Ground & Groundwater Conditions at Cork

Implications for the Lower Lee Flood Relief Scheme

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Foreword by Alistair Allen BSc PhD

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Cover Image: Map of Cork City c. 1870
Rear Image: Pacata Hibernia map of Cork (c. 1600)

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Summary

Cork’s distinctive geology and hydrogeology has not been adequately considered in the selection of parapet walls and cut-off measures as the preferred flood defence scheme. This situation is regrettable given widespread local knowledge that flooding in the city is derived both from the ‘open’ North and South Channels and from the ‘buried’ historical channels that flow under Cork’s streets. In addition, it is well established in academic literature and elsewhere that a shallow gravel aquifer has been a major factor in the city’s long history of flooding. The aquifer lies under the full width of the valley and is subject to tidal fluctuations. As a result, the chosen option has had to be modified extensively and continues to be associated with a high degree of uncertainty. The Supplementary Report on Groundwater (Arup 2017), which has now been prepared in response to submissions, represents a belated attempt to address the groundwater issue. It recommends additional measures including an unspecified groundwater pumping system that has introduced further complexity, cost and risk to the proposal.

New research has identified historical features that help to explain Cork’s vulnerability to flooding. The city is situated on an estuary where the natural drainage consisted of at least eight branching channels (anastomosing type). These channels survived from the preceding river environment, and as the city developed, were modified by the addition of crosscutting canals in the medieval (1090-1300s) and early modern (1500-1800) periods. In the eighteenth and nineteenth centuries, most of these historical waterways were placed in culverts. They are now part of the complex urban network of buried services that also include leaking water supply and drainage pipes. Therefore, the risk of flooding from subsurface sources would remain unacceptably high after installation of the flood-wall defences.

Under the layers of man-made filling, boreholes indicate that Cork City occupies a buried glacial valley, which has been filled with a succession of Quaternary sediments that exceed 50 m in thickness. A key feature of this valley is the tidally influenced, gravel aquifer, mentioned above. The high permeabilities measured in this aquifer, together with the good hydraulic connectivity between it and the surviving channels, are factors that have not been adequately addressed in the OPW proposal. As a result, the design does not demonstrate that surface water and groundwater flows in the city can be controlled during a flooding event. In addition, the proposal does not make sufficient allowance for the variable thickness of overlying silt, which only partially confines the underlying aquifer. It is understood, for example, that only one pumping test has been completed in floodplain areas that are away from the North and South Channels. Therefore, the likely impact of the groundwater dewatering system, proposed by the OPW to augment the walls option, is largely unknown.
It is considered that the proposed parapet walls, cut-off measures and groundwater dewatering system, would interfere with groundwater levels in the highly permeable gravels under the city. This is because sheet pile walls and other impermeable structures, extending below riverbed level, are likely to impede groundwater flow. Several consequences are likely. Firstly, the incidence of flooding is likely to be increased in areas of restricted groundwater flux. Secondly, where there is depletion of the aquifer (falling water table levels), there is a high risk of settlements and consequent structural damage to buildings in the centre of Cork City. A further complication is that confinement of groundwater, owing to the proposed cut-off measures around City Island, may also result in a reduction in groundwater quality in the gravel, which has been classified as a regionally important aquifer. In summary, installing cut-off walls and a groundwater dewatering system at Cork is an experiment in separating two interdependent surface water and groundwater systems, which is likely to fail.
Foreword

The following report by Tony Beese on the ground and groundwater conditions underlying Cork city centre and their implications for the OPW’s proposed Lower Lee Flood Relief Scheme, highlights the extreme heterogeneity and complexity of the subsurface based on a wealth of borehole information and numerous archaeological excavations. These subsurface characteristics control groundwater flow and behaviour within the city centre, and have a huge bearing on the viability of the flood relief scheme being proposed by the OPW. Tony Beese, whom I have known for over thirty years, is a highly experienced and competent geologist and is to be commended for the thoroughness of this report, and I am in full accord with the detailed subsurface geology he describes and with the conclusions and recommendations presented in the report.

It is useful to put the unique location of Cork, which has given rise to the subsurface characteristics of its city centre into context, by reviewing its geological setting. Cork city centre overlies a deeply weathered bedrock trench at the northern margin of the Cork-Midleton Syncline. The latter is a wide limestone valley that runs from west to east between Youghal and Crookstown. During the Pleistocene ice age, between 2.6 million and 11,700 ago, weaker bedrock types were preferentially eroded by advancing glaciers arriving from the north and west to form the deep trench that lies under Cork. Under the city, geophysical soundings have recorded depths to bedrock of more than 100 m. At the end of the ice age, when temperatures ameliorated and the glaciers began to retreat, meltwater filled this trench with variably rounded and sorted, but highly permeable sand and gravel. Subsequently, as sea level rose to its present level, deposition of the coarse sediment ceased, and transgression of the sea took place, resulting in deposition of the fine-grained and low permeability estuarine silt and mud at Cork city.

Thus, the River Lee floodplain, on which Cork city centre is situated, is underlain by the Lee Buried Valley with at least 50m proven depth of gravel and silt, the maximum depth of engineering boreholes. The margins of the buried valley are stepped, it is partially floored by highly karst-weathered and fractured limestone and it has an irregular floor with isolated pinnacles rising to 10m below ground level in places. Because of these marine and fluvial processes there is now a complex, heterogeneous character to the subsurface beneath Cork city centre, as highlighted in the following report. When combined with the subsequent modifications of the subsurface during the medieval and more recent development of Cork, this has given rise to the extreme variation and unpredictability in groundwater flow behaviour.
This unique geological setting has a major bearing on the viability of the OPW flood relief scheme. The scheme involves raising walls bounding the River Lee, installing cut-offs to depth below the walls and adding pumping stations to remove groundwater from behind the walls and cut-offs. None of these remedies are likely to be effective. The high walls would be unsightly, and would be ineffective, as there are many old unused sewage and sewer outlets into the River Lee, which have not been closed off and which back up during high tides leading to flooding of basements and cellars in city centre premises. In addition, it would be impossible and impractical to install cut-offs down to bedrock, nor could it be certain that solid bedrock encountered was not an isolated pinnacle. Furthermore, the fractured and karst-weathered limestone bedrock and adjacent and overlying gravels are in hydrological continuity.

Another factor mitigating against the OPW approach to flood relief in Cork city is that groundwater levels are controlled by the ebb and flow of the incoming and outgoing tides in the River Lee, which is estuarine as far west as the Cork City Waterworks, with maxima and minima of the water table corresponding closely with tidal maxima and minima, albeit with a slight time delay. It is the mass (weight) of the additional head of river water during incoming tides, which forces groundwater to move into the subsurface adjacent to the river, leading to water table rise in this adjacent ground. Cut-offs, regardless of the depth to which they are installed, would not prevent this groundwater forcing. Furthermore, installing pumping stations to dewater the subsurface behind the walls and cut-offs would also be totally ineffective in preventing flooding, as the pumped water would presumably be dumped back into the River Lee, where it would just add to the mass of river water forcing the water table to rise beneath the city. Thus, dewatering operations would not be viable and a considerable waste of money.

As indicated in the detailed report following, subsurface and groundwater conditions in Cork city centre have a major bearing on the viability of the proposed OPW flood relief scheme rendering it as impractical and a waste of taxpayer’s money. I fully endorse the following report by Tony Beese.

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1. Introduction

1.1 Scope of the Report

This report was requested by Save Cork City as part of an independent review of the Flood Relief Scheme that has been proposed by the OPW, Dublin. The report includes a reassessment of previous academic research by the author, detailed in the next section, and an overview of the available literature. The second part of the report is taken up by a critical discussion of the proposals put forward by the OPW in their Supplementary Report on Groundwater (OPW 2017).

1.2 Methodology

Review studies of the Quaternary deposits at Cork City have significance in urban planning and civil engineering. An initial project, part-funded by the Heritage Council and the Department of Archaeology, UCC, was completed between 2009 and 2012 (Beese 2012). The research was based on three main sources of evidence:

- Historical engineering boreholes
- The archaeological record
- Historical maps

The information arising from these sources was collated in databases and plotted on an Ordnance Survey map at 1:3,500 scale. The initial results from the Heritage Council study have now been updated to form the basis of this report. In addition, two chronologies have also been obtained. These comprise firstly, a stratigraphic chronology based on AMS radiocarbon dating (Beese 2014a) and secondly, a chronology for the land-claim and canal-building based on dendrochronology (Beese 2014b).

Historical Engineering Boreholes (1955-2012)

For fifty or sixty years, the assessment of ground conditions at Cork has been based on disturbed and undisturbed sampling in light percussion boreholes, traditionally referred to as ‘shell and auger’ or ‘engineering’ boreholes. Those organisations that have retained site investigation reports include the Geological Survey of Ireland; John O'Donovan and Associates, Consulting Engineers; Carraigex Ltd., Consulting Geologists; and Arup, Consulting Engineers, Cork. These overlapping archives have now been compiled and digitized by the author. It is estimated that the dataset includes most of the engineering boreholes that have been completed at Cork between 1955 and 2012 (Beese 2012).
The pilot area for this study (Figure 1) covers the central part of Cork City and is estimated to be 60ha in area. It extends across the full width of the floodplain and is defined by Dyke Parade to the west and St Patrick’s Street to the east. The archive comprises 113 site investigations and 242 engineering boreholes. Given the urban context, the large amount of data that was discovered was to be expected, and provides a confident basis for the deterministic modelling of subsurface geology (Beese 2017). For the purposes of modelling, the shallow strata, in order of increasing age, may be conveniently summarised as:

1. Made-ground (anthropogenic filling) dating from the medieval period.
2. Estuarine deposits of organic silt and peat (Cork Harbour Formation).
3. Fluvial deposits of sand and gravel (Ovens Formation).
The Archaeological Record (1970s to 2009)

The stratigraphy encountered in former archaeological excavations was also investigated (Beese 2012). The purpose of this study was to augment the borehole record. To date, records from fifteen of the monitored sites have been included in the database (Figure 2). At these sites, both anthropogenic and naturally formed strata were temporarily exposed. As well as providing subsurface data, the study helped to locate features such as channels and gravel bars.
Figure 3. Two examples of early modern maps used in interpretations of Cork’s former channels (Beese 2010): (a) the anonymous ‘Tower of London’ plan of Cork dated 1545 – the only version to survive is a lithograph copy by Peter Klasen (born c. 1817); (b) Extract from the military survey of the ‘Citty of Corke’ by Thomas Phillips, dated 1685 – this was the first scaled plan of the city.

Historical Maps (1545 – 1841)

As part of the initial study, historical maps of Cork were sourced and analysed (Beese 2010). Although the distribution of the old waterways and canals of the city is well preserved in the layout of modern streets (Johnson 2002), earliest surveys were not published until the mid-sixteenth century, some five hundred years after the first land-claim. Nevertheless, when historical maps were used in conjunction with subsurface borehole data (see Figure 9) and the archaeological record, it was possible to obtain a confident reconstruction of channels and later canals. Other historical documents relating to the former geography of Cork were also evaluated.
2. Waterways and Canal-Building in Cork

2.1 The Estuary

Some idea of the former character of the Cork’s intertidal wetland may be gained from historical documents. Even the city’s old Irish name, formally given as Corcach Mhór (na) Mumhan, or ‘big marsh (of) Munster’, drew attention to the awkward impasse caused by the estuary. The shortened name, Corcach appears in the Irish annals and in other documents such as the record of succession of the medieval abbots at St Fin Barre’s monastery. In Dineen’s dictionary, corcach, which is feminine, is glossed as ‘a moor, marsh, a low-lying swamp’, and it is likely that the word described a specific type of wetland because it is only one of several Irish words for bogs and related landscapes. Corcamore, or Corcach Mhór, in Co. Limerick, is similar in aspect. It was a large estuarine marsh, formed at the confluence of the meandering River Maigue and the River Shannon, but was reclaimed for farmland rather than settlement. Thus, the conclusion might be drawn that the monks at Cork lived adjacent to reed-swamps and tidal mudflats that were vulnerable to flooding but nevertheless were complicit in their development as a city.

The River Lee floodplain at Cork City is orientated approximately west to east according to the underlying bedrock geology (Figures 4 and 12). Thus, while the elevated ground on the north and south sides of the low-lying ground is formed from resistant bedrock types, the floodplain itself is defined by highly weathered rock, which has been eroded by successive glaciations to form a deep valley, and which is now filled with unconsolidated deposits of both glacial and interglacial (‘warm period’) origin. Thus, the course of the River Lee at Cork currently occupies a flat and narrow tract that separates ridges of sandstone/siltstone (Devonian) from limestone (Lower Carboniferous) to the north and south respectively. The width of the floodplain is variable because, the underlying bedrock has been dislocated by crosscutting faults, causing the bounding ridges to be offset along their edges. An average width of 500 m is estimated although there can be significant variation from this value. For example, the width of the floodplain between the lower ends of Shandon Street and Barrack Street reaches 750 m (Figure 4).

Within the city, this ribbon-like lowland extends for at least three kilometres, between the Salmon Weir, near Victoria Cross, where the River Lee divides into two channels, and the Port of Cork, where these channels rejoin (Figure 12). Thus, this portion of the floodplain is estimated to be some 200 ha in area. And although, the tidal range is reduced in the upper reaches of the city (Arup 2017, Figure 2), a significant mesotidal regime (defined as a tidal range between 2 and 4 m) is characteristic of the lower reaches of the city, near to the inner part of Cork Harbour. Critically, groundwater levels vary with the tides, albeit with a reduced range and delayed response.
The unit that immediately underlies the floodplain, and which therefore concerns us here, is a thin discontinuous layer of estuarine mud (see Sections 1.2 and 3). It comprises organic silt and peat that was deposited when the last marine transgression reached the locus of Cork City, between 6.2 and 5.6 thousand years ago (Beese 2014a). The inundation caused deposition of fine-grained sediment over the sand and gravel of the preceding environment, which was a fluvial valley. In archaeological terms, this means that the deposition of estuarine mud commenced at the locus of Cork in the late Mesolithic and early Neolithic periods.

A plan that shows a reconstructed view of the estuary is presented in Figure 4. It is based on the historical study described above (Section 1.2) and has been updated as new information comes to hand. The accumulating evidence demonstrates that some eight channels traversed the floodplain prior to Cork's first settlement in the late eleventh century. These natural waterways separated elongate marsh islands. Evidence from archaeology provides detail and shows that the intertidal environment at Cork was more complex because it included relict
gravel bars of fluvial origin, marginal reed-beds and exposed tidal mudflats (Beese 2014b). It appears, also, that the natural channels varied in scale from tidal creeks to navigable waterways.

A typical west-southwest to east-northeast trend for the secondary channels is apparent in the reconstruction, and contrasts with the west to east trend of the estuary itself and the primary North and South Channels along its margins. This divergence in geometry of the channels may be explained by the deflection of fluvial outflows by tidal inflows. Furthermore, the branching and sinuous nature of the estuarine channels provides topographical evidence for the sluggish flows in the former estuary, which persist today in the built environment. In simple terms, the formation of the estuary was the result of a confrontation between flows from the River Lee, discharging from its large catchment, and incoming tidal flows from Cork Harbour. In this way, the higher energy sand and gravel deposits of the preceding fluvial environment were overtaken by the deposition of organic silt and peat in an estuary.

Regional factors must also influence the potential for flooding in the River Lee. One hypothesis that has been put forward to explain the long history of flooding in the city is the variable width of its valley in between bedrock ridges (Figure 12) but there may be other causes. For example, it is possible that thick units of over-consolidated estuarine silt, which survive from an earlier interglacial estuary of probable Gortian age (Scourse et al. 1992, Figure 2; Coxon and Dowling 2015, Figure 17.1), may have played a significant role in the history of the city’s flooding. The preservation of these masses of impermeable silt near the mouth of the River Lee (Custom House Quay) and adjacent to deep gravels from the current interglacial period (Holocene), raises the possibility that the interglacial silt is restricting groundwater discharging from the gravel aquifer under Cork.
2.2 Modification of Cork’s Waterways (Canal-Building)

Ongoing research shows that the modification of Cork’s waterways began with an ambitious programme of canal-building during the medieval period (Figure 5), and continued in the early modern period with occasional excavation of more canals. These new waterways, which diverted and joined naturally formed channels, have created additional conduits for water during flood events. Many of the canals, which were used for navigation for ships, were relatively wide, while others were designed to facilitate smaller boats. For instance, in the eighteenth century, quay-lined canals at Grand Parade and Emmet Square exceeded 20 m in width, so that ships might berth on both sides. Historical maps indicate that the maximum development of canals occurred at this time (Figure 6). Soon afterwards, water transport came to be considered unfavourably and roads and bridges gradually replaced most of the canals and secondary channels. The change also came about because of the tendency for artificially formed waterways to clog up with silt and become un navigable.
Figure 6. Interpreted extent of canals and waterways in 1750s Cork.
Key as for Figure 4, land-claim is in orange and eighteenth century place-names are in italics.

The reclamation of Cork was accompanied by an attempt to raise ground levels by introducing filling. The main sources of this new material were silt excavated during canal construction, and refuse including food waste and building rubble. Eventually, river channels and canals constructed during the city’s development were placed in culverts or backfilled. The North and South Channels are the only primary waterways that have survived and these now run close to the margins of the River Lee floodplain (Figure 12).
Temporary excavations, opened during the Cork Main Drainage Scheme (1996-2005), intersected some of the historical waterways that lie just under street pavements. For example, archaeologists monitored a double-arched culvert extending west to east along Liberty Street. It was then possible to follow its course under the buildings of Paradise Place, under the terrace on the south side of Castle Street, and as far as Daunt Square (Power 1997). In addition, masonry walling, which may have been part of a quay, was exposed near the junction of South and North Main Streets (Figure 7a). Both these features are located along the course of the former ‘middle channel’, of which part was modified into an intramural harbour during the medieval period. An active north to south trending culvert of eighteenth century date was also uncovered at the northern end of Grand Parade, near Daunt Square, at the location of the former ‘eastern canal’ (Figure 7b). Clearly, the many waterways that lie under the city represent a significant source of flooding (see Section 3.1).
3. Engineering Geology and Hydrogeology

The unconsolidated sediments under the city date to the Holocene epoch (the second and last Quaternary time interval) and derive from succeeding glacial, fluvial, estuarine, and anthropogenic environments (for example, Davis et al. 2006, Beese 2012, 2018). Based on borehole evidence, this sequence has a thickness of at least 50 m. However, downstream of Custom House Quay there is a change in geology because much older interglacial muds survive. These date to the Pleistocene epoch, which is the first Quaternary time interval.

3.1 Made Ground (Anthropogenic Filling)

As would be expected, the made ground layer, or man-made filling, is markedly heterogeneous, comprising variably textured deposits (silt, sand, gravel, cobbles and occasional boulders) and including both inorganic and organic material. Reports from archaeological excavations (see Figure 2) and engineering excavations typically describe several metres thickness of filling that is dominated by domestic and building refuse (for example, see Cleary and Hurley 2003). Long et al. (2015) state that the made ground above estuarine silt, as observed in basement excavations, is often granular being composed of ‘rubble, brick and concrete fragments and ash’. Localized industrial deposits and contamination are also recorded. The introduced soils are usually layered, but owing to a long history of modification, are often disturbed and may be
discontinuous and irregular in form. In summary, both impermeable and permeable soils have been introduced as filling, beginning with the relatively impermeable organic mud that was excavated from channels and canals during the first land-claim in the medieval period (Beese 2012, 2014b).

It is not uncommon, therefore, in archaeological or engineering excavations, to encounter seepages of perched water (Figure 8), held up by relatively impermeable layers of introduced silt derived from the former estuary. Similarly, in engineering boreholes, several water strikes may be met at shallow levels, above the deeper level of the water table that marks the gravel aquifer. These seepages mark perched aquifers of small scale, and are expected to be derived from leaking services and storm-water runoff (Figures 13 and 15). These inflows percolate downward through the upper layers of made-ground, which are typically coarser, and therefore permeable. Indeed, urban water sources probably provide a significant volume of recharge to the underlying gravel aquifer (see Howard 2015, p. 2546). Allen (2007) estimates that 40% leakage from broken water supply pipes is equivalent to 26,000 m³/d, which represents significant ‘urban-enhanced recharge’ to the gravel aquifer. Part of this leakage derives from cast-iron water pipes and other services that have been corroded by brackish water intrusion. In conclusion, the variability of the top layer adds complexity to any proposal, and should be considered in groundwater models (see below). It has been recognised, for example, that for many cities the impact of anthropogenic filling on groundwater can be at least as important as the local geology (Howard 2015, pp. 2545-6).

### 3.2 Estuarine Deposits

The term alluvium¹, favoured by engineers, covers a wide range of generally fine-grained soils with low permeability. In the case of Cork City, the term has been attached to a layer of estuarine silt and peat that overlies the sand and gravel sequence. These organic sediments are now formally designated as the Cork Harbour Formation (Davis et al. 2006). In geological terms, this formation marks the marine transgression that replaced the preceding fluvial environment during the prehistoric period (Beese 2014a). Importantly, analysis of the thickness of organic silt and peat in historical boreholes shows that the distribution and thickness of these estuarine sediments is not uniform. Some 78 data points were obtained from borehole dataset and compiled as the deterministic model presented in Figure 9. In the analysis, there is no attempt to differentiate between organic silt/peat of estuarine origin and later medieval filling formed from the same material because both exhibit low permeability, and would therefore behave similarly during high water table events.

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¹ Alluvium is defined in the Oxford English Dictionary as ‘a deposit of clay, silt and sand left by floodwater in a river valley or delta, typically producing fertile soil.’ It is derived from the Latin, alluvius meaning ‘washed towards’.
A significant finding is that certain parts of the floodplain were never buried under estuarine silt (see also Figure 13). These areas, which are distributed near to the North and South Channels as well as upstream of the city centre, are coincident with slight rises in the gravel topography, interpreted as former fluvial bars and terraces. In addition, the resultant analysis shows that the thickest cover of estuarine sediment coincides with a deep palaeochannel lying between St Patrick’s Street and Oliver Plunkett Street. This elongate basin was filled with more than 6 m thickness of organic mud and peat. Thus, although the water table in the sand and gravel aquifer is partially confined for much of the Lee valley at Cork, in certain localised areas, it is unconfined and is, therefore, liable to fluctuate more widely owing to tidal forcing, or to an increase in the water table during flood events. All this assumes that the confining silt layer is integral and has not been fractured by urban structures such as piles, basements, boreholes and other structures.
3.3 Fluvial Sand and Gravel

This unit is now formally assigned to the Ovens Formation (Davis et al. 2006). The view that the thick sequence of sand and gravel is heterogeneous (Scourse et al. 1992, Long and Roberts 2008) is confirmed by observations of temporary excavations for basements and by borehole analysis (Beese 2018). Sedimentary structures and reconstructions of the topography of the subsurface gravel point to deposition by an anastomosing river system with branching channels and gravel bars. The borehole record indicates that individual beds range from fine to coarse sand, to sand/gravel mixtures, to gravelly cobbles. For example, based on samples recovered at Custom House Quay, Scourse et al. (1992) describe sedimentary units there as ‘poorly sorted gravel with sandy matrix’, ‘pebble gravel’, and ‘poorly sorted cobble-gravel within a matrix of pebbles and sand’. Unsurprisingly, the variation in sediment type is often associated with a variation in situ strength values (see Long and Roberts 2008).

It is now widely accepted that Cork is underlain by a partially confined gravel aquifer (see Section 3.2), and that this aquifer is (a) shallow, and (b) tidally forced. The term ‘gravel aquifer’ is used for convenience in hydrogeology, but in practice, includes saturated sand as well as gravel. Thus, in a typical engineering borehole, taken down through the estuarine silt layer, the water level rises as soon as groundwater is struck at the top of the sand/gravel layer. Subsequent monitoring of the water level invariably reveals fluctuations that match the tide cycle, although with some degree of lag. Based on measurements in monitoring boreholes, Arup (2017, page A9) have shown that the inference that the direction of groundwater flow follows surface water patterns is correct. Thus, the movement of groundwater is downstream, from west to east along the Lee River valley (Figure 12).

Historical observations made in pumping tests at eight sites along the Lee Valley (Long et al. 2015, Table 2) demonstrate that the intrinsic permeabilities for the sand/gravel aquifer are consistently high and typical of well sorted sand and gravel (Fetter 1988, page 80). Values range from $4.4 \times 10^{-4}$ to $4.8 \times 10^{-3}$ m s$^{-1}$, and similar permeabilities are understood to have been obtained in the boreholes completed for the OPW (Arup 2017). Given that permeability relates closely to hydraulic conductivity ($K$), then the transmission capacity of the gravel is estimated to between 38 m/d and 380 m/d. However, these figures are not groundwater flow velocities, which being much slower than surface water flow velocities, are expected to travel only a few meters per day. It is proposed here, that a primary cause for the variation in measured permeabilities is the variable sand and gravel content of the fluvial sequence. In any case, the close correspondence between the tidal cycle and variations in the water table confirm that there is clearly good hydraulic connectivity between the surviving river channels and the gravel aquifer. According to Arup (2017, page B9), the gravel aquifer exhibits between 50 and 90% of tide response. It appears from these high values that groundwater flows are most active in the upper few metres of the aquifer (Arup 2017). As Allen and Milenic (2003) state, the highly permeable nature of the gravel under Cork means that the aquifer itself is likely to flood, and that construction of subsurface structures can be problematic (Section 4).
3.4 Peat and Silt Interbeds within the Fluvial Sand and Gravel

Preliminary analysis of the borehole archive for Cork demonstrates that approximately one quarter of site investigations intersected peat or organic silt interbeds within the sand and gravel. This figure, which is significant, is nevertheless approximate because it is based on both preliminary driller’s descriptions and geotechnical reports. The organic interbeds occur near the top of the fluvial sequence, typically at elevations of between −2.5 and −6.5 m OD Malin Head (Figures 10 and 11), and must be laterally discontinuous given their scattered distribution. The typical thickness of layers is between 0.1 and 0.6m, although in a few cases, interbeds of more than 1m thickness have been encountered.
Initial appraisal shows that the peat and silt seems to be associated with shallower gravel areas, and especially along the North Channel. In contrast, the occurrences of these interbeds in the silt-filled basin to the southeast of the study area are few (Figures 9, 10 and 13). The relative absence of the interbeds in this area suggests that the upper part of the sand/gravel sequence was eroded by the marine transgression. However thick peat interbeds have also been recorded near Liberty Street, where the top of the subsurface gravel is relatively deep. The problematic nature of these compressible interbeds is discussed in Section 4.4.
4. Potential Impacts of the OPW Plan for Cork City

Based on the above discussion, Cork may be summarised as being impacted by a combination of five flood sources (see Figures 13):

- tidal (elevated tide levels and storm surges)
- fluvial (main river and ordinary watercourses)
- groundwater
- services (historical watercourses, surcharged drains and leaking water mains)
- surface water

The evidence of geography, engineering geology and hydrogeology indicates that these sources interact with each other.

Eight design elements are outlined in the OPW reports and in subsequent revisions (for example, Arup 2017, pp. 5-6). These are summarised below. The numbering is that of the author:

1. Flood forecasting system.
2. Revised dam operating procedures.
3. Creation of ‘washlands’ to periodically contain flood water.
4a. Direct defences (parapet walls and embankments).
4b. Deep cut-off measures associated with the direct defences.
5. Demountable barriers on some quays and most bridges.
6. A flow-control structure at the head of the South Channel.
7a. ‘Back of the wall’ drainage.
7b. Pumping stations (for drainage and groundwater).
8. Non-return valves at every drainage outfall to the river channels.

The proposed construction of parapet walls (No. 4a) is not a simple measure and cannot be considered in isolation. Implementing parapet walls, which represents a step towards canalization of existing channels, means that supporting design elements would be necessary to counteract groundwater and other flood sources (see Sections 4.2 and 4.3). The additional elements include deep cut-off measures taken down to below riverbed level (No. 4b) and some forty pumping stations (No. 7b). It appears also that the pumping stations would house more than one hundred surface water pumps to maintain the ‘back of the wall’ drainage (No. 7a).

Exhibition drawings (Arup 2016) provide examples of the different cut-off measures that are proposed along both sides of the North and South Channels (Appendix 1). Sample sections show (a) sheet pile walls to the front of the quays with associated backfill; (b) concrete-filled trenches behind the quays with associated grouting; and (c) combined stitching and grouting of existing quays and soil backfill. The formation depth of these modifications, however, is not shown on the drawings, but it appears that where grouting and related measures are proposed, they would extend down to or below riverbed. Where sheet pile walls are proposed, the
measures may extend to significant depths, and perhaps more than 3 or 4 m below riverbed. Thus, the measures would for the most part intersect the top of the sand and gravel layer (see Figures 9 and 13), and consistently interrupt the flux in the tidally forced gravel aquifer. Consequent changes to structural stability, water table levels and groundwater quality are discussed further below (Sections 4.4 to 4.6).

As an aside, it should be noted that one of the problems with driving of sheet pile walls in a historic city underlain by estuarine mud is that the vibrations, which are set up during installation, can cause cracking in old buildings (see Section 4.4). One solution is to complete pre-bored holes, and incur extra costs. Interestingly, prebored holes have already been specified in the city, during construction of the deep basement at Half Moon Street (Long et al. 2015).

4.1 The Risk of Flooding from Subsurface Watercourses

As discussed above in Section 2.2, a historical system of estuarine channels and canals now lie buried under Cork’s streets and buildings. It appears, also, that most of these old waterways were placed in culverts rather than being backfilled, and, therefore, remain active, connecting into the discontinuous and extensive system of local and private drains in the wider Cork district (Allen 2007, Cork City Council 2018). This complex network then feeds to interceptor drains installed as part of the Cork Main Drainage (CMD) Scheme in 2005. During high river flows and/or high tide elevations, there is a high risk of flooding owing to ‘sewer surcharge’ from these conduits, which are also joined to the two main channels of the River Lee. Harley (2018, page 2) describes how ‘back-flooding’ occurs when secondary channels become blocked by incoming tidal flows. Interaction between tidal flood and ‘sewer flooding’ has been frequently observed at Cork and is a feature of many coastal towns.

This system of interconnected rivers, waterways and drains is interpreted as being closely allied with groundwater movement. For example, it is proposed that seepages from the gravel aquifer are probably discharging into the North and South Channels, and to the buried historical channels (Section 4.2 below). This finding is based on the correspondence between individual channels (Figures 4 to 6) and unconfined portions of the gravel aquifer (Figure 13). The latter areas occur where the subsurface gravel topography is more elevated (typically as gravel bars) so that the overlying silt is absent (Figure 9). Thus, groundwater-fed river flows, or ‘gaining rivers’, are predicted for modern and historical channels at the following locations:

- Western Road/Dyke Parade/Grenville Place
- North Gate Bridge/Coal Quay/Emmet Place to St Patrick’s Street
- Sullivan’s Quay
4.2 The Risk of Groundwater Flooding

Following on from the preceding section, there is likely to be significant leakage from the underlying aquifer when the water table is elevated. Thus, there is a high risk of flooding across the full width of the Lee Valley. It needs to be emphasised that groundwater flooding would affect all the area underlain by the gravel aquifer, which includes not only ‘City-Island’, but also marginal ground to the north and south of the channels of the River Lee (Figures 12 to 14). This is a key point because it means that the ‘walls’ option is likely to become increasingly redundant, owing to the impacts of climate change and sea-level rise.

Figure 12. Map of the River Lee valley (Ordnance Survey of Ireland https://geohive.ie) showing the extent of the gravel aquifer in orange, as defined by areas of the floodplain that are underlain by alluvium (Geological Survey of Ireland 1905).

The long history of groundwater flooding in urban Cork has now been established (for example, see Allen 2007, p. 41) and is accepted by Arup (2017, p. 1) in their Supplementary Report on Groundwater.
Figure 13. Schematic cross-section showing hydrogeological units and urban water systems.

Key:

1. Anthropogenic filling (perched aquifers).
2. Estuarine silt and peat (aquitard).
3. Saturated sand and gravel (major aquifer, partially confined).
5. Sandstone and siltstone bedrock (minor aquifer). Note vertical exaggeration.
Blue arrows show flood sources and recharge.
MHWS = mean high water springs.
LW = water table at low tide (observed).
FWL = flood water level.

4.3 Problems with Dewatering of the Gravel Aquifer

In the same report, Arup (2017) propose ‘pumping stations’ that would facilitate drawdown of the water table at times of flood. However, dewatering of the gravel aquifer is often problematic because of its generally high permeability (Section 3.3). Allen and Milenic (2003) note, for example, that wells need to be sited close together to achieve the drawdown required in deep excavations with a large footprint. Indeed, a comprehensive study of dewatering for basements in the city (Long et al. 2015) has shown that permeability decreases with depth, a result that is not unexpected given that horizontal permeability is typically greater than vertical permeability for sand and gravel deposits (see Fetter 1988, p. 227). Long et al. (2015) conclude that sufficient drawdown is more easily achieved by extending cut-off measures (for basements) to more than -10 m OD, which is a considerable depth. This guidance elevation indicates that there is some degree of layering in the aquifer, and the view is that an upper unit of ‘medium dense sandy gravels’ (Long et al. 2015) with very high permeabilities (Long and Roberts 2008), overlies a lower unit of ‘dense gravels’ with lower permeabilities. Geophysical surveys, which formed part of the same study, confirm the interpretation.
It is understood that forty pumping stations have been proposed to maintain the city drainage network, and that these are intended to double as a groundwater dewatering system. The proposal appears to include bored wells and/or chambers, whose purpose would be to counteract the rising water table in the aquifer (Arup 2017). However, a comprehensive investigation with pumping tests has not been completed. In fact, it seems only one test well has been constructed away from the North and South Channels (Arup 2017, page A2), at Christ Church. Thus, the current design represents a largely experimental approach to controlling groundwater flooding, and is likely to be inadequate because of the high permeabilities measured in the gravel aquifer. Based on this fact alone, it would be expected that any dewatering programme would require a network of many boreholes located at closely spaced locations. Indeed, dewatering boreholes would need to be located across the full width of the River Lee valley rather than close to the North and South Channels alone, as presently envisaged.

Efforts to model groundwater behaviour during dewatering for a network of boreholes distributed over a large area can only be approximate because of the many variables that must be considered (Appendix 3). Some of the more important factors that would affect the rate of drawdown are as follows: (i) whether the aquifer is confined or unconfined; (ii) local variations in permeability; (iii) the degree of interaction in between boreholes during pumping (Miracapillo 2007); (iv) the amount of indirect recharge from leaking water supply pipes and drains; (v) whether there is additional recharge from the karst-weathered limestone aquifer; and (vi) the depth of the pumping system, pumping rate, location of outflow, etc.

It is worth pointing out that the model advanced in the Arup report (2017, Figure 4) assumes that the made ground layer (anthropogenic filling) is uniformly fine-grained, and therefore would act as a confining layer in the case of a rising water table. However, previous research shows that this interpretation is incorrect, and that instead the filling is heterogeneous and comprises a range of sediments that would both act as local aquifers and aquitards (Section 3.1, Figures 13 and 15). Furthermore, the use of the software SEEP/W to model dewatering of the gravel aquifer under Cork (Arup 2017) is not appropriate because it was designed to forecast groundwater behaviour for pumping wells established on a much smaller scale, for instance in the case of an individual structure. A letter from software providers, Geoslope International Ltd., which supports this opinion, confirms that their software is not capable of modelling complex three dimensional groundwater systems. In summary, there is a distinct experimental or ‘adaptive’ approach to the proposal that is likely to require modification.
4.4 The Risk of Settlements in Adjacent Buildings

Long et al. (2015), in their review of the dewatering experience in Cork, highlight the risk of potential settlement in nearby buildings owing to consolidation of estuarine mud and peat (alluvium). As already discussed, these compressible sediments are widespread and both overlie the gravel and are present as interbeds within it (see Figures 9 and 10). Since the amount of consolidation of peat and silt/clay is proportional to its moisture content then dewatering can lead to settlement of structures where these materials provide support to foundations. The authors recommend that, even though some of the ‘alluvium’ may be slightly over consolidated, only minimal external drawdown should take place during the construction of basements (see also Long and Roberts 2008). One way to achieve this is to construct recharge wells to maintain groundwater levels, but this incurs significant extra cost. In any case, each borehole would be associated with a ‘cone of depression’ during pumping, which may, of course, intersect the estuarine mud or the peat/silt interbeds. Consequently, there would be a high risk of settlements in adjacent buildings given the extensive nature of the dewatering scheme that would be necessary to control flood levels at Cork (see Section 4.3 and Arup 2017).

O’Kane (2017, p. 13) has already raised the issue of the risk to old buildings owing to any modification of the groundwater regime. It is expected that many of the historical buildings in Cork are supported at shallow levels by ‘traditional’ foundations. This is clear from the degree of movement that can be observed in the walls and floors of multistorey terraces and the poor structural condition of some properties. In a few cases, buildings underlain by weak ground have collapsed, including part of the terrace on the south side of Castle Street, which failed in August 2009. Interestingly, archaeological monitoring indicates that one of the culverts that carried the former ‘middle channel’ was located under the terrace. In summary, dewatering should be avoided, or at least very carefully considered, to avoid unacceptable movements in structures.

4.5 The Risk of Water Table Decline and Rise

The installation of the proposed cut-off measures would have two impacts. The first is to effectively canalise the two main channels, and the second, is to partially dam the shallow portion of the gravel aquifer. Thus, the deeper that the sheet pile walls are inserted into the sand and gravel layer, the more that the aquifer under ‘City Island’ would be isolated from those parts of the aquifer that lie outside the North and South Channels (Figures 12 and 14). As already discussed, the most permeable portion of the aquifer, where west to east flows are likely to be strongest, is within its upper part (Section 3.3). Miracapillo (2007) has described a case of an underground structure that permanently modifies groundwater flow. The structure, which is in Basel, Switzerland, consists of a bank wall beside the Rhine, which forces the groundwater flux to redirect. He interprets water table rise upstream of the structure and ‘death zones’ of immobile groundwater elsewhere.
Consequently, the cut-off measures proposed at Cork would add uncertainty to the impacts of the proposed scheme. One scenario is that in the short term, the recharge area would be reduced in size, with resultant aquifer depletion and falling groundwater levels. This in turn would lead to an increased risk of settlement to overlying structures (see Section 4.4).

Figure 14. Model showing restricted groundwater flows in the upper gravel aquifer after installation of proposed cut-off measures.

In the long term, however, the water table under City-Island may begin to rise, owing firstly, to ‘urban-enhanced recharge’ from surface water, and secondly, to the large volume of leaking water issuing from pipes in Cork (Section 3.1). In other cities, areas of ‘urban karst’, which is defined as cracks in roads, pavements and hard standings (Howard 2015, p. 2545), can facilitate recharge. One critical location would be where the North and South Channels join at Anderson’s Quay/Lapp’s Quay/Custom House Quay. Partial damming by using cut-off walls in this downstream location (Appendix 1, No. 4) would form a closure (Figure 12) that would reduce the aquifer’s capacity to discharge into the estuary below the city. Consequently, it is expected that there would be water table rise and increased risk of flooding in the lower reaches of the city. Admittedly, much of this scenario is speculative but it is used to illustrate how the cut-off measures would permanently modify groundwater flow in the gravel aquifer. Thus, the cut-off measures would introduce uncertainty and risk into the proposal and have not been adequately assessed.
The existence of deep basements may add to the problem, especially where the basements are situated close to cut-off measures. These structures extend to depths of up to 10m (-7.5 m OD) and may be considered as ‘vertical impermeable walls’ (Miracapillo 2007) penetrating deep into the gravel aquifer. Near the city centre, the width of the gravel aquifer has already been reduced by a third owing to deep basements at Half Moon Street, Opera Lane, Dunnes Stores and the Grand Parade Car Park (Figure 14). Other locations, where there has been a significant reduction in aquifer width owing to basements, can be found both up- and downstream of this location. It is understood that the potential impact of the increasing number of basements on the groundwater flows under the city has yet to be researched, and no mention of these structures are included in the Supplementary Report by Arup (2017).

4.6 The Potential for Contamination of the Groundwater Resource

The Geological Survey of Ireland (2018) have classified the gravel aquifer at Cork as a regionally important aquifer (Rg). Their assessment of the vulnerability rating for the groundwater resource is ‘moderate’ (M) or ‘high’ (H). Recent studies (Allen 2007) have shown, however, that the quality of the aquifer has already been compromised. Examples of contamination are some brackish water intrusion and exfiltration from sewers. Nevertheless, the sustainability of urban water quality is a matter of worldwide concern (Howard 2015). Therefore, the objective must be to preserve the groundwater under the city, so that it is available to be used as a resource. In any case, degradation of aquifer quality also means pollution in zones of discharge (Sections 4.1 and 4.2) such as along gaining streams and in the waters of the inner harbour.

Following on from the previous discussion (Section 4.5), redirection of groundwater flows in the upper, active portion of the aquifer by cut-off measures constructed around City-Island (Figures 12 and 14) may lead to a build-up of contaminants from sewers, etc. This partial damming of pollutants is most likely where permeability is greatest (Section 3.3). It is recommended, therefore, that baseline monitoring of water quality is undertaken in the three tide response zones identified by Arup (2017).
5. Conclusion and Recommendations

The opinion presented in this article is that the complex ground and groundwater conditions at Cork have not been adequately assessed in the OPW proposal. The Supplementary Report on Groundwater, which was submitted at a late stage, was prepared when the ‘walls option’ had already been selected. Its findings are incomplete and reliant on an oversimplified conceptual model, which does not take account of the available evidence. It is clear, for example, that there is a high degree of hydraulic connectivity between the gravel aquifer and its associated channels, both open and buried. It is significant, therefore, that many of the design elements would interfere not only with the highly permeable gravel aquifer under Cork City, but also with the associated tidal channels, by introducing cut-off measures and groundwater pumping stations. In addition, the model presented in the Supplementary Report is based on an unsuitable software package and introduces an unspecified groundwater pumping design, which is untested and unproven at the city scale. It is important to remember also that Cork represents a complex, densely urbanised environment (Appendix 3) and that the proposed scheme would introduce much uncertainty and risk to existing structures.

It is recommended that the OPW and their agents undertake a more detailed assessment of the geological and hydrogeological impacts, issues and risks, prior to making any decision to proceed with the ‘walls’ option. This assessment should cover the full width of the River Lee floodplain, which is underlain by the gravel aquifer, rather than being confined to locations along the North and South Channels. A revised assessment should be completed and include the following investigations:

1. **Review** the available geological and hydrogeological information for Cork.
2. Analyse **historical engineering boreholes** for the whole of the city, extending from Victoria Cross to the Port of Cork (Figure 12). Provide plans of the subsurface geology and hydrogeology for this area.
3. Complete a **historical study** to identify different flood sources in the city. For a preliminary evaluation, interview property owners and review newspapers to establish the oral history of previous floods. There are numerous anecdotal reports of ingress of water into urban basements, inflows from surcharged sewers, and water rising within buildings from cracks in floor slabs, etc.
4. Complete **further site investigations** to determine unknown geology and hydrogeology.
5. Determine whether appropriate software is available to **model** groundwater behaviour (qualitatively and/or quantitatively). The software should also model the likely impacts of the proposed walls, cut-off measures and groundwater pumping system, and should be based on new information that is available. It needs to be emphasised that there were fundamental errors in the first model (Arup 2017), which assumed, for example, that the anthropogenic filling layer was uniformly fine-grained and, therefore acts as a confining layer, and that there were no historical channels under the floodplain (Appendix 3).
6. Undertake a qualitative and quantitative risk assessment to assess uncertainties such as (a) groundwater flooding; (b) decline and rise of the water table owing to partial damming by the proposed cut-off measures; (c) structural settlements owing to water table decline, dewatering and vibrations; and (d) degradation of water quality in the groundwater.

7. Assess the scale of deep basements in the city, and interpret how these subsurface developments are inhibiting groundwater flows. Also assess the combined impact of basements and the proposed cut-off measures.

8. Develop the detailed design and cost of the proposed groundwater pumping system.

9. Reassess the flood defence options for Cork, once the impacts, costs and risks for the ‘walls’ scheme are fully understood and quantified.

In conclusion, based on this overview of the ground and groundwater conditions at the city of Cork, the proposed ‘walls’ scheme, which is designed to control the complexly interactive flood sources that are present in the River Lee valley, is not viable. It is to be expected that the residual risks associated with any implementation of the scheme would result in excessive costs and long-term disruption, especially given the urban context.
### 6. Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>aquifer</td>
<td>bedrock or sediment (gravel, sand, silt) that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs. A confined aquifer is overlain by a confining bed that has significantly lower hydraulic conductivity than the aquifer. An unconfined or water-table aquifer is characterised by the absence of confining beds between the zone of saturation and the surface.</td>
</tr>
<tr>
<td>aquitard</td>
<td>a low permeability unit that can store groundwater and transmit it slowly from one aquifer to another.</td>
</tr>
<tr>
<td>AMS radiocarbon dating</td>
<td>the determination of the age of an organic object from the relative proportions of the carbon isotopes carbon-12 and carbon-14 that it contains. The AMS method uses Accelerator Mass Spectrometry.</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>relating or denoting the fifth period of the Palaeozoic era, between the Devonian and Permian periods.</td>
</tr>
<tr>
<td>culvert</td>
<td>a tunnel carrying a river, stream or open drain under a road.</td>
</tr>
<tr>
<td>dendrochronology</td>
<td>the science of dating events, environmental change, and archaeological artefacts by using the characteristic pattern of annual growth rings in timber and tree trunks.</td>
</tr>
<tr>
<td>Devonian</td>
<td>relating or denoting the fourth period of the Palaeozoic era, between the Silurian and Carboniferous periods.</td>
</tr>
<tr>
<td>estuary</td>
<td>the tidal mouth of a large river, where the tide meets the river.</td>
</tr>
<tr>
<td>filling</td>
<td>anthropogenic or man-made layers that have been introduced.</td>
</tr>
<tr>
<td>floodplain</td>
<td>an area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.</td>
</tr>
<tr>
<td>Holocene</td>
<td>relating to or denoting the present epoch, which is the second epoch of the Quaternary period and followed the Pleistocene. A temperate stage that is also, referred to as ‘postglacial’. We live in the Holocene. From 11,700 years ago to the present.</td>
</tr>
<tr>
<td>interbed</td>
<td>(of a stratum) be embedded among or between others.</td>
</tr>
<tr>
<td>made ground</td>
<td>an engineering term for man-made filling or anthropogenic layers.</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>relating to or denoting the first epoch of the Quaternary period, between the Pliocene and Holocene epochs. From 2.6 million to 11,700 years ago.</td>
</tr>
<tr>
<td>Quaternary</td>
<td>relating or denoting the most recent period in the Cenozoic era, and including the Pleistocene and Holocene epochs. From 2.6 million years ago to the present. A period with successive ice ages.</td>
</tr>
</tbody>
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Note: The Glossary of Terms includes terms such as aquifer, aquitard,AMS radiocarbon dating, Carboniferous, culvert, dendrochronology, Devonian, estuary, filling, floodplain, Holocene, interbed, made ground, Pleistocene, and Quaternary. These terms are defined in the context of ground and groundwater conditions at Cork, with implications for the Lower Lee Flood Relief Scheme.
7. Sources of Information


Beese, A. 2014a. Preliminary radiocarbon dating indicates that the marine transgression reached the locus of Cork in the Late Mesolithic or Early Neolithic (between 6.2 and 5.6 ky BP). IQUA Newsletter. No. 53.


O’Kane, J. Philip. March 2017. A pre-emptive value-for-money audit of the WALLS project: proposed by the Office of Public Works, etc. Opinion for Save Cork City.


Appendix 1: Sample sections through North and South Channels showing the proposed cut-off measures (Arup & OPW, 2016)

1. Tyndall National Institute to Grenville Place: proposed sheet pile wall in North Channel with backfill to front of existing quay wall (Sections CIW-16 and 17) (Arup & OPW, 2016).
2. Pope’s Quay East to Camden Quay: proposed grouting behind existing quay wall (Sections NNC-13 and 14) (Arup & OPW, 2016).
3. Lavitt’s Quay East: proposed mass concrete wall, insertion of stitching bars, and grouting behind existing quay wall (Sections CIE-8 and 9) (Arup & OPW, 2016).

4. Albert Quay West: proposed sheet pile wall to front of existing quay wall, with tie-back anchors through quay wall (Sections SSC-3) (Arup & OPW, 2016).
Appendix 2: Correspondence

A. Letter concerning the software Seep/w

The following email extract is from Marc Lebeau, Research and Development engineer with GEOSLOPE International Ltd. It is in reply to John Morehead, who enquired about the validity of using the software SEEP/W to model groundwater conditions under Cork City (Arup 2017). The email was sent on May 16th 2018 from Marc Lebeau at Geoslope International Ltd.

Hi John,

This is a very interesting and complex problem. Although the software is mostly designed for modelling groundwater flow at specific sites, such as excavations, dams, and ponds, it can also be used to model groundwater flow in confined aquifers at the local scale. Yet, as it stands, it cannot be used to model groundwater flow in complex three-dimensional groundwater systems. We are, however, working on a three dimensional version of the software, with a planned release in the last quarter of this year. This new software could be used to model your problem, but it will require significant computational resources.

I hope this answers your question. Please don’t hesitate to reach out with any other question or comment.

Kind Regards,

Marc

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Upcoming Public Workshops:
May 23-25, 2018 in Bangkok, Thailand
May 24-26, 2018 in Rio de Janeiro, Brazil
June 25-27, 2018 in Madrid, Spain
September 13-15, 2018 in Pretoria, South Africa
September 17-19, 2018 in Pittsburgh, USA
B. Letter to the Newspapers

A copy of a letter from the author, and published in the Irish Times on Monday, 20 March 2017, is presented below. The letter, which was also published in the Irish Examiner on Saturday, 18 March 2017, comments on the archaeology and history of reclamation in Cork and raises the issue of difficulties with engineering developments because of the city’s geology and hydrogeology:

Cork’s underlying problem

Sir, – The decision by the OPW to opt for unsightly parapet walls, in order to counter Cork’s flooding problems, has become controversial. No wonder, for it seems to be driven mostly financial considerations that are only valid in the short term. It seems, also, to be an overreaction to the major, and partly avoidable, river flooding of November 2009, and the subsequent refusal by insurance companies to continue to indemnify those unfortunate citizens who suffered damage.

But the history of the city’s vulnerability stretches much further back than the disastrous events of 2009. Indeed, much of Cork’s charm derives from its peculiar situation “in between two channels” of the Lee – idir dhá shruth! It was only in the 11th and 12th centuries that its first canals could be dug, and the mud, which was cut from them, dumped onto the marsh without being washed away. And like other medieval ports, as Cork grew, it continued to suffer inundation; frequently becoming trapped in between rising sea level and excessive river flows.

And angry cries of “obfuscation!” by Cork Business Association against the scheme’s opponents, do not respect an issue that is far from simple. In my own area of expertise, I know of one major factor that has not been addressed. What is the impact of modern basements on flooding potential? These deep structures continue to be built under new developments in Cork despite the fact that they obstruct groundwater flow in the underlying gravels. Like toy ducks floating in a child’s bath, if you push the ducks down with your hand, then the water level rises!

Surely, the city needs corrective measures that firstly, do not pretend to rid us of an ancient problem, and secondly, that are based on wider perspectives? Cork deserves better. – Yours, etc,

Dr ANTHONY BEESE,
Consulting Geologist,
CORK.

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Appendix 3: A qualitative model for assessing flood risk in the urban environment of Cork

The factors that are relevant to assessing flood risk in Cork City can be represented in terms of mathematical variables. Eleven variables are shown in Figure 15. This cross section is adapted from Figure 13, which showed typical hydrogeological units and urban water systems at Cork, together with likely groundwater and surface water movements.

![Figure 15. Schematic cross-section showing flood risk factors in the urban environment at Cork.](image)

Key as for Figure 13 except: T = tide cycle (springs), T<sub>S</sub> = tidal surge, F<sub>1</sub> = fluvial flow in the North Channel including tributary streams, F<sub>2</sub> = ditto for the South Channel, F<sub>H</sub> = fluvial flow in historical channels, G = groundwater, S<sub>U</sub> = surface water recharge from urban ‘karst’ (cracked pavements) and green areas, R<sub>U1</sub> = recharge from leaking water mains, R<sub>U2</sub> = recharge from surcharged drains, R<sub>L</sub> = recharge from karst-weathered limestone, P = perched aquifers (locally developed).

Preliminary assessment indicates that any quantitative analysis appears to be impossible because the scale of risk for certain parameters such as F<sub>H</sub>, S<sub>U</sub>, R<sub>L</sub>, and P, is unknown. In addition, the number of permutations for Cork are obviously large and location dependent. For example, risk assessments for those low-lying parts of the city that are most vulnerable to tidal flows and surges should be separated from assessments of upstream areas that would be impacted first by fluvial flooding. Similarly, analysis of areas underlain by the unconfined gravel aquifer, and where G may be significant, should be separated from analysis of areas underlain by the confined gravel aquifer, where variables such as P, S<sub>U</sub>, R<sub>U1</sub> and R<sub>U2</sub> may be significant. In addition, the scenarios for the maximum and minimum tides is different. Areas with relatively shallow limestone bedrock (R<sub>L</sub>) may need to be assessed and so on. It is likely that a series of two-dimensional models would be necessary to cover both the upstream and downstream parts of the city.
The following are examples of some of the questions that need to be addressed in models:

Q1. In those parts of the city underlain by estuarine mud (unit 2), is the contribution to flooding from shallow perched aquifers (P) significant during tidal surges? This question could also be asked of other factors such as surface water run-off (SU), and leaking services (RU1 and RU2).

Q2. What is the impact of historical channels (FH) for those parts of the city where the anthropogenic filling (unit 1) is underlain by estuarine mud (unit 2), and for those parts where the filling is underlain by the gravel aquifer (unit 3)?

Q3. In those parts of the city where the sand and gravel aquifer (unit 3) is directly overlain by anthropogenic filling (unit 1), is there a drainage effect during low tide level (T)? This question arises because during calibration of river flooding after the November 2009 event, Halcrow Group Ireland Ltd. (2012) demonstrated that for the city downstream of the Waterworks Weir (near Victoria Cross) modelled flood levels were consistently more than observed levels. This pattern suggests that the unsaturated portions of units 1 and 3 may provide effective drainage of the floodplain during low water.

Q4. Has recharge from the limestone aquifer (RL) contributed significantly to the flooding problem at Cork?
Anthony Beese is a consulting geologist who has lived and worked in Cork for thirty-five years. He is a Professional Geologist and Companion Member of Engineers Ireland. After reading geology at Exeter and Hull Universities, he moved to Ireland to complete a post-doctorate research at University College Cork (UCC) under the broad heading of ‘Environmental geology of Cork Harbour’ (1981-5). In 1986, he established Carraigex Ltd., a small company of specialists that provided geological services to the public and private sectors in Ireland. He gained experience in the management and reporting of many projects, covering geotechnical investigations, engineering geology, geohazards, geoarchaeology, hydrogeology and geophysics. Case studies included assessments of pottery clays in Munster; geology of the River Lee Dams (Inniscarra and Carrigadrohid) for ESB International Ltd.; supervision of the borehole investigation for the Ballincollig Bypass, the potential for karstic subsidence at various developments for consulting engineers and Cork County Council; origins of groundwater pollution for private clients; causes of ground subsidence in Cork City; and assessment of rock-slope stability in the Cork district. Examples of two collaborative projects that he has managed in recent years are: ‘The medieval reclamation of estuarine Cork’ (2009-12), which was supported by the Heritage Council and the Department of Archaeology, UCC; and ‘Impact of the 1755 Lisbon earthquake-tsunami on West Cork’ (2015), also supported by the Heritage Council. He has received several research awards for AMS radiocarbon dating from the Irish Quaternary Association and Royal Irish Academy. His publications include book chapters, peer-reviewed articles and short communications.