;

c) For the study of **fluvial processes**:

- Long-term river flume experiments to understand tipping points related to climate change forcing;
- Experiments on river flow and groundwater flow interactions, e.g. groundwater flow behind water defences, including interaction between flow and biofilm;
- Experiments with erodible banks to investigate channel change, bank failure mechanisms and flood impacts (Figure 4);
- Modelling of extreme events that may become more frequent as a consequence of climate change, such as flash flooding and drought conditions;
- Changes in vegetation resulting from climate change may result in increased or decreased growth rates for existing and/or new species, therefore experiments are needed to better understand the interrelationships between vegetation growth/decline and fluvial processes;
- The impact of native and invasive species on sediment erosion and bank stability requires more attention;

Figure 4. Morphodynamics responding to climate change trends over long timescales. Tagliamento River, Italy (Source: Jochen Aberle)

Figure 5. Surrogate vegetation in laboratory (Source: Jochen Aberle)

d) For the study of **ecohydraulics**:

- Tests using natural ecosystem characteristics to study bio-geochemical, biological, ecological and sedimentary interactions under extreme conditions for extended periods;
- Tests with surrogates to study the conditions needed to use them effectively (Figure 5);
- Tests to analyse the impact of environmental parameters on biomechanics that cannot be properly reproduced in our facilities today (light, climate, temperature, salinity, and acidification);

In summary, the physical modelling of the interactions between structures, waves, flows, sediments, ice, and biota need to be continuously developed and will remain essential for the improvement of our knowledge and understanding of hydrodynamics. The future will require greater focus on nonlinear and unsteady phenomena and on a wider range of spatial and temporal scales.

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ANNOUNCEMENT

1st ACCR International Conference on Coastal Reservoirs

Professor Tang Chair of the University Council and Founding-Chair of the China Chapter of IACRR

The 1st International Conference on Coastal Reservoirs will be held by Hohai University in Nanjing (China) in October 19-22th, 2020. Coastal reservoirs could provide a solution to the water problems of many coastal cities, but their successful development faces various challenges. These challenges require close cooperation between scientists, engineers, water resources managers and policy makers. In this regard, the conference will provide a forum bringing together participants from academia, consulting firms, local, provincial and national government agencies, and offering them an opportunity to interact in an informal and relaxed environment. The conference will provide students an opportunity to discuss with renowned and well-established researchers and professionals in this field.

Hohai University, founded in 1915, has the largest number of researchers studying water-related problems in the world and has gained worldwide reputation for its focus on water. Hohai is a state key university under the direct administration of the Ministry of Education of China. The university has been collaborating closely with various academic organizations including the International Association for Hydro-Environment Engineering and Research (IAHR). Seven colleges at Hohai are relevant to the topic of coastal reservoirs, including the College of Environment, College of Hydrology and Water Resources, College of Water Conservancy and Hydropower Engineering, College of Harbor, Coastal and Offshore Engineering, College of Oceanography, College of Civil and Transportation Engineering, and College of Mechanics and Materials. Professor Hongwu Tang, the Chair of the University Council and the Founding-chair of the China Chapter of the International Association for Coastal Reservoir Research (IACRR), cordially invites you to attend the conference.

The conference is co-sponsored by IAHR.
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