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PHYSICAL-COMPUTATIONAL MODELLING COMPARISON IN IRELAND

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Abstract A detailed physical model of the River Dargle was constructed at HR Wallingford's physical modelling laboratory on behalf of Bray Town Council to examine the performance of a proposed channel re-grading and re-alignment of the river through Bray, south of Dublin, in Ireland. This physical model was unusual due to the complexity of the river channel, the size of the flood plain and the detail with which the urban areas were represented. Although built to address specific engineering questions, the model was subsequently used to run a series of fifteen additional tests aimed at better exploring a number of the key flow and modelling variables. Special attention was given to the urban floodplains where numerous control points were setup in order to capture detailed water-levels and velocity measurements. This has established a calibration data set for the floodplain and overland flow paths; areas where such data are not generally available for this type of modelling exercise.

A numerical model comparison was then undertaken to represent the physical model at model scale within InfoWorks RS (an integrated 1D-2D software solution for simulating flows in rivers and on floodplains), allowing direct comparison with the physical model results. The numerical model will subsequently be re-run at prototype scale to investigate the magnitude of real world effects and to allow an evaluation of the scaling from model to prototype scales and how this relates to the adoption of scaling laws typically adopted for this type of model (e.g. Froude laws for vertically exaggerated models). This paper presents a description of the physical and numerical models used, along with some preliminary study findings.

Keywords: physical modelling; numerical modelling; comparison; river; flooding

1. INTRODUCTION

Fluvial flooding is a complex process, and its modelling usually consists of two inter-related elements: river channel modelling and floodplain modelling. While the existence of flow and water level calibration data for the river channel is commonplace, particularly for larger rivers, floodplain flood data is usually very scarce.

Floodplain flood data only become available after major (and infrequent) flood events, and is usually recorded in the shape of sparse spot maximum water- levels based on flood debris marks, or on estimated maximum flood outline. The quality of such data is very variable, ranging from professional survey of flood marks and aerial photography, to simple anecdotal statements from residents affected by the flood. Finally, the reliability of the data depends on many factors such as the timing of the measurement, the presence of waves, or the presence of other sources of flooding such as sewer or groundwater.

An inter-model comparison between a physical model and a numerical model (at the same scale) was undertaken to assess the suitability of numerical models to represent floodplain flooding and complex channel flows. Some relevant results for this are reported in this paper.

An inter-model comparison between a numerical model at prototype scale and at model scale will be undertaken to assess scaling affects. The results for this are not currently available.

The very detailed data collected from the River Dargle physical model provided an opportunity to test the performance of numerical models in flood scenarios, provided some useful calibration data, and assisted in our understanding of which model parameters are important and how they influence the results.

2. RIVER DARGLE PHYSICAL MODEL

2.1 PHYSICAL MODEL LAYOUTS

A detailed 3D physical model of the River Dargle was constructed on behalf of Bray Town Council to examine the performance of a proposed channel re-grading and re-alignment of the river through Bray, south of Dublin, in Ireland [4]. This model was unusual in its complexity of the river channel, the size of the flood plain and the detail with which the urban areas were represented. The model initially represented the existing layout, then various proposed flood mitigation options were investigated (Figure 1).

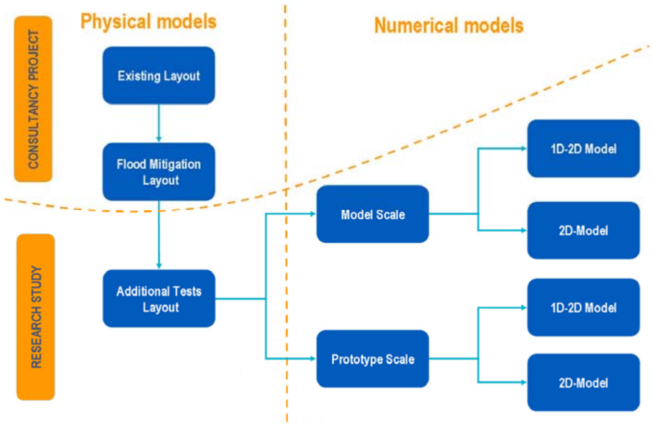

Figure 1: The various stages of the Dargle projects

Once the consultancy project was completed, the model was modified by removing the some roughness elements. This physical model was then used to run a series of fifteen additional tests aimed at compiling a calibration data set for the flood plain and overland flow paths.

2.2 PHYSICAL MODEL DESCRIPTION

The physical model represented approximately a 3.3km length of the River Dargle from the Silver Bridge upstream of the La Vallee to the harbour entrance, see Figure 2 below.

The model was constructed using topographical data from a river and floodplain survey. A total of 57 cross-sections surveyed on the River Dargle and 20 cross-sections surveyed on tributaries were used in constructing the model.

The model was constructed to a distorted scale of 1:100 horizontal and 1:50 vertical. Froude scale relationships were used, which are as follows:

- Horizontal scale (H) 1:100
- Vertical scale (V) 1:50
- Velocity scale ($V^{0.5}$) 1:7.071
- Discharge scale ($HV^{1.5}$) 1:35,355

- A distorted scale was chosen in order to give sufficient flow depths in the floodplain that would allow accurate water measurements to be taken.
- The model river channel was constructed of sand cement mortar on a well compacted sand and gravel fill in a model facility which measured approximately 36m long by 8m wide.
- Silver Bridge, Bray Bridge (shown in Figure 3) and the Bray Harbour road and rail bridges over the River Dargle were reproduced accurately to scale in wood. Buildings on the floodplain considered to influence flood water levels and flood flow paths were reproduced in high density foam. Walls and fences were constructed from wood or perforated sheet.

The physical model was run in steady state flow. The discharge at the upstream end was supplied via a header tank supplied by a centrifugal pump and measured using a pre-calibrated electromagnetic flowmeter (giving a basic accuracy of around ± 1%).

At the downstream end of the model a tilting weir was used to adjust the tailwater/tide level. Water surface levels in the river channel on the model were measured using up to 28 manually operated vernier point gauges. These point gauges may be read to an accuracy of ± 0.1mm. To convert measured water depths in water levels, the elevation of the model topography for each of the point gauge locations was surveyed with a topographic level. The overall absolute accuracy of measurement of water levels in the model was estimated to be 4cm in prototype terms for readings from the point gauges.

Figure 2: Aerial view of the lower section of the River Dargle physical model

3. SCENARIOS AND DATA COLLECTED

A total of 15 tests were run [5] for different layouts and flows, including:

- 2 tests with water level at (i) bank level and (ii) at flood defence level (used for channel calibration);
- 13 tests including combinations of various breaches of flood walls (Figure 3) on both sides of the river with a range of different steady state flows (used to assess various conditions on the floodplain);

The tests carried out do not represent real cases and were selected for research purpose: no conclusion should be drawn regarding actual flood risk.

Velocity measurements at points of interest were measured with a miniature current meter with a 10 mm impeller; measurements generally were taken at approximately 0.6 of the depth from the water surface. The flow velocity at each position measured was determined from a reading averaged over a 10 second time period.

Each test included a video record; photo coverage and overhead pictures; Extent depth and velocity measurements in the river and flood plain; Sketches of flow path (identified with dye tracers released on the flood plain).

Once the modelling tests were completed, the model was scanned using a Trimble GX 3D laser scanner. This was first done with the buildings in place, in order to capture a maximum of detail of the building location. The scan was then repeated with the buildings and other features in the floodplain removed, in order to have a bare-earth elevation model. The bare-earth scan resulted in 2.9 million points of data, while the with-building scan contains 5.5 million points. Both datasets were combined and processed (cleaning of artefacts, datum and shift correction) to form a final DTM that was used to construct the numerical model. At the location of the point gauges, a comparison was carried out between this DTM and the elevations previously surveyed with the topographic level (refer to Section 2.2). The absolute level error (DTM-level survey) was 0.85mm on average (about 4.3cm at prototype scale).

4. NUMERICAL MODEL

4.1 NUMERICAL SCHEMES OVERVIEW

A numerical model of the physical model test setup at the actual physical model scale was built using the software InfoWorks RS 2D (IWRS2D). This includes both a 1-dimensional (1D) component for the main channel and a 2-dimensional (2D) component for the floodplain.

4.1.1 Overview of the 1D engine.

The 1D component of InfoWorks-RS simulates flows in channels, as well as hydraulic structures such as weirs, sluices, etc [9]. Within this component the Saint-Venant equations are used as the mathematical representation of 1D flow.

The solution algorithm is based on the Preissmann four-point implicit finite difference scheme [10]. After discretisation, the 1D system is solved by inverting a sparse matrix. There is no time-step condition, the time-step is fixed by the user.

4.1.2 Overview of the 2D engine

The 2D engine in InfoWorks-2D is based on the algorithm described in Alcrudo and Mulet-Marti [1]. The shallow water equations (SWE), that is, the depth-averaged version of the Navier–Stokes equations, are used for the mathematical representation of the 2D flow. The conservative formulation of the SWE is discretised using a first-order finite volume explicit scheme [9]. The time-step is calculated in order to satisfy the Courant–Friedrichs–Lewy condition. Roe’s Riemann Solver is used to calculate the fluxes at the interfaces between cells. The flux splitting technique ensures the well balanced property by balancing the slope with the pressure terms at rest. Many previous studies testing the model performance have been conducted [2], [3], [7].

The 2D algorithm can be used with unstructured meshes which gave the following advantages for our project: accurate representation of the buildings and resource efficiency as details can be varied as needed. The algorithm is also appropriate for representing rapidly varying flows (shock capturing) as well as super-critical and trans-critical flows.

Figure 3: Details of the physical model at Bray Bridge, looking upstream.

4.1.3 Overview of the linking method

The link between 2D cells and 1D channels is made by means of lateral or in-line spills. The method used for discharge and momentum transfer between the 1D and the 2D modules is similar to that described by Liang et al.[8].

4.2 BUILDING OF THE NUMERICAL MODELS

As indicated in Figure 1, four numerical models were constructed;

(i) at physical model scale;

- Linked 1D model of the channel with 2D model of the floodplain.
- Full 2D model of the entire model area.

(ii) at prototype scale accounting for both vertical and horizontal distortion;

- Linked 1D model of the channel with 2D model of the floodplain
- Full 2D model of the entire model area.

Only the results for the numerical model at the actual physical model scale are presented in this paper. The results of the numerical model at prototype scale have yet to be completed (at time of writing).

4.2.1 The linked 1D-2D model of the channel and floodplain was built using the physical model DTM ground levels. This is shown in Figure 4, where the background colour represents the DEM elevation (red= high, green=low). The river sections are shown in light blue.

The upstream boundary is represented by a constant flow time series reproducing the inflow to the physical model. The downstream boundary of the numerical models was moved slightly downstream of the Bray Bridge in order to simplify the model.

Bridges have been included in the 1D model. The bridge having the greatest impact on water levels (Bray Bridge) has been modelled as an Arch Bridge unit within the InfoWorks-RS software, containing accurate dimensions of the arch widths and levels. A secondary bridge (Footbridge) has been modelled in a simpler manner using Bernoulli energy losses based on area reduction ratios.

4.2.2 The full-2D model domain includes the main channel and the full left and right bank floodplain. The same boundary conditions as used in the 1D model were specified. The domain consists of an irregular triangular mesh with a maximum triangle area of 0.001m^2 and breaklines along key edges. The buildings have been represented as voids (i.e. no storage or conveyance) and the walls either as impervious or porous walls as needed.

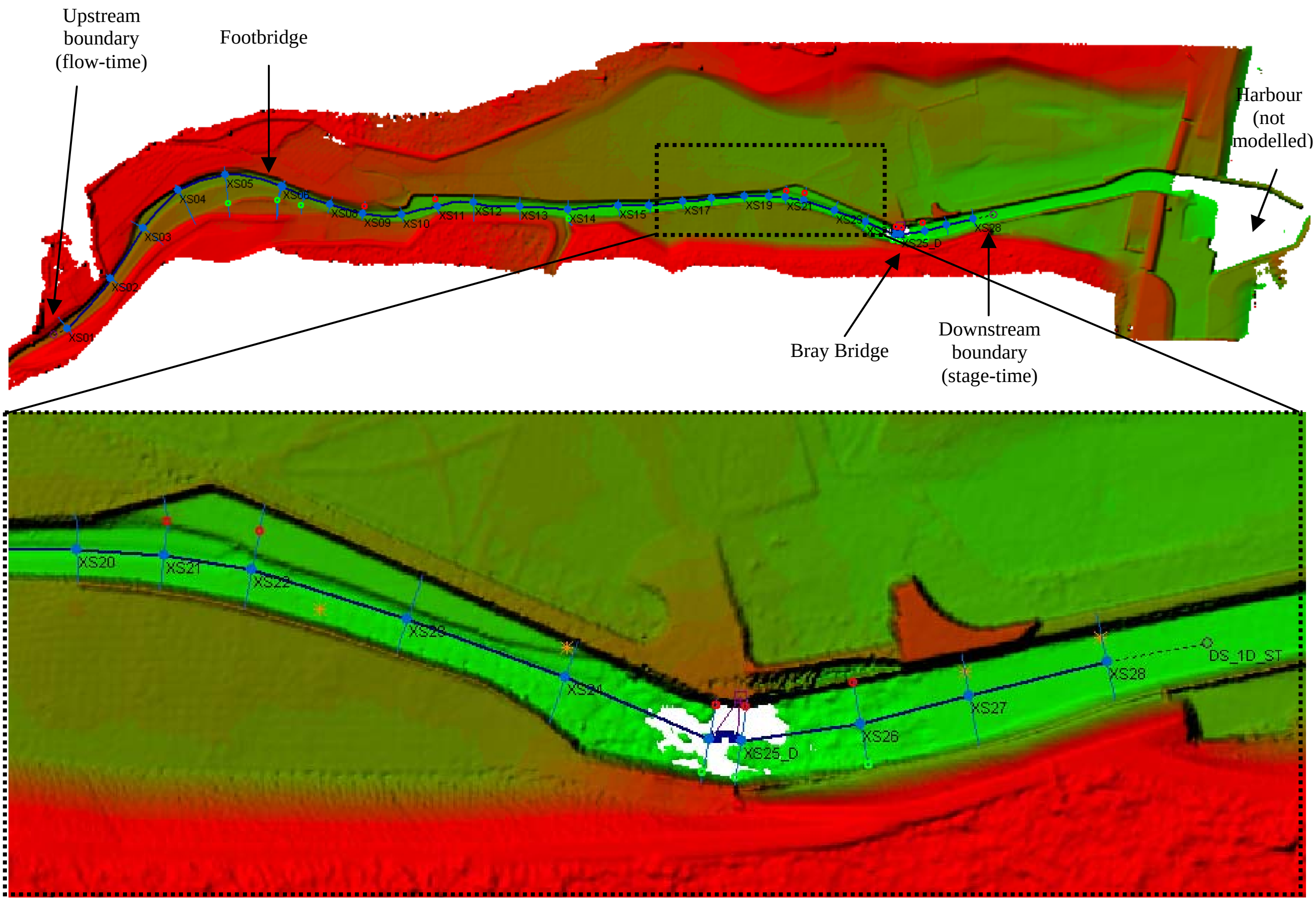

Figure 4: 1D model schematic (top) and enlargement around the main bridge (bottom).

5. PRELIMINARY RESULTS

The tests described in Section 3 were run using the numerical model at physical model scale. Firstly the in-channel portion of the model was calibrated. Then three aspects of the floodplain flooding were investigated: flow paths, water depth and velocity. The sections below discuss only the preliminary results of breach scenarios on the left bank of the river.

5.1 CALIBRATION OF THE IN-CHANNEL MODELS

1D model: The main factor influencing the calibration of the 1D channel is the channel frictional roughness (losses due to structures and non-conveyance areas have also been investigated). In the downstream section of the model the effect of varying roughness is very limited (the stage is largely controlled by the downstream water-level boundary). It was found that a roughness of 0.010 (Manning's n) gave the best overall fit to the physical model. The 1D model did not reproduce a steep water level variation which was observed in the upstream part of the physical model, but rather smoothed the water profile in this area.

It is important to remember that a 1D model represents a horizontal water surface in the transverse direction (along a cross section), and with area-averaged velocity. In reality there can be lateral variations (e.g. at bends), and depending on where along the cross section the physical measurements are done, water level will be recorded slightly differently. This introduces additional uncertainty when comparing the measured physical model water levels to those of a 1D numerical model.

2D model: The same roughness value as in the 1D model was used. After careful construction of the 2D mesh, water level variations such as the steep water level variation mentioned above were well represented. In addition phenomenon such as horizontal recirculation (eddies) are directly captured by the numerical scheme, and require less assumption in the modelling process. The 2D model of the channel nevertheless did not result in a significant improvement in the overall calibration, potentially due to limitations on the mesh size. In order to check the full suitability of a 2D model for in-channel flows, further tests at prototype-scale will be conducted.

5.2 DEPTH AND WATER LEVEL IN THE FLOODPLAIN

The floodplain was built with the same material as the channel, therefore the same calibrated friction value was used.

A series of results analysis points were created in the numerical model at the same location as the physical model gauges to allow for direct one-to-one comparisons. The comparison with the linked 1D-2D model is shown in Figure 5 for one of the tests (test#3). The mean error is -0.6mm, while the mean absolute error is 1.3mm.

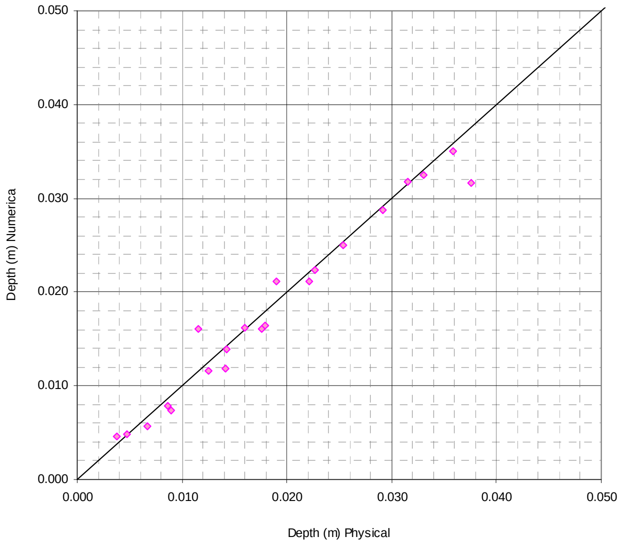

Figure 5 Comparison of physical model and 1D-2D numerical model flood depth in the left floodplain, Test#3.

The same comparison has been done for the full-2D model, and yielded slightly better results: for test#3 the means error is -0.4mm, while the mean absolute error is 1.1mm. After calibration both numerical models provide satisfactorily match with measured physical model data.

5.3 5.3 FLOW PATHS AND VELOCITY DOWNSTREAM OF THE BREACH.

An important benefit of using a 2D model in the floodplain is the availability of velocities (and therefore flow paths), how these vary with changing conditions, and how they interact with flow obstacles (such as buildings).

The velocity and flow path of several tests have been compared (physical model, 1D-2D numerical model, and full-2D numerical model). An example for test#7 (breach on the left side of the river) is shown in Figure 6. The velocity vectors of the water passing through the breach in the 1D-2D model are perpendicular to the breach (spill), while in the full 2D model these are skewed in the direction of the river flow. Comparison with the middle picture shows that the full-2D model provides a better replication of the physical model observations. This is explained by the fact that in the full-2D model the transfer of water from the river to the floodplain is more realistic than in the 1D-2D model. As commented in Section 4.1.3, the transfer of water momentum between the 1D and 2D model is based on a modelling artifice [8], which uses some simplifications to estimate an initial water momentum for the 1D-2D boundaries (e.g. flow direction perpendicular to 1D-element, as seen on Figure 6).

It may be possible to modify the 1D-2D model in order to direct the flow through the breach in a given direction (e.g. porous wall), but the direction would need to be constant. Others tests have shown that the degree of the skew is dependent on the width of the breach and on the water level at the breach.

Further downstream from the breach (about 3m, which is equivalent to 300m in prototype scale), the floodplain flow patterns are controlled more by the topography and the urban layout and the results between the 1D-2D and full-2D model become similar, both match the physical model observation very well.

A qualitative assessment of velocities also shows that the full-2D model matches the physical model observations better than the 1D-2D model, especially around the breach.

6. CONCLUSION

A new set of flood plain data has been generated by extending the use of a physical model originally built for a consultancy project. Further analysis is underway and will complement these preliminary findings.

Complex local flow processes observed during the physical modelling in the channel were not reproduced accurately by the 1D model. However, reasonable calibration on individual scenarios could be achieved in the areas of interest. The 2D model of the channel captured more of these processes but did not result in a significant improvement in the overall calibration, potentially due to limitations on the mesh size.

The tests show that both the 1D-2D model linked through spills and the full-2D model provide broadly similar accuracy for flood depths once properly calibrated. The flow paths for both models also match observations well except in the vicinity of the breach area. A 1D-2D model appears therefore sufficient for most large scale studies were depth is the primary focus, or where the flooding is a slow process (less importance on momentum).

The testing also highlighted the poor representation of flow paths immediately downstream of breaches in the 1D-2D model. A full 2D model is needed in order to correctly replicate the transmission of water momentum during the spilling process at the breach location and the flow paths in the vicinity of the breach (required for estimating localised hazard).

Further tests will be carried out where the numerical model is re-run at prototype scale to investigate the magnitude of real world effects, to overcome the limitation of the numerical model at extremely small scale, and to allow an evaluation of the scaling effects from model to prototype scales and how this relates to the adoption of scaling laws typically adopted for this type of model (e.g. Froude laws for vertically exaggerated models).

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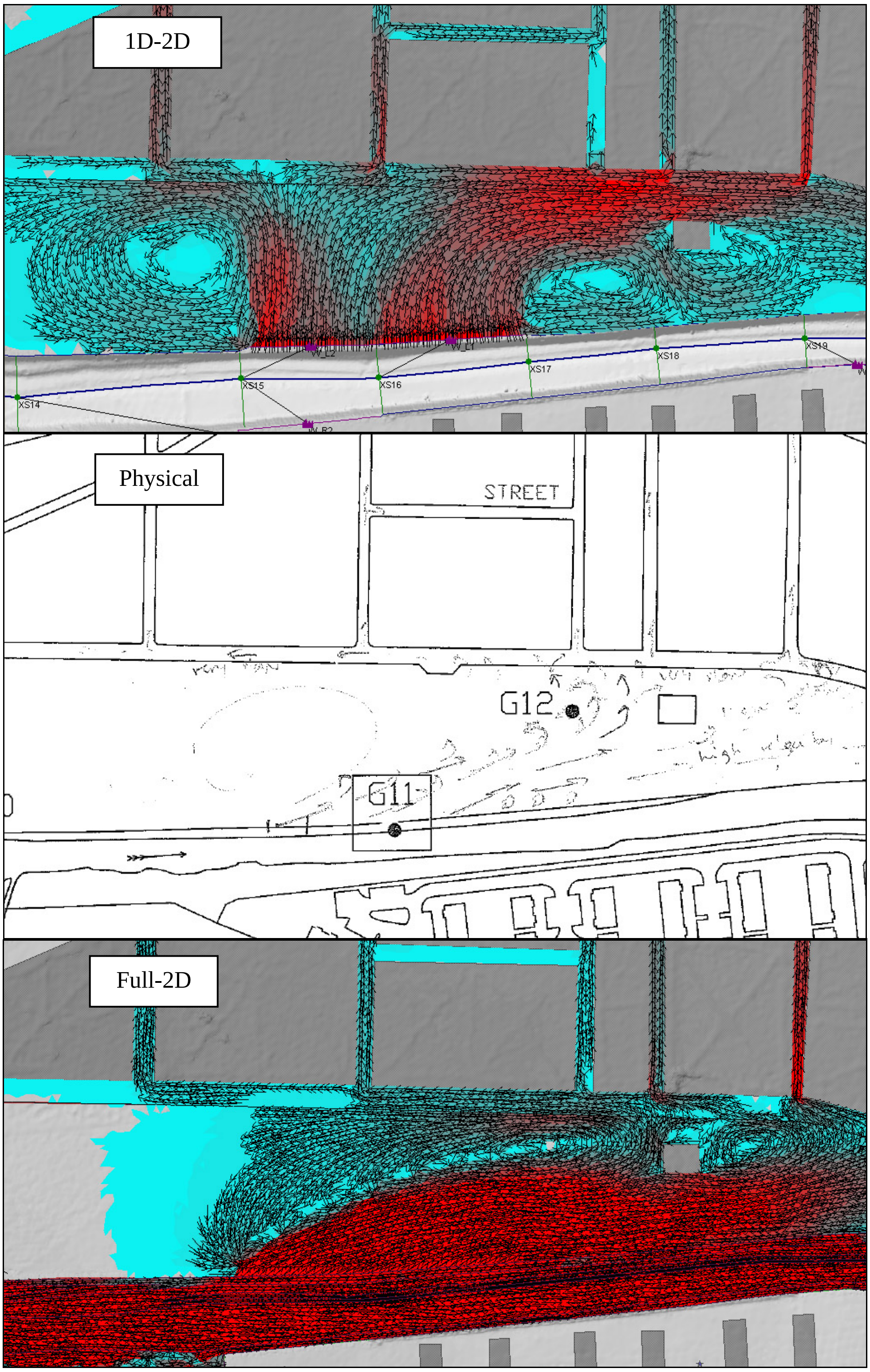

Figure 6: Comparison of velocity pattern between the 1D-2D numerical model (top), observed flow path sketch of the physical model (middle) and the full-2D numerical model. Arrows shows the direction of the flow, red background represents high velocity zones, blue background represents low velocity zones

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