APPLICATION OF AN INTEGRATED 3-DIMENSIONAL HYDROLOGICAL–HYDRAULIC MODEL, COUPLED WITH AN HIGH RESOLUTION DIGITAL ELEVATION MODEL, ON A WETLAND AREA IN THE SOUTH-WEST OF IRELAND.

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Abstract: The lower Feale catchment is a low-lying peaty area of 200 km2 situated in southwest Ireland and contains 15 hydraulically independent polders. It is the largest polder landscape in Ireland. A system of sluiced culverts dewaters the polders into embanked tidal waterways. The gradual settlement of the land over 50 years has reduced the capacity of the culverts to discharge water from the polders. The water table has risen and marsh plants have returned; periodic flooding has increased, leading to a political demand for renewal of the original arterial drainage scheme.

At present a pump experiment is being carried out in one of the 15 polders, as part of a flood alleviation test scheme. This study is focused on monitoring and modelling two polders: the so-called pump polder and the control polder, where no actions are taken. The target is to evaluate the effectiveness of the pump experiment, by comparing the two polders, for eventual implementation in a flood mitigation strategy in the remaining part of the catchment.

The computer model is developed using the Mike SHE / Mike11 modelling system. The combined model contains the surface drainage network and hydraulic controls, the surface and subsurface hydrological processes, and integrated with a high-resolution digital elevation model. The hydrologic/hydraulic model includes important features of the hydraulic infrastructure such as storm surge gates, sluiced culverts, back-drains, bridge openings and channel embankments.

The input/calibration data required by the complex model are provided by a number of state-of-the-art, high-frequency instruments, installed in the two polders. The instruments include: an eddy correlation station to measure water vapour and carbon dioxide fluxes, radiometers, soil

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temperature and soil water content probes, ground water level gauges, water level gauges and rainfall gauges. An electrical resistivity investigation and a ground-penetrating radar survey were carried out to collect subterranean data. A number of deep boreholes were drilled to calibrate the two surveys. A dynamic geographical database, built in ArcGIS (ESRI) software, stores the wide range of collected data and the results of the different surveys carried out. This paper presents current results.

INTRODUCTION

The hydraulic infrastructure of the Lower Feale catchment consists of the Lower Feale River - an embanked, tidal channel, about 23 kilometres in length - and three smaller, embanked, partially tidal tributaries. At low tide, a complex network of land-drains and back-drains drain into these main channels through sluiced culverts, located every 1,000 metres or so along the channels. During very heavy rainfall and high tides, these drains fill up and flood the surrounding fields, which are low-lying and very flat. This flooding can be severe.

A previous study examined in detail various solutions for flood alleviation. A complex one-dimensional hydrodynamic computer model of the hydraulic infrastructure in the lower Feale catchment, integrated with a model of the surface and sub-surface hydrological processes including a very high-resolution digital elevation model, was realized using the Mike SHE / Mike11 (Danish Hydraulics Institute - DHI) modelling system. The main objective was to understand the arterial drainage infrastructure, and in particular the performance of the sluiced-culvert system and the relationship with flooding. A detailed evaluation of various degrees of engineering intervention for the alleviation of flooding (dredging, pumping, etc) was carried out with the complex computer simulation model. Installation of pumps was determined to be the most effective solution from both engineering and an economical point of view. As recommended in the first phase of the project, three pumps were installed in one of the most heavily effected polders, C2M in figure 1, in July 2002.

The current project aims at bringing the results of the previous project to a higher, more refined level in terms of simulation model sophistication and, perhaps even more importantly, field data collection for model calibration and verification. The project objectives can be divided into the following components:

- Install and monitor water level, soil moisture, radiation and energy balance, and micrometeorological sensors for increased understanding of the hydrodynamics of the Lower Feale catchment and for hydraulic simulation model calibration.

- Couple the Mike-11 waterway model for the Feale River with the Mike-SHE watershed hydrology model for a better representation of the hydrologic dynamics of the watershed and arterial drainage system.
- Evaluate the effectiveness of pumping and possible installation of pumps in the remaining polders by means of the coupled model and analyses of the data collected.
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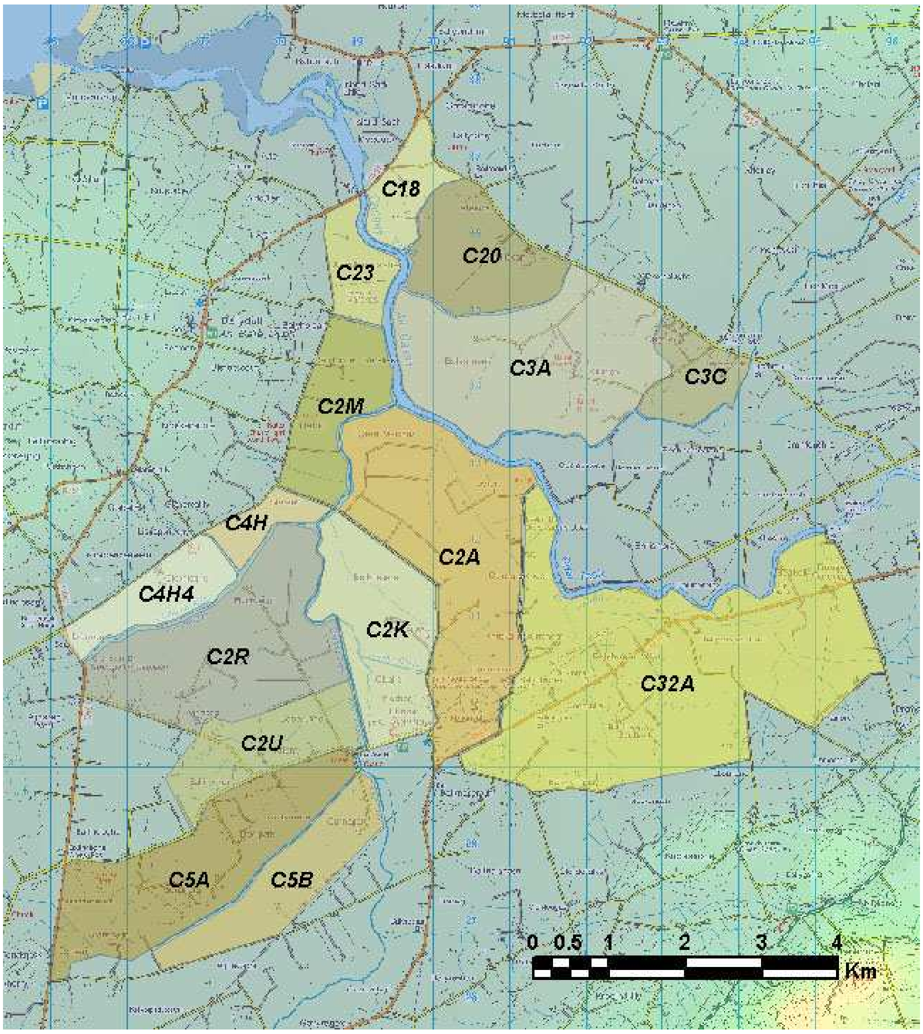

Figure 1. Lower Feale River network and its fifteen polders.

This study is focused on two polders of the Lower Feale catchment: the polder where pumps are installed, C2M, the ‘pumped or study-polder’, and an adjacent

polder, C23, with no pumps, which provides a control for the pumped polder. See figure 1.

ARTERIAL DRAINAGE SCHEME IN THE LOWER FEALE CATCHMENT

The Lower Feale catchment is a low-lying flat peaty area of about 200 km^2 located in southwest Ireland. The catchment is characterized by an extensive arterial drainage scheme. The Office of Public Works (OPW) designed and built the complex hydraulic infrastructure in the early 1950s to alleviate flooding. The Lower Feale catchment consists of the Lower Feale River, a large tidal channel that is about 23 kilometres in length and mostly embanked, and three smaller embanked partially tidal tributaries. Embankments, land-drains, back drains, sluiced culverts with flap valves, sluiced barrages, and weirs are the main hydraulic structures of the arterial drainage scheme.

Networks of interconnected drains, (small, un-embanked channels or ditches) dug in these low-lying areas, collect and store rainfall runoff. “Land-drains” collect rainfall runoff water from the land, and lead it to drains that lie adjacent to the embanked rivers on both sides, called “back-drains”. Culverts, with steel sluice gates (see Fig. 3) at their downstream end (called sluiced culverts), link these back-drains to the embanked river at regular intervals of 1,000 to 2,000 metres. These provide a means of gravitational drainage from the back-drain into the embanked rivers when the water level in the tidal river drops below the back-drain water level. When high water levels prevail in the embanked river, these sluiced culverts close and rainfall runoff is stored in the back-drains (see Fig. 2). Under normal circumstances at this location in Ireland, two periods of drainage occur during low tide in each 24-hour period.

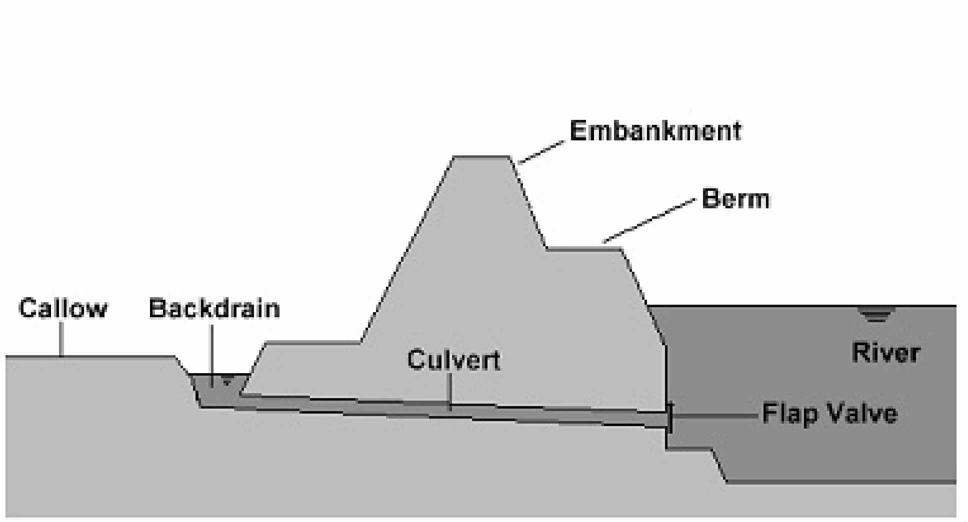

Figure 2. Cross section of embankment showing sluiced culvert link between back-drain and main embanked river.

Figure 3. Steel flap valve used at downstream end of sluiced culverts. This flap gate has a seal of Ertalon Bush, and the edges of the circular gate fit flush into the steel ring surround, which is fixed to the concrete outlet structure.

The Lower Feale catchment is made up of 15 polders. A polder is an area of land that is drained by a hydraulically independent network of back-drains and land drains, linked to an external drainage channel by sluiced culverts or pumps. During and after heavy rainfall, the water levels in the external drainage channels (tidal, embanked rivers) and in non-tidal tributaries stay higher for longer as they drain rainfall-runoff from upstream hilly areas of the catchment. As the lowland (floodplain) becomes saturated, the rate of rainfall-runoff into the land-drains and back-drains increases and they fill very quickly (see Fig 4). Arterial drainage through sluiced culverts is reduced for two reasons:

- Since the water level in the embanked rivers is higher for longer, the period of time for which there is a positive drainage head from the back-drain into the embanked river is reduced.
- Because the level in the embanked river at low tide does not drop as low during heavy rainfall, the magnitude of the drainage head is reduced, in turn reducing the magnitude of the discharge through the open sluiced culvert
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Figure 4. This back-drain is full and will shortly flood onto the surrounding field when fed from higher ground.

These two effects result in insufficient volumes of drainage from the back-drains into the drainage channels during the opening of each sluiced culvert. This reduces the available storage volume for further runoff in the drainage system. The drains fill up and overtop onto the surrounding land, causing flooding (see Fig. 5). (*Martin*, PhD Thesis 2002).

The arterial drainage scheme was initially very successful. The effectiveness of the hydraulic infrastructure has declined gradually over the past 45 years and may be due to the following factors:

- increased bed levels and water levels in the tidal drainage network (sedimentation, channel silting, bank erosion)
- land subsidence (largely affected by shrinkage and bio-oxidation of peat). (*Prus-Chacinski, T. M.*, 1962; *Prus-Chacinski, T. M. & Harris, W. B.,* 1963 and *Schothorst, C. J.,* 1977).

Figure 5. This photograph shows the overtopping of back-drains and land-drains in the lowlands of the Lower Feale catchment. (Office of Public Works, 1998).

INSTRUMENTATION ON SITE

DESCRIPTION

The first phase of the current project was focused on the installation of a set of state-of-the-art instruments able to monitor the on-going pump experiment. Figure 6 shows the study area (study-polder and control-polder) and the instrumentation installed.

A combination of 12 gauges (Orphimedes) monitors water levels in the drainage network and ground water levels in the polders. These are all automated gauges of similar design developed and distributed by the Ott company. The gauges are comprised of a pressure transducer, infrared communications port, battery, data storage module and are analyzed using Hydras 3 application software. There are nine Orphimedes used as ground water level gauges that record on a 60 min time interval, and three Orphimedes used as water level gauges installed in back-drains which record on a 15 min interval. Two tipping bucket precipitation gauges with 0.1 mm resolution are also included in this instrumentation. The Orphimedes datalogger operates on the basis of the bubble-in principle and are installed with a bubble chamber. Compressed air generated by a piston pump flows through a measuring tube and the bubble chamber into the ground/surface water to be measured. The excess pressure thus formed in the measuring tube is directly proportional to the depth of the water column above the bubble chamber. By comparing the difference between air pressure and the bubble-in pressure, the Orphimedes calculates the height of the water level above the bubble chamber. The OTT Company claims a resolution of 0.01 m for theses gauges. Figure 6 shows a typical water level gauge set-up in one of the back-drains in the study polder. Additional information about gauge installation is indicated in Table 1, and the placement of the gauges in the project area is indicated in Fig. 7.

Figure 6. OTT Orphimedes water level gauge.

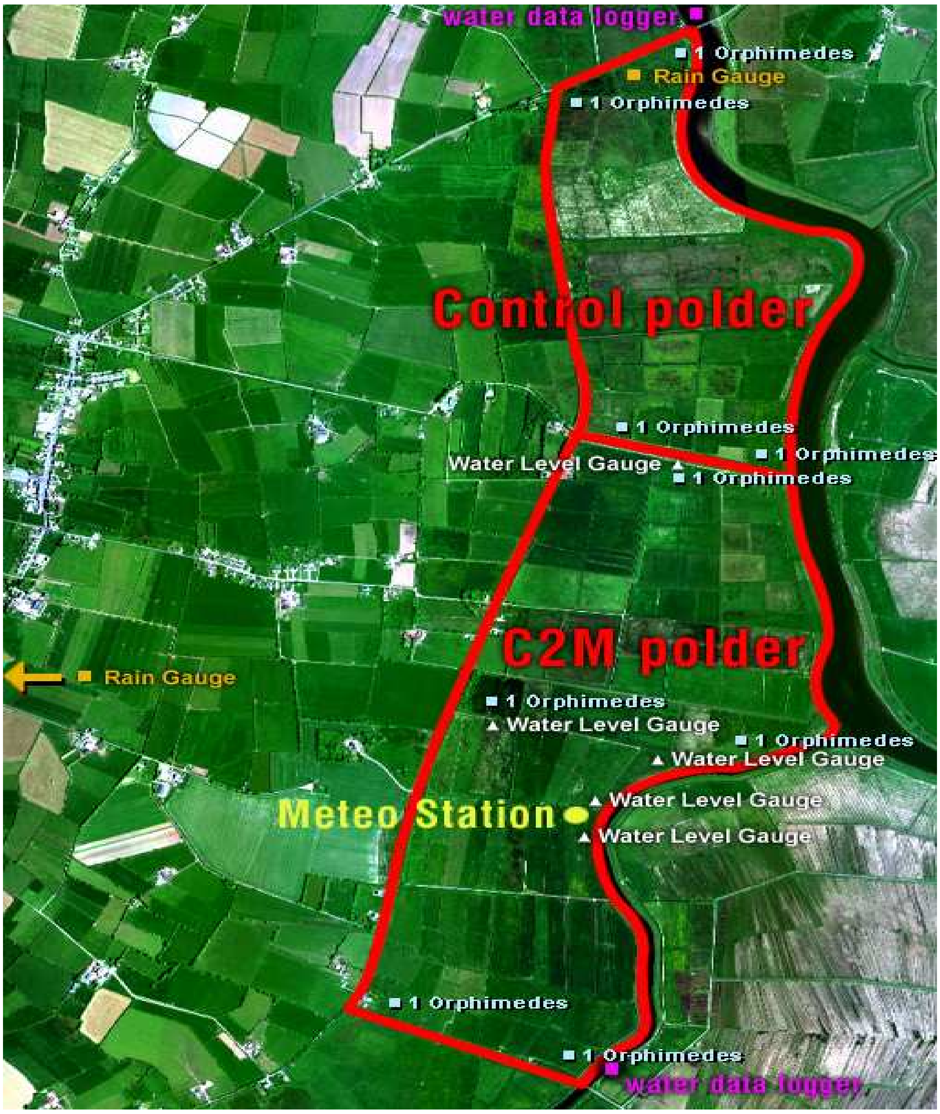

Figure 7. RGB image of the two polders showing instrument location. The upland area to the left provides rainfall-runoff into both polders.

Table 1 Water level, ground water level and rain gauges installed**.**

Location	Instrument	Measured Parameter	Installation Date	Meas. Frequency
Ground Water Level Gauges				
1	Orphimedes	Ground water level	19 June 2002	60 min
2	Orphimedes	Ground water level	20 June 2002	60 min
3	Orphimedes	Ground water level	25 July 2002	60 min
4	Orphimedes	Ground water level	19 June 2002	60 min
5	Orphimedes	Ground water level	26 July 2002	60 min
6	Orphimedes	Ground water level	27 June 2002	60 min
7	Orphimedes	Ground water level	26 June 2002	60 min
8	Orphimedes	Ground water level	27 June 2002	60 min
9	Orphimedes	Ground water level	26 June 2002	60 min
Water Level Gauges				
WL1	Orphimedes	Water level	10 Nov. 2002	15 min
WL2	Orphimedes	Water level	10 Nov. 2002	15 min
WL3	Orphimedes	Water level	15 Nov. 2002	15 min
Rain Gauges				
RG1	Tipping bucket rain gauge	Precipitation	27 Sept. 2002	Instant.
RG2	Tipping bucket rain gauge	Precipitation	27 Sept. 2002	Instant.

A series of sensors to measure most components of the radiation balance and all components of the diurnal energy balance were installed in July 2002. The major objective of this station is to quantify the evapotranspiration component of the hydrologic balance and its impact on the watershed. The instrumentation included in the eddy correlation and micrometeorological station is indicated in Table 2. The location of this station within the instrumented polder is shown in Fig. 7 while Fig. 8 shows the station set-up. It can be observed from Table 2 that a number of water table and ground water level sensors are built into this system. These are in addition to those sensors indicated in Table 1, which are distributed throughout the study polder.

One major component of the eddy correlation system is the CSAT 3D sonic anemometer, which resolves wind speed in the two normal horizontal directions (making up the x-y plane) and the vertical direction (z-plane) at a frequency of 10 Hz (i.e. 10 times per second). A second major component is the Licor 7500 open path infrared gas analyzer capable of measuring concentrations of CO_2 and H_2O at the same 10 Hz frequency. The sensible heat flux, based on 10 Hz temperature measurements, is done either using the fine wire thermocouple or the sonic temperature calculated using the CSAT 3D.

Figure 8. Eddy-correlation SVAT (soil, vegetation, atmosphere) station.

Table 2 Eddy correlation-SVAT (soil, vegetation, atmosphere) station sensors and configuration, installed on the 22nd of July 2002.

Sensors and Units	**Measured Parameters**	**Meas. Interval**	**Storage Interval**	**Num.**
Main Station Unit				
CR 23X and CR 5000 Microloggers				1
Enclosure				1
16/32 Channel Relay Multiplexer				1
Channel Vibrating Sensor				1
Tripod				1
GSM-communication system				1
Sensors				
Water table pressure transducer	Water level	60 s	15 min	2
Tipping bucket rain gauge	Rainfall	60 s	15 min	2
Vaisala Temperature and RH Probe	Air Temp and R.H.	60 s	15 min	1
Heat Flux Sensor	Soil heat flux	60 s	15 min	2
Skye Pyranometer	Solar radiation	60 s	15 min	1
Kipp and Zonen NR-Lite Net Radiometer	Net radiation	60 s	15 min	1
Wetness Sensing grid Leaf Wetness Sensor	Dew deposition	60 s	60 min	1
Thermistor Probe (Soil Temp)	Soil temperature	60 s	60 min	3
Water Content Reflectometer	Soil moisture content	60 s	15 min	4
GEOKON-Vibrating Wire Piezometers	Ground WL and pres.	60 s	15 min	4
Eddy Correlation System				
Open path CO_2/H_2O infra-red gas analyzer	H_2O & CO_2	10Hz	15 min	1
CSAT-3D Sonic Anemometer	Wind Comp. (x, y, z)	10Hz	15 min	1
Averaging Soil Temperature Probe	Soil Temperature	60 s	15 min	1
Fine Wire Thermocouple	Atm. Temperature	10Hz	15 min	1

SAMPLE RESULTS

Data collected from the OTT gauges are stored in the Hydras 3 software database. Hydras 3 is a high-performance database application and provides communication with OTT devices. The main database features are: station management, graphical evaluation, multiple graphics, flexible importing and exporting options. The Hydras 3 main window is divided into two sections: the left section includes a tree display with workspaces, regions, stations and sensors hierarchically organized; the right section of the screen contains a map which allows geographic display the selected stations and sensors.
The data collected can be easily accessed and graphically displayed by double-clicking on the sensor name. The data display window has several options available for specific selection of the time range or the measured values displayed. It allows for a numerical display of the data as well. All the water levels recorded are relative to the Irish national Ordinance Survey datum (Poolbeg). Figures 9, 10, 11, and 12 show multiple graphs of the data evaluation window for the Hydras 3 database.

Figure 9 shows a Hydras 3 multiple graphic including two ground water level gauges (GWL3, GWL4) and the rainfall gauge (RG3) located in the control polder (see Fig. 6 for exact location). The data evaluation window displays a five-month period (January to end of May) and sensors with levels referred to the Poolbeg datum. This figure highlights a good correlation between the two ground water level gauges located at different distances from the main river and a similar response of the ground water table to rainfall. The largest ground water table fluctuations are on the order of 50 to 60 cm depending on rainfall events.

Figure 10 shows a Hydras 3 multiple graphic that includes one ground water level gauge (GWL5) located in the pumped polder and the rainfall gauge (RG3) located in the upland area (see Fig. 1 for exact location). This figure displays the variations of the ground water table over a one-year period and its response to different rainfall events, i.e. storms. The largest rise (about 90 cm) in the water table was recorded between the beginning of October 2002 and the middle of November 2003, following a particularly wet period (about 210 mm of accumulated rainfall in the same time frame).

Figures 11 and 12 show multiple graphs with the same sensors but different time-scales. They both show data collected from the rain gauge located in the control polder and the two water level gauges, respectively located in the main river (Ferry Bridge gauge – OPW autographic recorder) and in the back-drain north of the pump house (WL1). Both graphs show a clear tidal signal recorded in the back drain, which is in almost perfect phase with the tidal signal recorded in the main channel at Ferry Bridge. The occasional small difference in levels and time for the low tide peaks in the two signals is due to the different location of the two sensors. The autographic recorder at Ferry Bridge is indeed about 4.3 km further downstream in the river drainage compared to the other sensor (WL1). Figure 11, which shows data collected in a one month period (05/01/2003-05/02/2003), highlights the main features influencing the complex system:

- Neap and spring tidal-cycle in the main river.
- Sluiced culvert operation: It is easy to recognize the intermittent drainage through the system of sluiced culverts into the main river. When the level in the back drain is higher than the water level in the main river, the sluiced culverts provide a means of gravitational drainage from the back drains to the embanked river channel. When the sluice gates open, the water level in the back drains drops about 15 to 25 cm relatively quickly (in 2 to 3 hours), depending on the overall situation.
- Leakage through and/or around the culverts: This is clearly highlighted by the tidal signal recorded in the water level gauges. The two signals are almost in perfect phase. The water level in the drain keeps rising until the sluiced culvert gates open up, then it may drop. This is very evident during a dry period.
- Pump operation: Within the month included in Fig. 11, the pumps went on several times maintaining the water level below the switch–on level (2.785 m OD equivalent to a reading of 1.2 m on the adjacent staff gauge). The pump operation modifies the typical tidal signal recorded in the drains and drops the water level in the drains less efficiently compared to the drainage by the sluiced culverts. This is due to the adopted pump strategy, where one pump comes on when the water level reaches 2.785 m in the back-drain and the goes off when the level drops to 2.585 m. The additional two pumps come on when the water level reaches 2.835 m and go off again at 2.585 m. The water level in the back-drain rarely keeps rising after the first pump comes on, so in most cases recorded in this first year of operation, only one pump is active, slowly reducing the water level to the switch-off point.

Figure 12 shows a shorter time frame (6 days) and highlights the main factors explained above. Drainage by the sluiced culverts and their leakage are easy to recognize. Following a relatively small rainfall event (14 mm/d) on 14 April 2003, the water level in the back-drain reached the first pump switch-on level. After the first pump comes on, the water level stops rising and slowly drops to the pump switch-off level.

Figures 13 and 14 show data recorded from the eddy correlation and micrometeorological station. The graphs show a week of data measured at a frequency of 10 Hz and averaged over a 15-minute period. In particular, Figure 13 shows wind speed velocity components in the two normal horizontal directions (x-y plane) and in the vertical direction (z-plane). To interpret these velocity components on one graph, the z-axis has been magnified by a factor of 20. The vertical velocity (z-axis) is therefore considerably smaller than the horizontal velocity, but it is the velocity component responsible for the vertical fluxes of heat and water vapour. The graph shows how the velocity component measured in the vertical direction is almost in perfect phase with the velocity component in the y-direction for the time period shown.

Figure 14 shows a typical graph of the four major components of the energy balance, these being net radiation, soil heat flux, latent heat flux (evaporation), and sensible heat flux (calculated using the sonic temperature), as measured by the eddy correlation system. From the net radiation trace we can see that day of year (DOY) 225, 226 and 228 are predominantly clear days, while DOY 227, 230 and 231 are partly cloudy days, and DOY 229 is very cloudy. These conditions are not unusual for this region of Ireland in July. It can also be noted that for the period given, the latent heat flux is usually slightly larger than the sensible heat flux, while the soil heat flux is much smaller in magnitude than the other two.

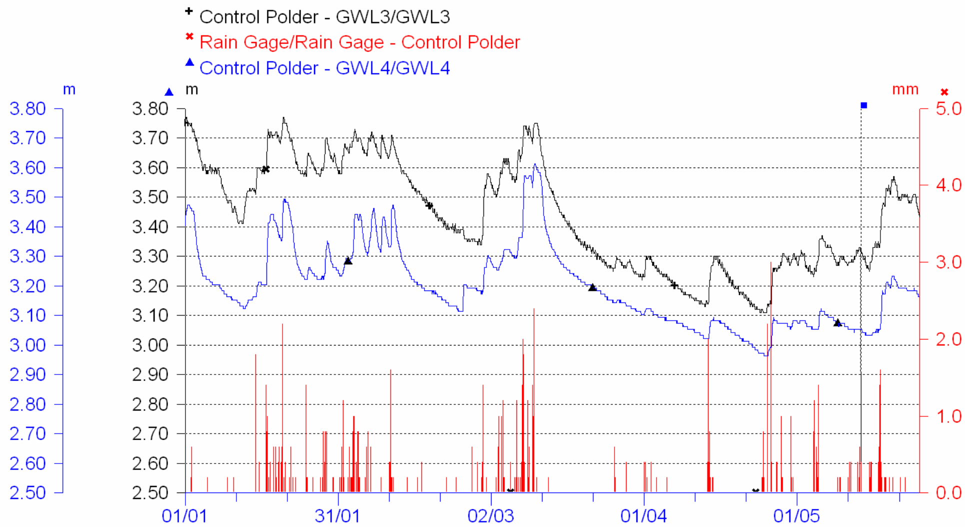

Figure 9. Hydras 3 Multiple Graphic: Rain Gauge (RG3) and two Ground Water Level Gauges (GWL3, GWL4) located in the Control Polder. Rainfall quantities in mm on the right-hand scale. Groundwater levels in m on the left-hand scale with an interval of 0.1m. Period: 01/01/2003-25/05/2003.

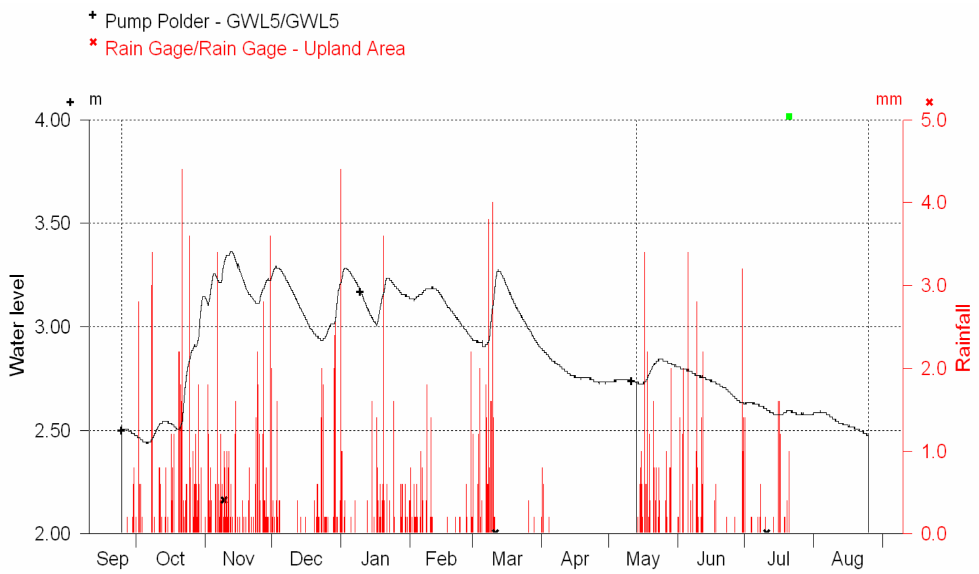

Figure 10. Hydras Multiple Graphic: Rain Gauge (RG4, red) and Ground Water Level Gauge in the Pump Polder (GWL5, black). Period: 09/2002-09/2003

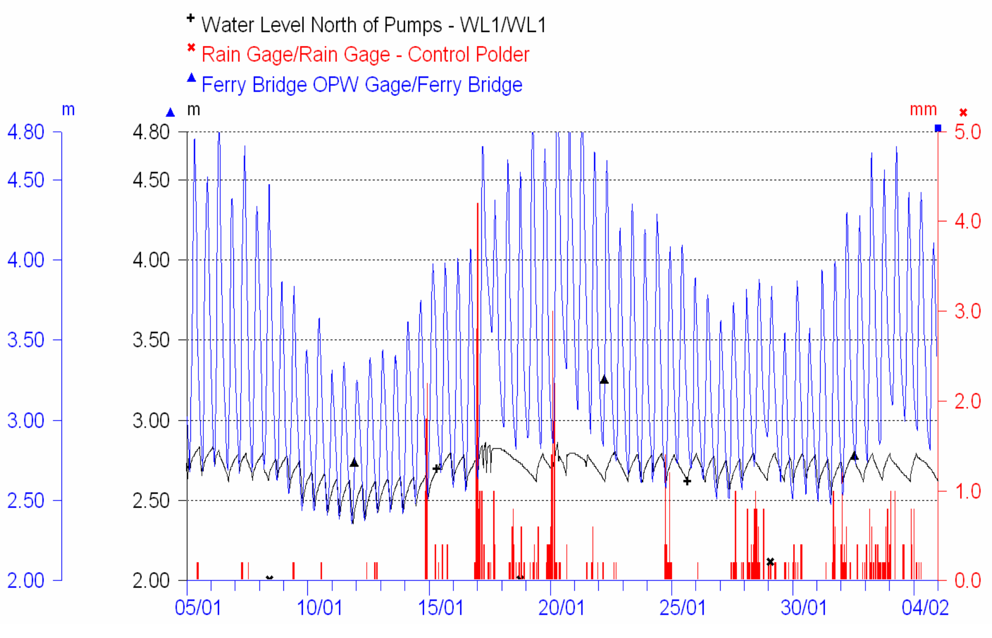

Figure 11. Hydras 3 Multiple Graphic: Rain Gauge (RG3) and two Water Level Gauges (Ferry Bridge-OPW and WL1). Period: 05/01/2003-05/02/2003.

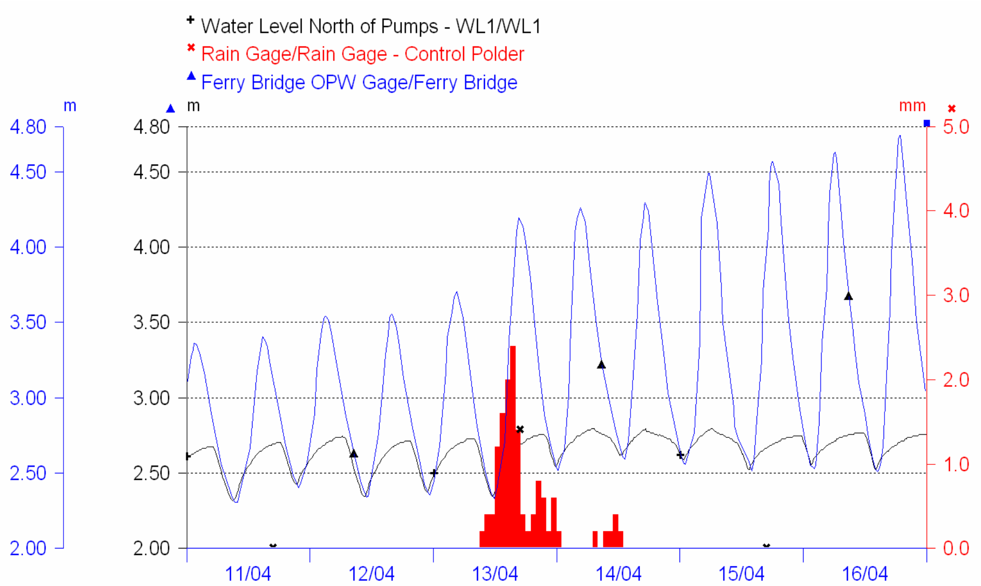

Figure 12. Hydras 3 Multiple Graphic: Rain Gauge (RG3-red) and Water Level Gauges [Ferry Bridge-blue and WL1-black]. Period: 11/04/2003-17/04/2003.

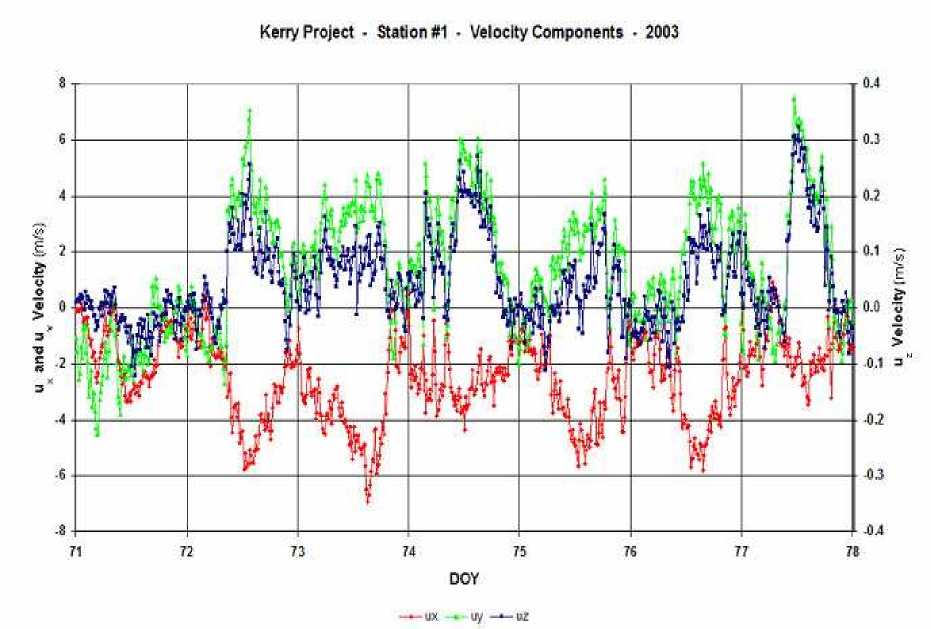

Figure 13. Velocity components ux (red) and uy (green): left-hand scale in units of 2 m/s. Velocity component uz (blue): right-hand scale in units of 0.1 m/s. Components in the x, y and z directions recorded by the Eddy Correlation station. Period: 11/03/2003 – 18/03/2003: DOY – days of the year.

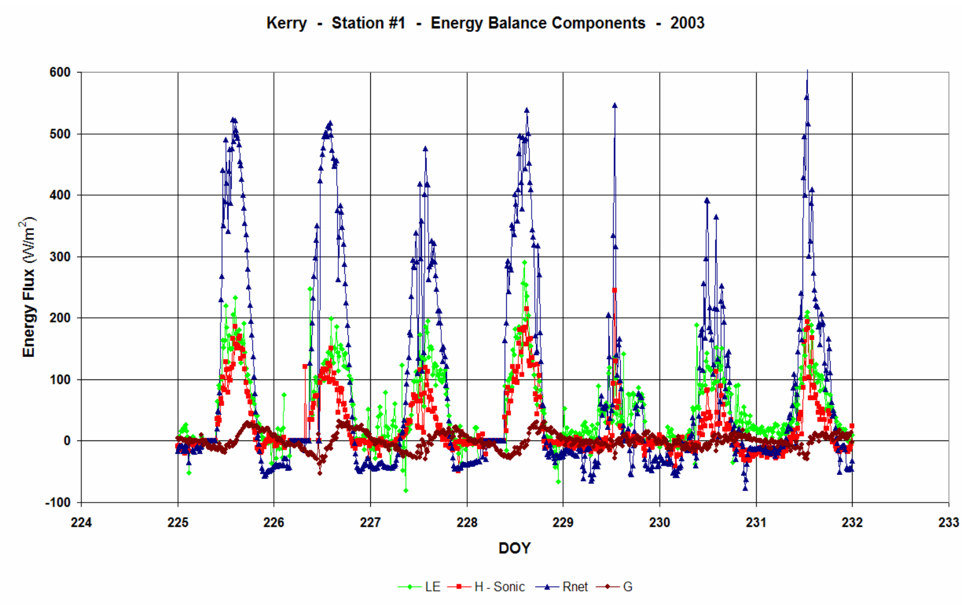

Figure 14. Energy fluxes recorded from the eddy correlation station. Period: 02/07/2003 – 08/07/2003 – DOY days of the year. Rnet (blue) is net radiation flux; LE (green) and H (red) are latent and sensible heat fluxes respectively; G (brown) is the soil heat flux. All units are Watts per square meter. Vertical interval is 100W/m^2.

ELECTRICAL RESISTIVITY SURVEY

A series of electrical resistivity traverses was carried out over the study area to collect subterranean data. Samples of the resulting profiles are shown in Fig.16 and 17. These results showed that the Quaternary overburden thickened to the south of the project area. In other words, the depth to bedrock deepened from 14 m north of the pump station to 19 m just south of the pump station. The bedrock to the south shows evidence of increased weathering and oxidation. The bedrock surface over the whole area surveyed is somewhat undulating. The depth to bedrock is shallower moving away from the river, and is found at a depth of 10 m close to the upland part of the catchment. Four boreholes were drilled to calibrate the electrical resistivity survey (see Fig. 15 for borehole logs). The first borehole (BH1) was used to calibrate the survey. The depth to bedrock was predicted in all other surveys, and confirmed in the following three boreholes drilled (BH2, BH3 and BH4).

The results of the geophysical survey showed some variation that was dependant on the amount of recent precipitation. The surveys were also sensitive to the state of the tides. Surveys repeated at hourly intervals showed a tidal signature at depth (15 to 20 m), with resistivity values increasing slightly at high tide. This was thought to be due to increased water pressure at this depth. The resistivity values in the shallow subsurface (0 to 7 m) were < 10 ohm-m in parts, indicating saline incursion into the area. It was noted that the back-drains filled as the tide rose, but did not empty in keeping with the tide. There was a delayed response. Data collected from the boreholes, in conjunction with the geophysical survey, allowed a clay layer to be mapped out.

The variation in depth of the clay is shown in Figs. 16 and 17. The clay causes a perched water table in the Rattoo Bog at a depth of roughly 4 m below surface, the average depth of the peat layer. This is a major control on the flooding of the area. The regional ground water table was found at 14 m depth below the surface.

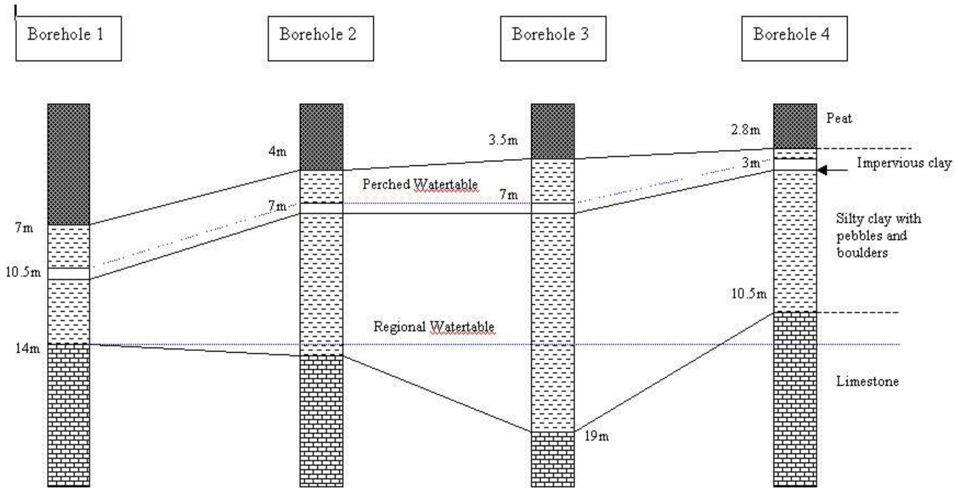

Figure 15. Boreholes logs from the study polder. Borehole logs 1 and 2 were recorded from chippings. Borehole logs 3 and 4 were recorded from core samples. The positions of the perched watertable and associated impervious clay were inferred from borehole water strikes and electrical resistivity cross-sections.

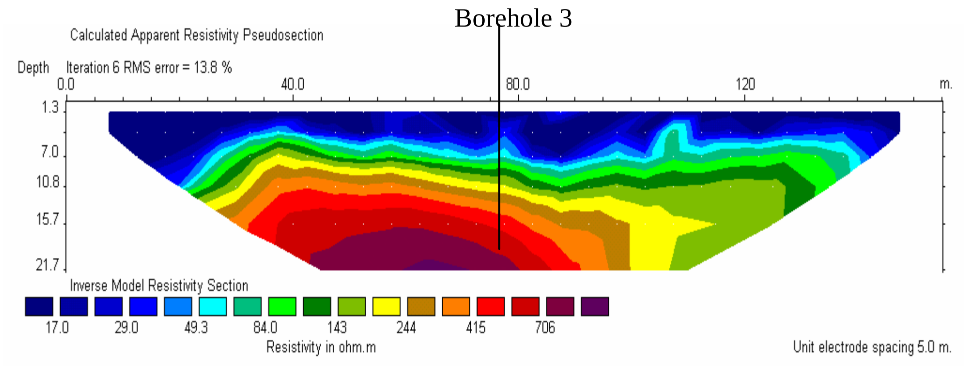

Figure 16. Electrical resistivity line. Location: study polder, about 100 m from the pump house, parallel to the embankment. Resistivity in ohm-m on the colour bar from 17.0 to 706. Horizontal interval 5m; vertical scale from 0.0 to 21.7m. Unit electrode spacing 5m.

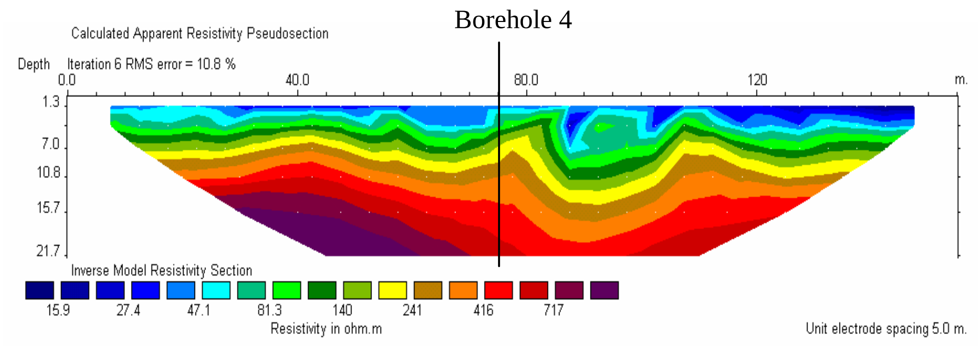

Figure 17. Electrical resistivity line. Location: study polder, 1400 m from the pump house, parallel to the embankment. Resistivity in ohm-m on the colour bar from 15.9 to 717. Horizontal interval 5m; vertical scale from 0.0 to 21.7m. Unit electrode spacing 5m.

ARCGIS DATABASE

A dynamic geographical database, built in ArcGIS (ESRI) software, stores the wide range of data collected and the results of the different surveys carried out. ArcGIS is a complete, single integrated system for geographic data creation, management, query, mapping, integration, and analysis. The software is logically structured into separate applications for mapping, data management and geoprocessing. The following three integrated core applications are the main components of the ArcGIS database:

- ArcMap is the central application in ArcGIS. It is the GIS application used for all map-based tasks including cartography, map analysis and editing.
- ArcCatalog is used for managing all the spatial data. It includes tools for browsing and finding geographic information, recording, viewing and managing metadata, quickly viewing datasets and defining the structure for the geographic data layer.
- ArcToolbox provides many common GIS data conversion and geoprocessing tools.

ArcMap, ArcCatalog, and ArcToolbox are designed to work together to perform all GIS tasks. A most useful attribute of ArcGIS is the possibility to work with a variety of file-based data. ArcMap and ArcCatalog allow working with an extensive array of data sources, such as computer-aided design files (CAD), numerous image and table formats, and many other data types.
Figure 18 shows the ArcMap window layout for this project. In the left-hand side there are the different items included in the database, which were imported from ArcCatalog in the first place. The Kerry Project database includes several different items:

- All the sensors installed in the area (eddy correlation station, water level gauges, ground water level gauges, rain gauges),
- The different surveys carried out (ground penetrating radar survey, resistivity survey, boreholes),
- Gauges installed in the area maintained by the Office of Public Works,
- Pump discharge time series
- The Red-Green-Blue multi-spectral high resolution (30 cm pixel) images available from the two surveys carried out by the Deutsches Zentrum für Luft- und Raumfahrt (DLR or German Aerospace Centre).

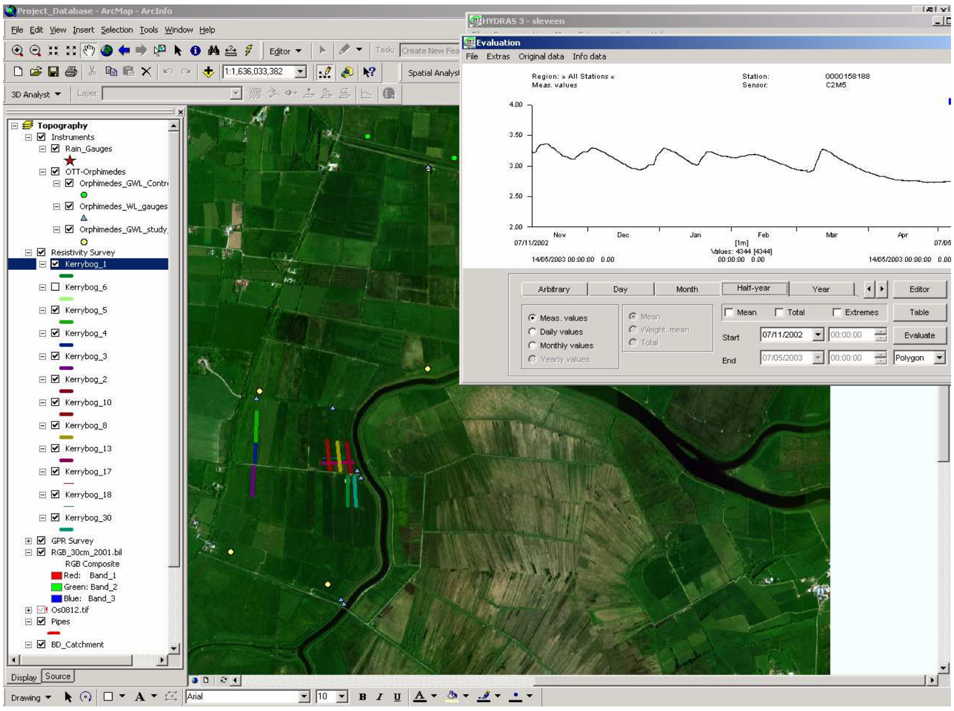

Figure 18. ArcGIS Database, ArcMap layout.

On the right-hand side of the figure it is possible to distinguish in the RGB panchromatic image several symbols and lines representing sensors and surveys included in the database. By double clicking the different symbols it is possible to pull up an extra window showing data collected or results obtained from the different surveys. Figure 18 for example, shows the data collected from the ground water level gauge (Orphimedes - GWL5) located in the north part of the pumped polder. The result files are opened with the respective default software. In the particular case shown in the figure, the Hydras 3 database has been opened up to show data from the ground water level gauge. As mentioned above, the possibility to integrate all file-based data in ArcGIS has proven to be one of the most useful advantages.

EXISTING ONE-DIMENSIONAL INTEGRATED COMPUTER MODEL

A one-dimensional integrated computer model was made in the previous project to represent the complex hydrodynamic/hydraulic and hydrologic system of the Lower Feale surface system. As part of the complex integrated computer model, three computer models were made. The hydrodynamic model (built using the DHI-Mike11 modelling system) simulates the flow through the embanked tidal channels, drains and sluiced culverts. The NAM rainfall runoff model (DHI) simulates the hydrology of the catchment and the resultant rainfall runoff fed into each of the back-drains and field drains. The Digital Elevation Model (DEM) simulates the topography of the landscape. By integrating these three models it is possible to simulate fully the flooding of the catchment and to test the effectiveness of many environmentally sensitive hydraulic solutions. The following sections contain more detailed descriptions of the three models mentioned above.

THE ONE-DIMENSIONAL NETWORK MODEL

The one-dimensional network model of the Lower Feale and its hydraulic infrastructure is a very complex network model that represents over 90 interconnected water branches. Four of these represent main embanked river channels that drain back-drains and field drains by means of sluiced culverts. These are the Feale/Cashen, Brick, Gale and Crompaun rivers. Over 45 of the branches in the model represent back-drains and field drains.

The remaining 40 water branches in the model are small narrow “sluice channels” into which a culvert and its sluice are inserted. These channels run at right angles from a point in a back-drain to an adjacent point in a main embanked channel. Sluiced channels in the model are typically 20 to 30 metres long with a culvert of 600 mm in diameter and 18 metres in length. The Office of Public Works, Ireland, provided invert level data for each sluiced culvert, as well as their dimensions and the number of culverts at each sluice outfall. All sluiced culverts are modelled with “Positive flow valve regulation” to simulate the effect of the flap valve gate. Leakage is modelled with the same feature but applied to fictitious branches in the opposite direction.

Cross section data for the four main channels, the Feale/Cashen, Brick, Gale and Crompaun rivers, were provided by Global Positioning System (GPS) surveys of the river edges combined with acoustic depth surveys of the underwater sections at 200 metre intervals. The hydraulic structures in the Feale river network consist of sluiced culverts, sluiced barrages and culvert crossings across drains. The model identifies the location of all features along the branches of the network using the branch name and the distance along the branch. The model includes two sluice barrages as well as over 40 sluiced culverts. These require the same data as the sluiced culverts, and only differ in the size and shape of the gates. Bridges are modelled in the same way as sluiced culverts, but with the valve regulation set to “none”. (*Martin, J. and O'Kane, J.P.*, 2000).

RAINFALL-RUNOFF MODEL (NAM)

A separate rainfall runoff model was set up to simulate the hydrology of the catchment using the NAM (“Nedbor-Afstromnings-Model”, DHI) rainfall-runoff model. The catchment is divided into several sub-catchments, each feeding into either the length of a different back-drain, or a point in one of the main channels. The boundary file assigns three boundary conditions (rainfall, evaporation and temperature) to each sub-catchment in the model. The input time series have a daily frequency and are the same for all sub-catchments. Another input file is the rainfall runoff parameter file, which defines the parameters of the soil that determine the rate and volume of rainfall runoff from each sub-catchment. This file requires extensive data regarding the catchment area, surface storage, root-zone storage, ground water depths, initial conditions etc. Due to the lack of information required, all sub-catchments in the model were given the same rainfall/runoff parameters. Flow records, from one V-notch weir data logger, were used to calibrate the NAM rainfall runoff model. This was accomplished by comparing the predicted rainfall runoff time series for a given sub-catchment with the measured outflow hydrograph for the same area. The NAM result file is defined as an input file in the hydrodynamic simulation and the branches into which each sub-catchment feeds are defined within the river network setup menu. In this way, each back-drain is modelled to collect the rain falling on a different sub-catchment. (*Martin, J. and O'Kane, J.P.*, 2000).

DIGITAL ELEVATION MODEL – DEM

In November 1998 the German Aerospace Agency (DLR) carried out a remote sensing survey of the lower Feale catchment in southwest Ireland using the airborne multi-spectral High Resolution Stereo Camera (HRSC-A). The first very high-resolution digital multi-spectral airborne stereo camera provided high-resolution (100 cm, 50 cm, 20 cm) radiometrically and geometrically calibrated digital elevation models and images of an area of 200 km^2. The HRSC-Airborne provided high-resolution digital images in the red, green and blue (RGB) bands, as well as the near infrared (nIR) band and the panchromatic (false-colour) visible band. The system also collected and processed high-resolution digital stereo images for the generation of digital elevation models.
Interference by clouds reduced the coverage achieved in the first survey. To fill the most important gaps, a second digital aerial survey covering a smaller (80 km^2) central portion of the catchment was carried out in May 2001. The second campaign used the German Aerospace Centre HRSC-AX system. The "AX" (Airborne, Extended-Generation) version of the HRSC has been in commercial operation since late 2000 and produces similar very high resolution (100 cm, 50 cm, 15 cm) multi-spectral ortho-rectified images and related DEMs. The DEMs from both surveys were geo-referenced to the Irish National Grid to a claimed relative accuracy of 20 cm in all three directions.

The remote sensing system applies a push-broom principle: nine Charged Couple Device (CCD) line detectors are mounted in parallel at the focal plane of the Zeiss optical instrument and nine simultaneous image strips are acquired almost simultaneously by the forward motion of the aircraft over the terrain. Five of these CCD lines are arranged at specific viewing angles to provide stereo imaging and photogrammetric viewing capability (DLR, 1998). The camera is mounted on an inertial support system within the aircraft. The aircraft was flown at a speed of about 250 km/hr at an altitude of 3,000 metres. (*Lillesand, T. M. and Kiefer, R.*

W., 2000; *DLR*, 2000 and *Wewel, F., Scholten, F., Neukum, G., and Albertz, J.*, 1998)

The DEM provides the digital topography files required by the integrated flood modelling system. The high-resolution images provide information required for the network set-up of the hydrodynamic model and are used as reference images for flood maps.

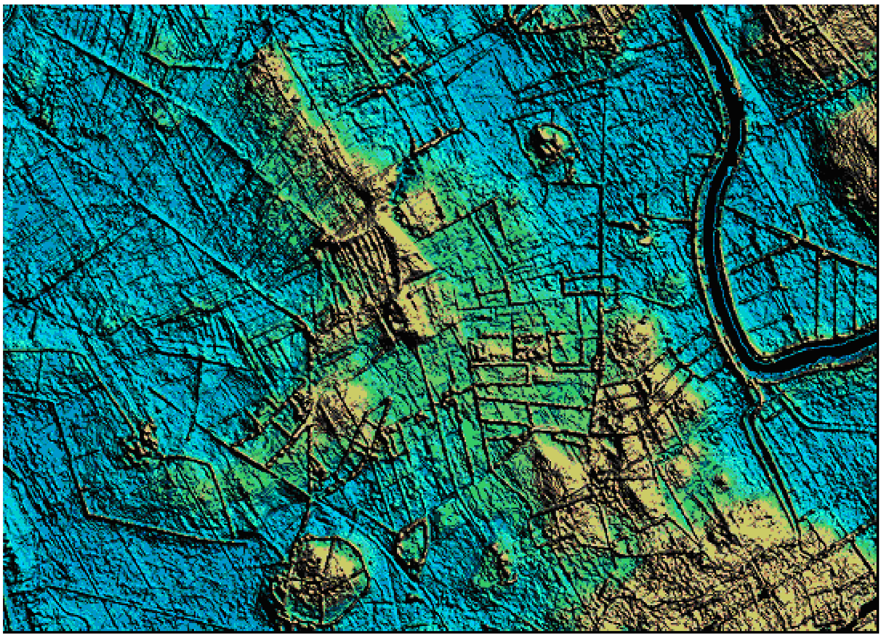

Figure 19. Shaded DEM, November 1998 dataset, 1 m horizontal resolution.

NEW COUPLED MODEL BUILT USING DHI'S MIKE11-MIKESHE MODELLING SYSTEM

One of the main objectives of this project is to improve the existing hydraulic model of the Lower Feale catchment and bring it to a more refined level in terms of simulation model sophistication. This is accomplished by coupling the existing one-dimensional hydraulic model with a three-dimensional hydrological model built using the DHI-MikeSHE modelling system. This is a spatially distributed, physically based modelling system for simulation of hydrologic processes in a watershed both above and below ground. It simulates the hydrologic cycle including evapotranspiration, overland flow, channel flow, soil water and ground water movement. By coupling the new 3-D model to the existing network model the weakest part (rainfall-runoff model) of the existing integrated computer model of the Lower Feale catchment has been strengthened. The NAM model, a lumped, conceptual rainfall-runoff model, has been replaced by the distributed, physically-based model implemented in the Mike SHE system.

MikeSHE solves the partial differential equations for the processes of overland and channel flow, unsaturated and saturated subsurface flow. The model is completed by a description of the processes of snow melt (not required in the Feale), interception and evapotranspiration. The flow equations are solved numerically using finite difference methods. In the horizontal plane the catchment is discretized in a network of grid squares along which run the river system boundaries. Within each square the soil profile is described at a number of nodes, which above the ground water table may become partly saturated. Lateral subsurface flow is only considered in the saturated part of the profile. Figure 20 illustrates the structure of the MikeSHE modelling system. In the DHI version of SHE it is embedded in a graphical user interface (GUI) with a variety of tools to process, analyze, and present input and output data.

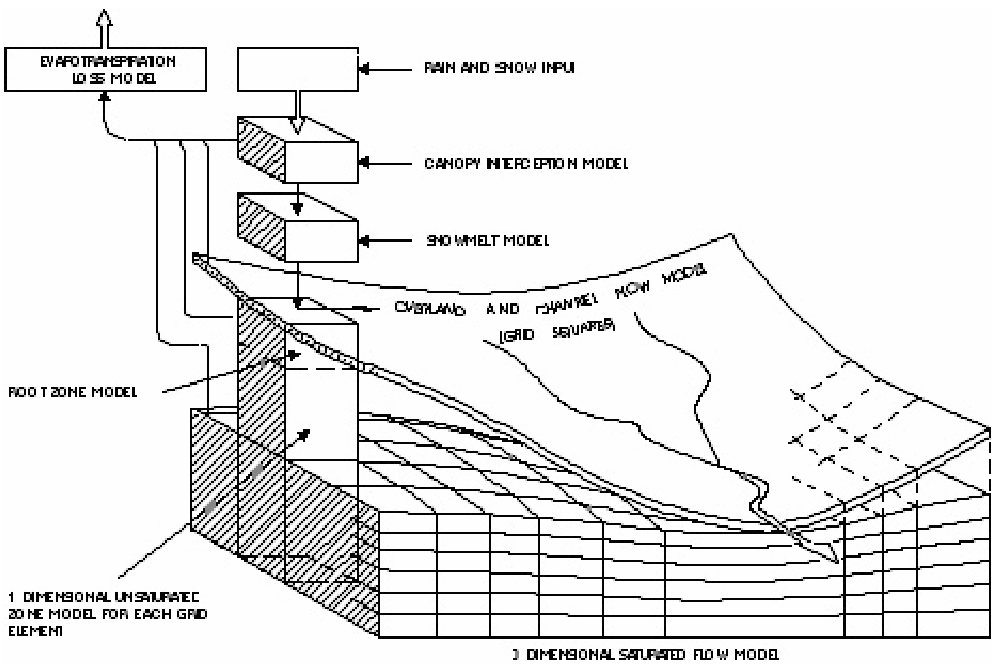

Figure 20. Schematic presentation of the SHE modelling system – image not to scale.

As mentioned above one of the greatest advantages in using Mike SHE is the possibility of coupling it with Mike11. A Mike11-MikeSHE model allows the full dynamic interaction of the surface and subsurface processes, together with the hydraulic infrastructure, and presents important advantages compared to stand-alone hydrological models. Thanks to Mike11 the coupled model implements the complete one-dimensional partial differential equations of open channel flow (Saint Venant) in the defined river network. A stand-alone MikeSHE model would only solve the Saint Venant equation with a kinematic wave approximation applied.

Mike11 allows the inclusion of all the different hydraulic structures present in the study catchment. On the other hand, a disadvantage is that the coupled Mike11-MikeSHE model requires a large amount of additional information compared to a stand alone hydrological model, data, which may not always be available.

The coupled Mike11-MikeSHE model is limited to a sub-catchment of the Lower Feale system for this phase of the project. The model includes the two polders of interest in this phase of the project (the study and control polders) and their catchment area of approximately 40 km^2. For this study, MikeSHE has a 5-meter resolution digital elevation model of the area and has a cell size equal to 30 meters. This cell size allows the model to fully resolve the complex Mike11 network, but requires long computational times. The wide range of extra data required is provided by new set of different instruments installed and by the different surveying campaigns carried out in the first phase of the project, as previously described.

The coupled model is still going through a calibration phase, which is proving to be longer than expected, mainly due to the high levels of detail required by the model. We present here some preliminary results of the work done to date. Figure 21 shows a good correlation between observed water level and calculated water level in the back-drain north of the pump house. The figure clearly shows how the model represents the sluiced culvert operation and leakage and is in very good agreement with the observed time series. The figure covers a 9-day period of simulation. Figure 22 shows the calculated and observed ground water table in location GWL8 of the study polder. The general trend over a 2.5-month period of simulation is quite good but can be improved. Problems are mainly due to the difficulties in simulating the thick layer of peat present in the two polders. A proper test on the hydraulic properties of local peat would surely improve the simulation results, which are currently based on general values in the literature.

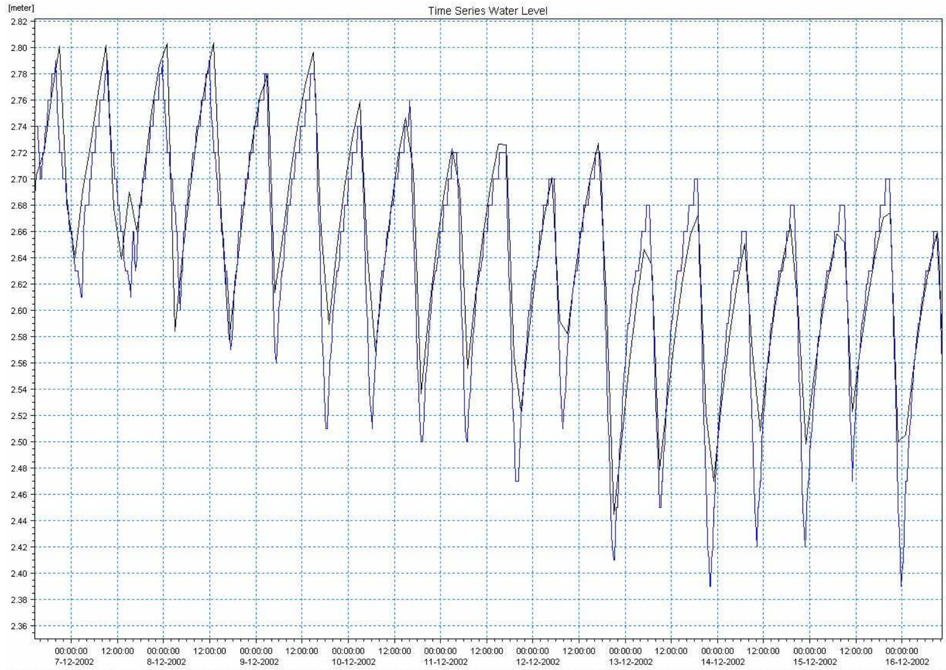

Figure 21. Water level measured (WL2-Blue line) and calculated (Mike 11/SHE result file - black line). Vertical interval: 0.02m. Period: 07/12/2002-16/12/2002.

Figure 22. Ground Water level measured (GWL8-upper line) and calculated (Mike 11/SHE result file - lower line) Period: 01/11/2002-15/01/2003. Vertical interval 0.1m.

CONCLUSIONS

Some further work remains to be done on the calibration of the groundwater component of the combined model. The importance of leakage in driving the control of the pumps during dry weather has been demonstrated and provides a tool for investigating the costs and benefits of leakage reduction.
Extensive data has been collected under dry conditions, but the object of the current phase of the study is the effectiveness of the pumps during wet conditions. We await the arrival of minor and major flood events to complete the evaluation of the pumping system.

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