# ECOHYDROLOGICAL STUDIES OF THE GWENT LEVELS, SOUTH WALES

**Report:** 1712_r1.13 & Final, February 2022

**Prepared for:** Royal Society for the Protection of Birds

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**English** - This project has received funding through the Welsh Government Rural Communities - Rural Development Programme 2014-2020, which is funded by the European Agricultural Fund for Rural Development and the Welsh Government.

**Welsh** - Cyllidwyd y prosiect hwn drwy Cymunedau Gwledig Llywodraeth Cymru - Rhaglen Datblygu Gwledig Cymru 2014-2020, a ariennir gan Lywodraeth Cymru a'r Gronfa Amaethyddol Ewrop ar gyfer Datblygu Gwledig.

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# 1 Introduction

## 1.1 Background

The Gwent Levels are one of the most extensive areas of reclaimed wet pasture in Great Britain, and the largest in Wales. They form a wide coastal plain from Cardiff in the west, through Newport, to Caldicot in the east (Figure 1.1-1). Comparable sites in England are the Somerset Levels, Romney Marsh and the Pevensey Levels.

The Gwent Levels landscape is entirely man-made, with much of the land below mean high water and the sea kept out by extensive sea defences. Traditionally, fields are drained by a micro-topographic system which promotes surface runoff (often termed ‘ridge and furrow’) into the ditches which surround each field. These ditches feed into an inter-connected network of larger watercourses, known as reens, which eventually discharge at intervals to the Severn Estuary via tidal gates. The watercourses were carefully constructed so that the system drains by gravity at low tide; they are managed by National Resources Wales (NRW) under the Caldicot and Wentlooge Internal Drainage District (IDD).

Much of the Gwent Levels is designated as Sites of Special Scientific Interest (SSSI), with a contiguous suite of eight SSSIs covering the area (Figure 1.1-1). The SSSIs were mostly notified because of the range of aquatic plants and invertebrates associated with the aquatic habitat in the reens and field ditches of the drainage system. The survival of these interest features depends partly on sympathetic management of the surrounding land, and so the land in-between the watercourses is included within the SSSI boundaries.

Water levels are managed by penstock sluices (boards), tilting weir sluices and automatic sluices. For about six months over the summer, water levels are kept high in the ditches to protect the SSSI interest features. These ditches traditionally provide water for livestock, to effect field boundaries where they often also act as ‘wet fences’ to manage livestock, and for irrigation. In winter the ditch water levels are lowered to reduce the risk of flooding. The historic use of boards to pen the water levels in summer led to the establishment and preservation of the special aquatic flora and fauna for which the SSSIs were notified. Maintaining high and stable summer water levels is considered critical to support the plant and invertebrate features.

NRW manage and maintain the main reens by casting and de-weeding as necessary to maintain flood storage and conveyance capacity. Maintenance of field ditches is the responsibility of individual landowners.

The Gwent Levels Landscape of Outstanding Historic Interest is included in the Register of Landscapes of Historic Interest in Wales. This recognises the Gwent Levels as one of the most significant historic landscape areas in Wales. The quality of this uniquely rich historical and archaeological resource also makes it of international significance.

## 1.2 Requirement for this project

The following is copied directly from RSPB’s invitation to tender; *ITT_Gwent Level under-drainage.docx*:

*Because the water table of the Gwent Levels is generally high, some farmers would like to under-drain the land to extend the growing and grazing season, making farms more productive and viable. This activity, which requires the legal consent of NRW, is considered likely to be damaging for several reasons:*

- *The traditional system of field grips was (and where they still exist, are) effective at removing surface water but did/do not affect the underlying water table. With gripping alone, the water table is thought to be as little as 15cm below the surface, although this requires verification. With under-drainage, it is NRW’s understanding that water can be held 50-100cm below the surface.*

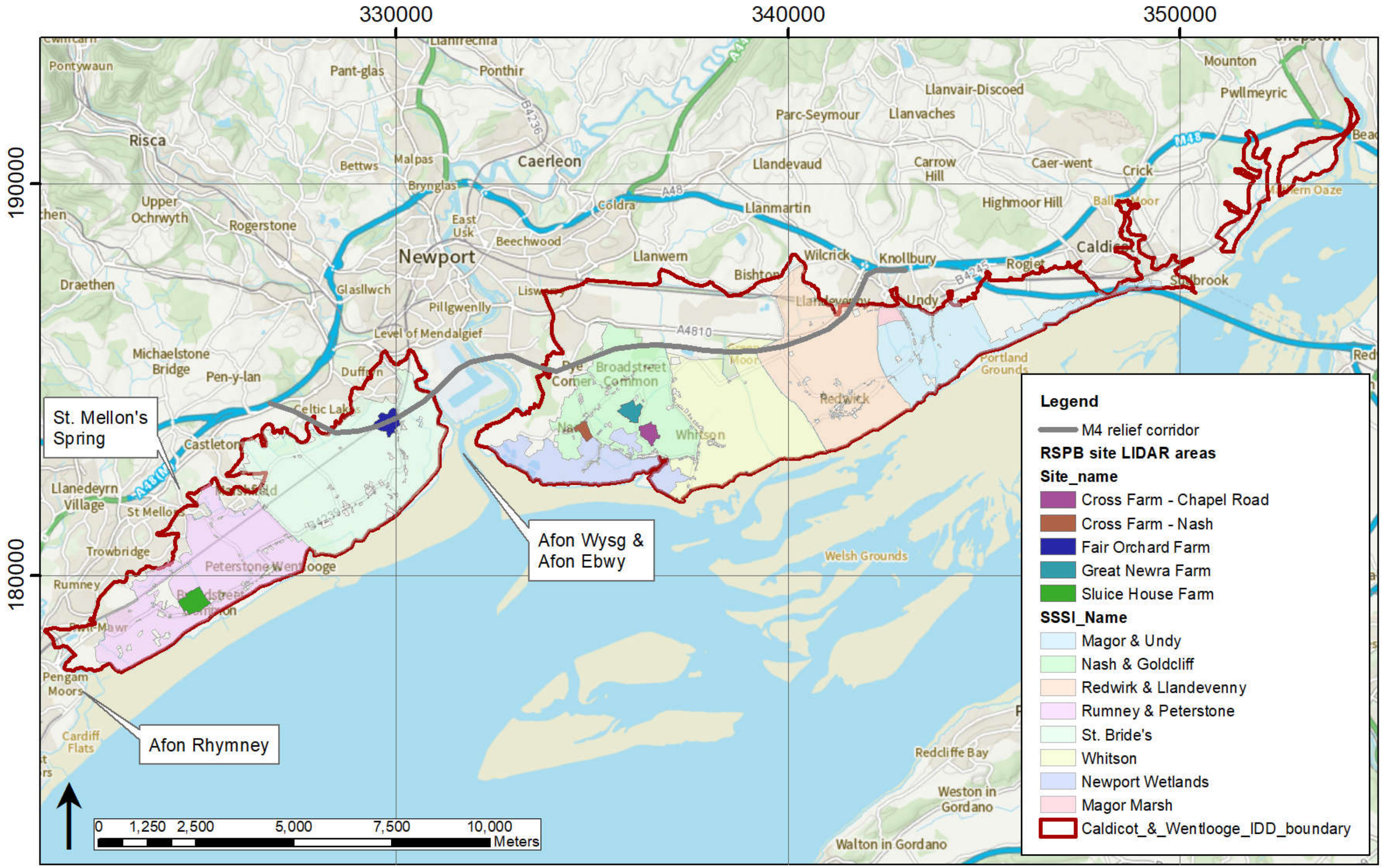

Figure 1.1-1. Map showing the extent of the Gwent Levels IDD area, and the locations of the project monitoring sites

- *NRW considers that the likely impact of lowering the water table in the fields would be that water in surrounding ditches and reens would need to be 'held' at a lower level so that the drainage system pipes can work. The water storage capacity of the fields might also be altered. Widespread impacts could include changes to flood and drought resilience and altered habitats. Ditches could also be lost entirely as, except for very large fields, under-drainage systems require only one reen whereas grips require two.*
- *Faster run-off rates are likely from under-drained fields, resulting in a system that is more 'flashy' with possible flood issues, water quality impacts, and damage to SSSI features and wider biodiversity, especially if nutrients are over-applied.*
- *Possible risk of increased nutrient and pesticide application as the farming season is extended or type of farming changes, with possible impacts to water quality and biodiversity.*
- *Direct loss of grips and grazing marsh habitats of cultural and biodiversity significance; the impact of draining of these habitats could be likened to the draining of a bog.*
- *Potential loss of sub-surface archaeological remains and/or damage to surface features as a result of drying of surface soil layers*
- *Permitting under-drainage in one place might also set (damaging) precedents for other sites and increase pressure for other damaging activities such as ploughing.*

*While under-drainage has not been permitted to date by NRW, requests to allow this activity are increasing. To ensure that the Gwent Levels is a protected and resilient landscape, a more detailed hydrological understanding of the system, including the traditional ridge and furrow drainage system is needed. In addition, better evidence about the impact of modern under-drainage systems and an understanding of how to balance the cultural and biodiversity value of this landscape with economic and farming needs and flood defence is required.*

## 1.3 The scope of work for this project[1]

Relatively little work has been carried out on the ecohydrology of the SSSI interest feature ditch communities within the Gwent Levels and, indeed, at a national level. The RSPB project was divided into two parts:

1. Assessment of the ecohydrological sensitivity of SSSI ditch community interest features to differences in types of field drainage.
2. Assessment of wider socio-environmental sensitivities to differences in types of field drainage.

During late-2019, RSPB commissioned Rigare Ltd, with associates, to carry out Part 1 of the project, and also selected lots of Part 2. The following is a summary of the work awarded to Rigare Ltd:

### 1.3.1 *Part One*

<u>Ecohydrological conceptual modelling</u>

1. Provide a qualitative conceptual assessment of the current hydrological regime of the Gwent Levels as a whole, and the six Gwent Levels SSSIs in particular.
2. A conceptual understanding of two key issues should be developed:
    a. the hydrological supporting conditions (HSC's) which the wetland feature/s requires at the site in question, and,
    b. the key mechanisms of water supply, water retention and water loss which enable HSC's to develop and be sustained.
3. The conceptual model should first establish how the existing traditional gripped drainage system works, including an assessment of the overall water budget across the system and how it affects water levels in field ditches and reens. Once that has been established the

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[1] Summarised from RSPB's invitation to tender; *ITT_Gwent Level under-drainage.docx*.

model should be applied to improve our understanding of the impacts of modern under-drainage systems.

Modern under-drainage

There are likely to be several types of under-drainage system that landowners might choose to use on the Gwent Levels. Coupled with this there are several different ‘field drainage systems’ typical of the landscape. The consultant is thus required to:

4. Detail and agree the modern under-drainage systems that should be considered as part of this study, and in doing so define what is meant by ‘modern under-drainage’ for the purpose of this study;
5. Determine and agree with the Under-drainage Project Team a number of locations where empirical data is to be collected. These locations should represent the range of field systems that are typically found on the Gwent Levels and should include fields with existing traditional gripped drainage systems (usually permanent pasture); under-drained fields with no surface grips (usually ploughed and in ley, silage or arable); fields with no surface grips but not currently under-drained. It may also be appropriate to include a field with historic/deteriorating under-drainage that is currently not being maintained.
6. If necessary, (following development of the conceptual model) define what further data and investigative methods to be employed e.g. dipwells or piezometers, and provide a rationale for their use.
7. Develop a model to help us understand what hydrological changes would occur should these modern under-drainage systems be installed, to include impacts on water levels in field systems, and in field ditches and reens. We also need to know the spatial scale of impact, whether impacts will be local or across some or all of the wider system, and how impact changes cumulatively.
8. Develop a model to understand the levels of drying in waterlogged soils that would occur as a result of hydrological changes and how this might affect buried archaeological features.

Impacts on the Gwent Levels SSSIs

The principal aim of this study is to better understand how different drainage practices and hydrological management might affect the features of the Gwent Levels SSSIs. The consultant is therefore required to:

9. Advise how the existing hydrological system (particularly gripped field drainage) supports the notified and qualifying features of the SSSI;
10. Advise how hydrological changes resulting from modern under-drainage might affect the notified and qualifying features of the SSSI (for example by affecting water levels or water quality in field ditches and main reens);
11. Advise whether modern under-drainage practices are compatible with the maintenance and enhancement of qualifying SSSI features;

### 1.3.2 *Part Two*

Address the following questions:

12. How habitats and biodiversity (in a wider context than SSSI alone) might be impacted;
13. How would hydrological changes result in changed drought or flood risk resilience?
14. How might hydrological changes impact on buried and surface archaeology?

Further questions under Part two of the project have been addressed by Reading Agricultural Consultants Ltd; these questions primarily addressed the relationship between field drainage type and farming, including costs and benefits for farmers, and how they might compare to maintaining traditional drainage systems.

## 1.4 Technical approach, project challenges and workflow

### 1.4.1 *Variety of drainage approaches under consideration*

It was recognised at an early stage of the project that monitoring of soil and ditch water levels would be required at a number of test sites. Unfortunately, primarily because of the need to maximise the monitoring period within the relatively short duration of the project, it was not possible to be selective over the sub-types of traditional drainage and under-drainage which were represented within the fields chosen for monitoring. As such, two sites with similar under-drainage were selected as representing a generic under-drainage type, and two fields with similar traditional drainage were selected as representing a generic traditionally-drained type. This has meant that, with the knowledge of the client and stakeholders, the requirements of items 4 and 5 under Section 1.3.1, relating to the variety of drainage systems which should be considered, have not been completely fulfilled; it is not thought that this limitation has reduced the utility of the results of the project significantly.

### 1.4.2 *Strategy for gaining time-series field discharge data*

Also at an early stage of the project, it was recognised that ditch water depth regime was the primary variable through which hydrological supporting conditions for ditch plant and invertebrate SSSI interest features can be defined (Section 3.3.2). The sensitivity of ditch water depth regimes to field drainage type is directly related to the temporal variation of the rate of water entering ditches from fields (i.e. field discharge), and therefore, ideally, field discharge would be measured directly. However, a number of problems were identified in this regard, such as:

- The technical challenges presented by site-specific installations, such as; 1) pipe diameters and elevations, and broken (or an absence of) headland pipes in the case of traditional drainage systems, 2) the likelihood that flow monitoring devices on the ends of field drainage pipes would be transiently ‘drowned-out’ by high ditch water levels, and 3) the low expected velocity being outside of the instrument specification for significant periods of the monitoring programme.
- The difficulties in precisely defining a catchment for a particular drainage pipe, which would be important in relation to calculating drainage rates per unit area.

It was decided that any attempt to measure field discharge directly within the timescale of the project would carry a very high risk of compromising data availability and quality, and it was not attempted. Rather, it was decided to monitor soil water levels and ditch water levels (Section 5) and; 1) to interpret the resulting data to understand hydrological functioning, and 2) using the monitored soil and ditch water levels to verify that relatively simple numerical groundwater/surface water models were representing the hydrological system adequately, and then using these models to simulate field discharge.

### 1.4.3 *Direct and indirect environmental impacts of under-drainage*

In assessing environmental sensitivities to drainage practices, which has ultimately been focussed on the possible effects of more widespread implementation within the Gwent Levels, a distinction has been made between:

- Direct impacts. Such impacts would be a direct effect of the change to drainage including, for example, any impacts on the ditch water depth regime through which hydrological supporting conditions for the ditch-based SSSI interest features are defined. They also include effects on flood or drought risk. These impacts are assessed separately, in Sections 9 and 10.
- Indirect impacts. These impacts relate to secondary changes, driven by socio-economic factors, which might occur as a result of more widespread adoption of under-drainage. Identification of these secondary changes is, of course, somewhat speculative, and therefore assessment of their impacts is provided as a ‘what if’ scenario for the relevant environmental managers. The secondary changes which might result from a more widespread adoption of under-drainage, and their possible ecohydrological and hydrological impacts, are discussed in Section 11.

### 1.4.4 *SARS-CoV-2 Pandemic*

It is worth noting that the duration of the project (January 2020 to August 2021) was coincident with the initial and worst part of the SARS-CoV-2 Pandemic (February 2020 to mid-2021), and associated travel restrictions. Fortunately, whilst field visits were severely limited during the worst of the Pandemic, the only related limitations have been:

- Hydrometry at three of the five sites was installed in March 2020, a short time before unnecessary travel was stopped. This meant that installation of hydrometry at the other two sites occurred five months later, during August 2020, with obvious data loss. Fortunately, the first three sites to be instrumented included a traditionally-drained site, an under-drained site, and the under-drained site with traditional drainage micro-topography. As such, datasets representing the full possible monitoring period were available for each drainage type.
- Ideally, the automatic water level recorders (AWLRs) would be downloaded on a six-monthly basis to avoid data loss. This was not possible during this project, although no AWLR failures were encountered, so no data were lost in this regard.
- A stilling well, an AWLR and an automatic barometric pressure recorder (ABPR) were lost to ditch-clearing operations at Sluice House Farm; it might have been possible to replace this monitoring during the monitoring period had more frequent visits been possible. In fact, the second stilling well provided high-quality ditch water level replacement data for the lost stilling well, and the ABPR located in the Caldicot Level has successfully been used for all data processing.

It is concluded that the quality of project deliverables has not been affected significantly by the Pandemic.

### 1.4.5 *Workflow*

The main project events have been:

- Autumn 2019; project awarded.
- January 2020; visits to prospective monitoring sites.
- March 2020; installation of hydrometry at three sites.
- July 2020; surveying of ditch plant and invertebrate communities at the monitoring sites, as reported in Graham and Hammond (2020), with a summary included here within Section 3.
- August 2020; installation of hydrometry at the remaining two sites.
- April 2021; first complete download of AWLRs and ABPR.
- August 2021; retrieval of AWLRs and ABPR, moth-balling of dipwells and stilling wells.
- August and September 2021; analysis and reporting.

## 1.5 This report

This report is organised as follows:

- The larger-scale ecohydrological conceptual model for the ditch plant and invertebrate SSSI interest feature communities is developed firstly through an examination of the hydro-environmental setting of the Gwent Levels in Section 2. The ecohydrological aspects of the conceptual model are presented in Section 3, including identification of the variable through which the hydrological supporting conditions for the SSSI interest features can be defined.

  The large-scale ecohydrological conceptual model for the ditch plant and invertebrate SSSI interest feature communities is then presented in Section 4.
- The methods used for hydrological data collection, and site-specific details of data collection are given in Section 5.
- A qualitative interpretation of the hydrometric data for all of the sites individually, and then in comparison, is given in Section 6.

- Separate small-scale, or field-scale, ecohydrological models for traditionally-drained and under-drained fields are presented in Section 7.
- The groundwater and surface water modelling, which was used to derive field runoff data, is described in Section 8, including the design and construction of the model, demonstration of its capability to simulate the monitored behaviour, and key simulation outputs.
- Assessment of the ecohydrological effects of installation of under-drainage, when compared with traditional drainage is included as follows:
    - Section 9; assessment of the direct ecohydrological effects.
    - Section 10; assessment of the drought- and flood-risk implications.
    - Section 11; assessment of the indirect ecohydrological effects, i.e. those that would occur following secondary land-use and practice changes which might result from more widespread adoption of under-drainage.

## 1.6 Definitions

Traditionally, fields on the Gwent Levels have been drained through a *ridge and furrow* system which routinely consists of an orthogonal grid of shallow, linear drainage lines (furrows) separated by higher ground (ridges).

Pickup (2015) notes that ridges were often five to seven yards from crest to crest, although there was considerable variation[2]. The common ridge and furrow morphology is evident as the corrugations seen in the monochrome LIDAR image on the front cover of this report, and is easiest to identify in the field during wet periods, when the furrows are often inundated (e.g. Figure 1.6-1).

## 1.7 Acknowledgements and contact details

The help and cooperation of the following people are fully acknowledged:

- Lewis Stallard (RSPB project manager) who emigrated to Canada during summer 2021.
- Fiona Walker (RSPB project manager).
- Angela Hunt, Kate Rodgers and Kerry Murton (NRW, primary stakeholders).
- John Southall (NRW IDD manager).
- Tony Pickup (retired NRW IDD manager).

And the following farmers who kindly allowed investigations, primarily water level monitoring on their farms:

- Andrew Waters of Cross Farm, Nash.
- Jeff Rowland of Great Newra Farm, Broadstreet Common.
- Derek David of Fair Orchard Farm, nr. St Bride’s Wentlooge.
- Andrew Prosser of Sluice House Farm, nr. Peterstone Wentlooge.

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[2] The field drainage terminology used here is that from Pickup (2015) which identifies ridges, furrows and grips. The first two are described in the main text above. Grips are described as shallow trenches which are dug at the base of furrows, and sometimes at right-angles to them. They required frequent cleaning to maintain their function. It is possible that ridge and furrow micro-topography developed over a long period of time through repeated clearance of grips, with arisings cast on to adjacent ridges. No grips were present within the monitoring sites chosen for this project, and none have been seen by the author on visits to other sites. It was concluded that they are currently uncommon, and therefore their hydrological influence has not been considered here.

It is worth noting that furrows are often referred to as grips; the distinction between furrows and grips, as defined in Pickup (2015), is maintained here for clarity.

Requests for further information relating to the project should be directed to:

- In the first instance, Fiona Walker, RSPB project manager; fiona.walker@rspb.org.uk.
- Or Rob Low, project consultant; rob@rigare.co.uk.

Figure 1.6-1. Oblique aerial photograph looking south-east across part of St. Bride's SSSI (February 2020, Nick Beddoe). The orthogonal ridge (dry ground) and furrow (standing water) topography within the fields can be seen.

# 2 Hydro-environmental setting of the Gwent Levels

## 2.1 Climate

### 2.1.1 *Rainfall*

Climatic averages for the Cardiff (Bute Park) weather station, reported on the Met Office website[3], are given in Table 3.2-1. This station is located c. 5 km west of the western end of the Gwent Levels, within the centre of Cardiff, and at a similar altitude to the Gwent Levels (i.e. close to sea level).

Rainfall data were also obtained from NRW for Colister Pill raingauge (344501 186791) at the eastern end of the Gwent Levels. The average (2005-2020) annual rainfall for this gauge was 927 mm.

Assuming that the climate monitored at Cardiff is reasonably similar to the climate on the Gwent Levels:

- The Gwent Levels are warmer than the UK average, in terms of both maximum and minimum temperature, reflecting both their location in the southern half of the UK, and the maritime influence here.
- Average annual rainfall on the Gwent Levels is very similar to the UK average, as is the average number of rain days.
- The reported average annual rainfall at Collister Pill is slightly less than that at Cardiff; this discrepancy is probably explained by the period for which the averages are calculated being different, and the raingauges being separated by c. 30 km.

Table 2.1-1. Annual climatic averages (1981-2010) for the Cardiff (Bute Park) weather station.

| **Parameter** | **Cardiff** | **UK** | **Cardiff v. UK*** |
|---|---|---|---|
| Max. temperature (°C) | 14.7 | 12.4 | +2.3 |
| Min. temperature (°C) | 7.0 | 5.3 | +1.7 |
| Sunshine (hrs) | 1549.4 | 1372.8 | +176.6 (+12.9%) |
| Rainfall (mm) | 1151.9 | 1154 | -2.1 (-0.2%) |
| Rainfall (>1 mm) days | 148.6 | 156.2 | -7.6 (-4.9%) |

* Percentages calculated with respect to UK average

### 2.1.2 *Potential evapotranspiration*

Daily potential evapotranspiration (PEVT) data, calculated through the Meteorological Office Rainfall and Evaporation Calculation System (MORECS)(Hough and Jones, 1997) was obtained from the Meteorological Office for the period 1st January 2020 to 1st July 2021. The data were obtained for the 40 x 40 km square No. 156, which covers most of the Gwent Levels. The daily PE values reflect the equivalent depth of water which would transpire from a grass pasture if there was unlimited water. In practice there are usually water constraints; these were estimated during the numerical modelling (Section 8).

Figure 2.1-1 shows the time series daily PEVT values along with a nine-day running mean. It can be seen that there is a 'sine-wave' annual progression of PEVT, falling to a nine-day mean of c. 0.5 mm/d during December and January, and rising to 3.5-4.0 mm/d during June and July. The daily highest values of 6-7 mm/d in late-May and late-June 2020 appear to have been exceptional.

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[3] https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gcjszmp44 accessed 11th August 2021.

No data were available to place the PEVT data for the monitoring period in the context of long-term averages, but it is generally accepted that the progression and magnitude of PE varies relatively little year-to-year, and certainly much less than rainfall.

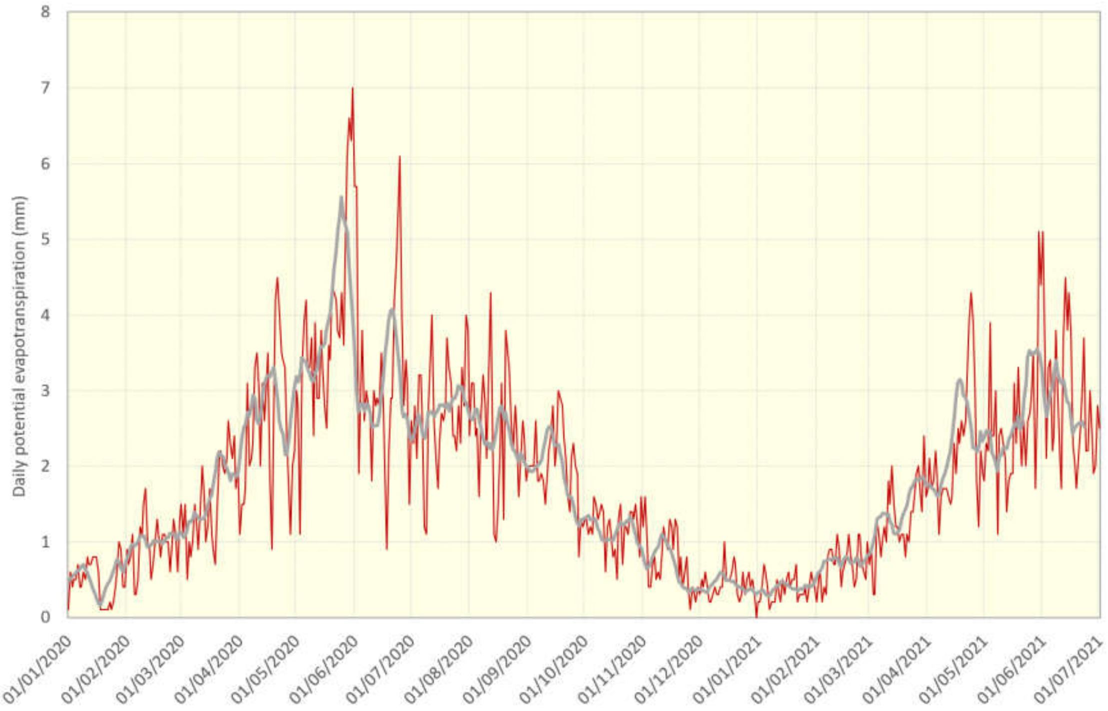

Figure 2.1-1. Time-series daily PEVT and nine-day running mean.

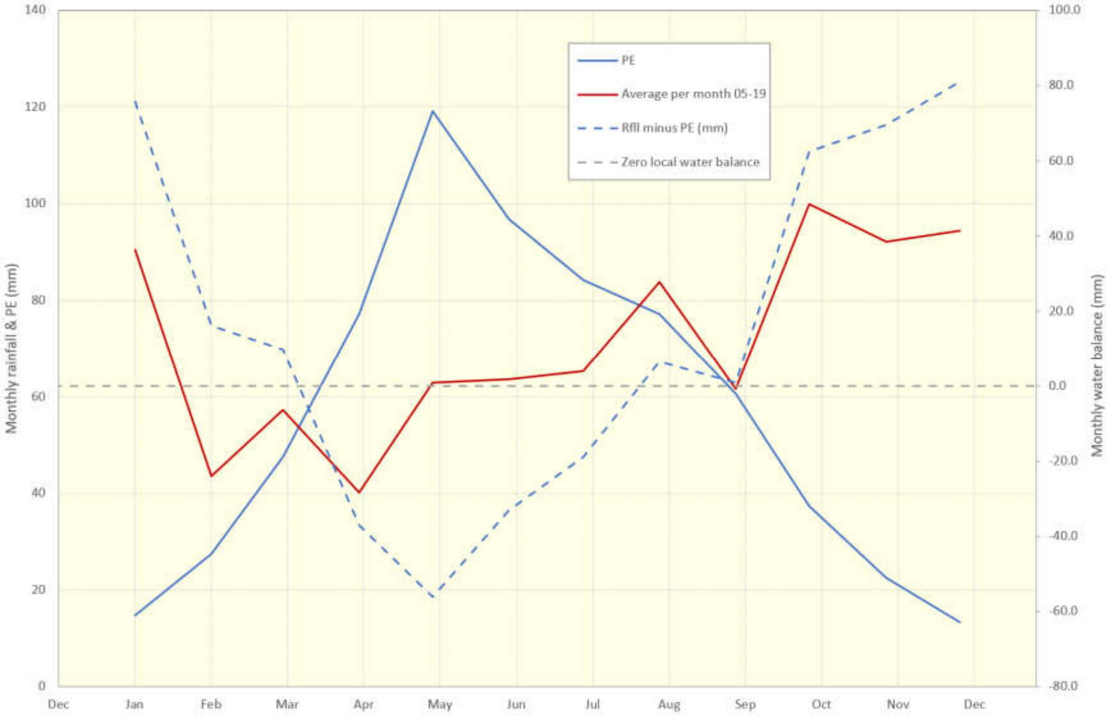

Figure 2.1-2. Scoping-level monthly local rainfall, evapotranspiration and water balance for the Gwent Levels.

### 2.1.3 *Monthly rainfall and PEVT balance*

In order to contribute to an understanding of the larger-scale hydrological functioning of the Gwent Levels, it is useful to consider the dynamic balance between rainfall and evapotranspiration. If rainfall is higher than evapotranspiration, the local water balance is positive, whereas if rainfall is less than evapotranspiration, the local water balance is negative.

Figure 2.1-2 shows time-series monthly aggregate values for:

1. Average (2005-2020) rainfall for the Colister Pill raingauge.
2. Monthly PEVT for MORECS square 156 (Section 2.1.2) for the period 1st January 2020 to 31st December 2021.
3. Rainfall minus PEVT, i.e. the local water balance.

The use of PEVT for the calculation of the water balance here is potentially simplistic as actual evapotranspiration (AEVT) can be less than PEVT because of soil water availability dynamics. However, since monitoring (Section 6) has shown that soil water levels were almost always above 1.5 mbGL, and therefore within the rooting depth of grass, it can be assumed that actual evapotranspiration is mostly at potential rates for this initial, scoping analysis. Model-simulated actual evapotranspiration for the monitoring plots is discussed in Section 8.

Considering Figure 2.1-2, it can be seen that the local water balance is negative, or very close to negative, for the warmer months, April to September inclusive. During this period, on average more water is lost to evapotranspiration from the Levels than is gained from rainfall. Therefore, if the Levels were isolated from other sources of water, the volume of water stored within the levels would gradually reduce, meaning that soil and ditch water levels would fall.

## 2.2 Topography

At the regional scale the Gwent Levels form a relatively flat coastal plain, with the break of slope running along its north-western edge (roughly coincident with the northern boundary of the IDD in Figure 1.1-1); the ground rises relatively steeply from this line, to the higher ground north of Cardiff from the Wentlooge Level, and Wentwood Hills north of the Caldicot Level.

The more subtle topographic variation within the Gwent Levels is of more interest for this project. Figures 2.2-1 and 2.2-2 (included at the end of the section) present colour-coded ground surface elevations for the Wentlooge (western) and Caldicot (eastern) areas of the Levels respectively, derived from the LIDAR[4] data available from the Welsh Government *Lle.gov.wales* website.

Considering Figure 2.2-1:

- It is worth re-stating the ‘flatness’ of the Levels, which is evident in this figure. The IDD area of the Wentlooge Level is around 11 km long, and practically all of the ground falls within the 3.5-7.0 maOD bracket.
- That said, systematic large-scale, small magnitude topographic variation is apparent, with a large nucleus of the lowest ground in the central northern area (surrounding Marshfield). The ground rises consistently, but gradually, from the nucleus, to reach the highest levels at the north-eastern and south-western ends.
- In general, and perhaps counter-intuitively, the ground generally falls inland from the coast; this reflects its reclaimed origins.

And Figure 2.2-2:

- The IDD area of the Caldicot Level is around 15 km long, over most of which ground levels fall within the 4.0-6.5 maOD bracket.
- Again, there is systematic large-scale, small magnitude variation; in general, the lowest ground is along the central reach of the northern boundary, and ground levels rise towards the coast to the south, and the Usk estuary to the west.
- The artificial ground levels associated with industrial and other development can be seen in the north-western part of the Caldicot Level, along with the line of the M4 motorway to the north-east.

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[4] Light Detection And Ranging

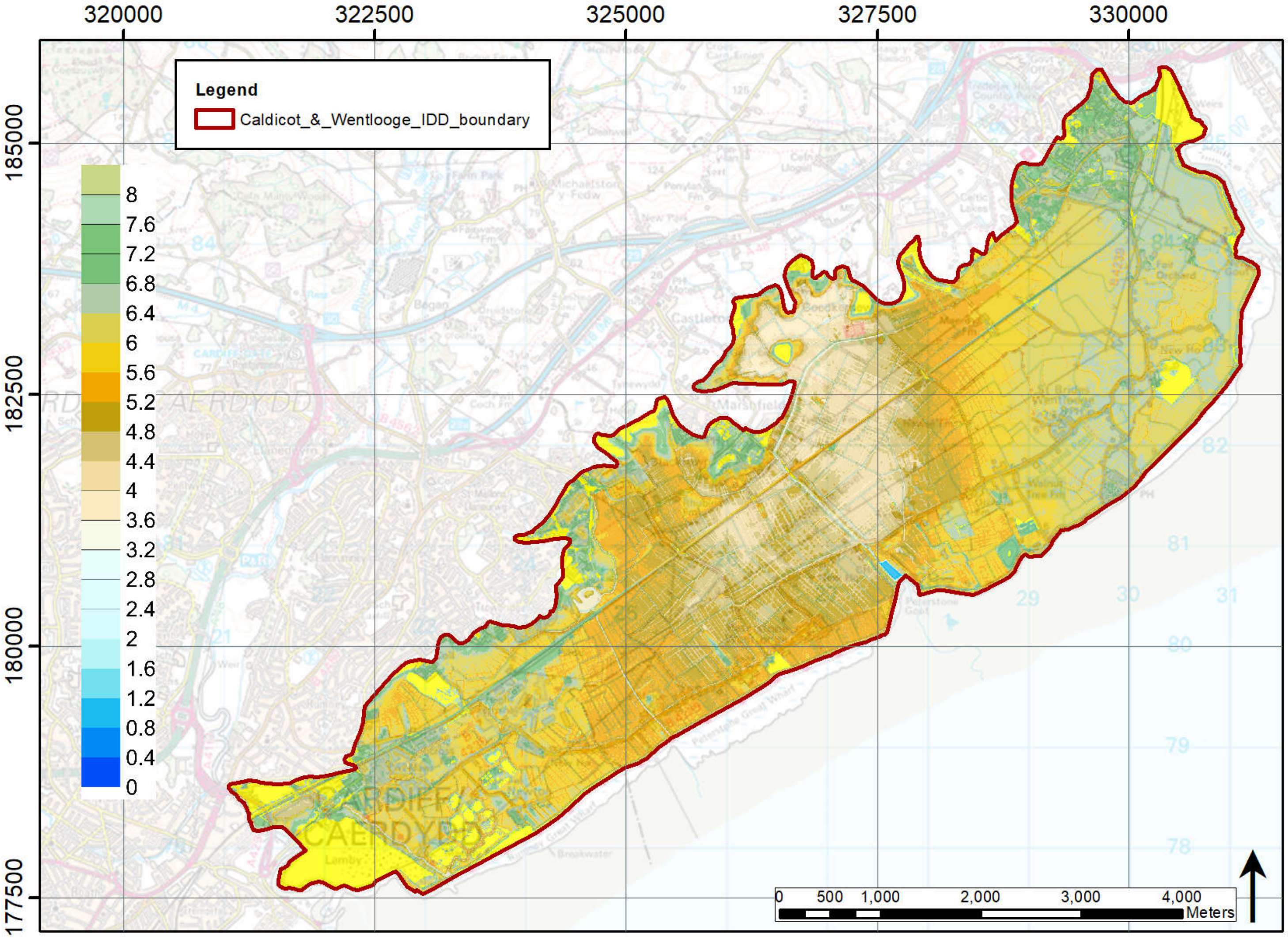

Figure 2.2-1. Colour-coded ground elevation LIDAR data for the Wentlooge Level (bright yellow areas are above 8 maOD).

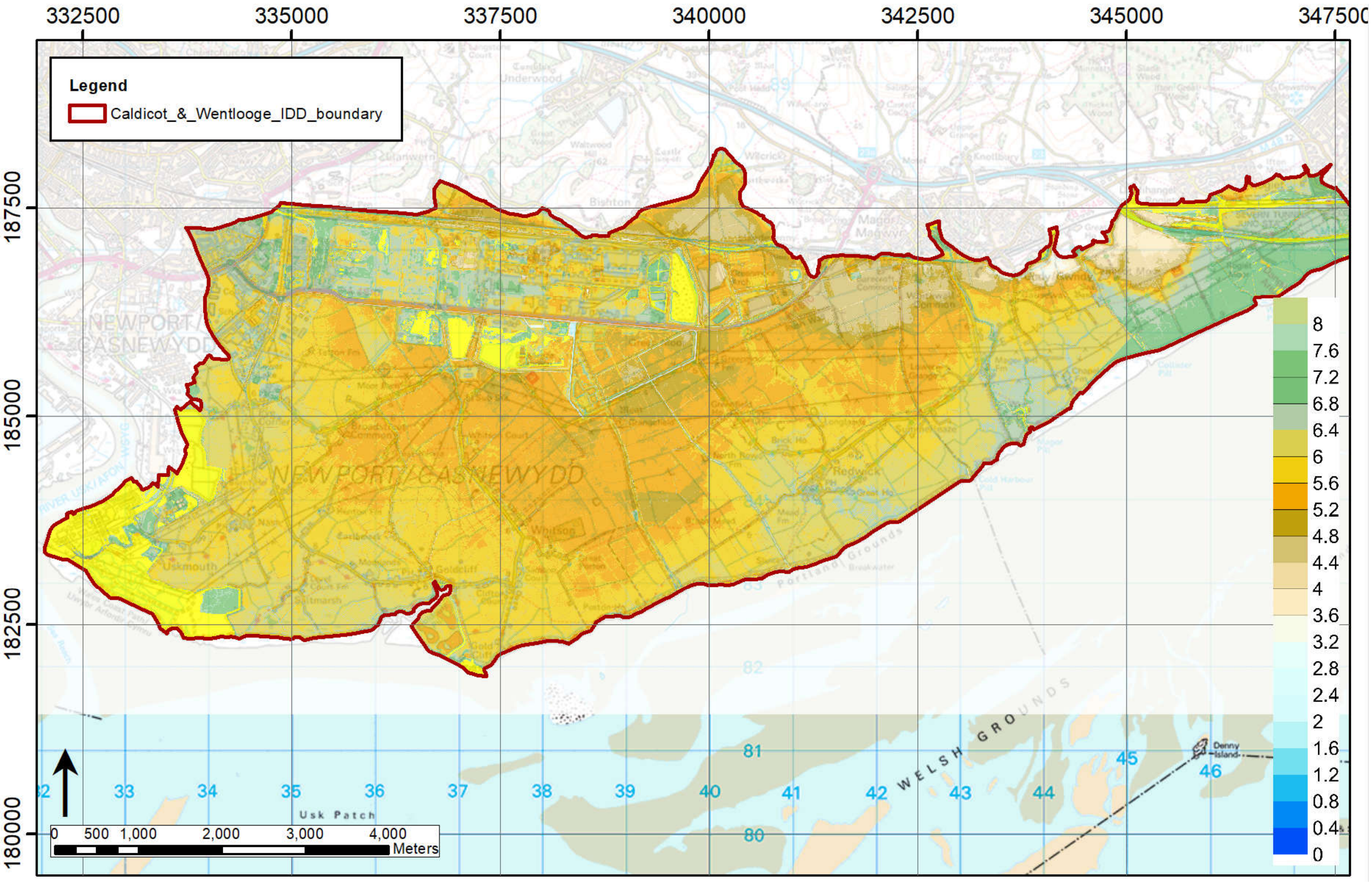

Figure 2.2-1. Colour-coded ground elevation LIDAR data for the Caldicot Level (bright yellow areas are above 8 maOD).

## 2.3 Geology

Geology in the UK is routinely considered under a higher-level, two-division scheme, as follows:

- Superficial deposits. These are the youngest geological formations (less than 2.6 million years ago); they are largely unconsolidated and cover much of the bedrock in Britain. They generally include sediments deposited during the Pleistocene (Quaternary) glacial episodes, and subsequent Holocene rivers and coastal systems.
- Bedrock. These are the largely solid (consolidated), and older rocks which lie beneath superficial deposits, or crop out at the surface where there are no superficial deposits.

The bedrock geology of South Wales is relatively complex, and because the study area is relatively large, it encompasses quite a lot of that complexity. However, in the context of the study, only a general understanding of the bedrock geology is sufficient. Figures 2.3-1 and 2.3-2 are bedrock geology maps, based on the British Geological Survey (BGS) 1:50,000-scale mapping. The bedrock geology can be divided into two parts:

- Older rocks are at the surface (i.e. crop out), generally immediately to the north of the Gwent Levels. These are the Ditton and Brecon sub-groups of the Devonian period (formerly called the Old Red Sandstone) to the north of the western and central parts of the Gwent Levels, and the Carboniferous Limestone to the north of the eastern part. These rocks represent the southern limb of the larger South Wales syncline (the axis of which runs approximately east-west across the South Wales valleys); the rocks which crop out to the north of the Gwent Levels re-appear at the surface much further north, in the Usk valley, on the northern limb of the syncline. These older rocks dip at the large-scale to the north-north-west in the vicinity of the Gwent Levels, although there is local variation.

  Moving north away from the Gwent Levels, the St Maughan's Formation, and then the Raglan Mudstone Formation, crop out. The Brownstones Formation crops out to the east.

  Squirrell and Downing (1969) notes that there is wide lithological variation within the Old Red Sandstone. Red marls, striped or spotted green, predominate in the Raglan Mudstone and St. Maugham's Formations, and are subordinate in the Brownstones Formation. Sandstones occur sporadically in the Raglan Mudstone Formation, and more commonly in the St. Maugham's Formation, where they are locally very thick in the lower half of the succession. The lowest bed of the St. Maugham's Formation is commonly a white or pale grey, sometimes conglomeratic sandstone. The Brownstones Formation is dominated by sandstone.

  One of the most characteristic features of the Old Red Sandstone is the abundance of calcareous deposits in the Raglan Mudstone and St. Maugham's Formations, ranging from limestone nodules in marl to beds of limestone up to 8 m thick.

- Mercia Mudstone Group rocks, of the younger Triassic period, underlie most of the Gwent Levels. These rocks are unconformable with the underlying older rocks, meaning that they were deposited after tectonic alteration and/or erosion of the older rocks. The general situation is illustrated in Figure 2.3-3, which is a geological cross-section running approximately north-south through Cardiff (after BGS, 1986).

  Squirrell and Downing (1969) describes the Mercia Mudstone Group rocks as red, brownish-red or purplish-red mudstone or silty mudstone.

The BGS 1:50,000-scale mapping of the superficial deposits shows the Gwent Levels to be almost completely covered in Tidal Flat Deposits (Clay and Silt), with small outcrops of River Terrace Deposits, and larger expanses of Glacial Till, occurring immediately to the north of the Levels. The mapping is not reproduced here.

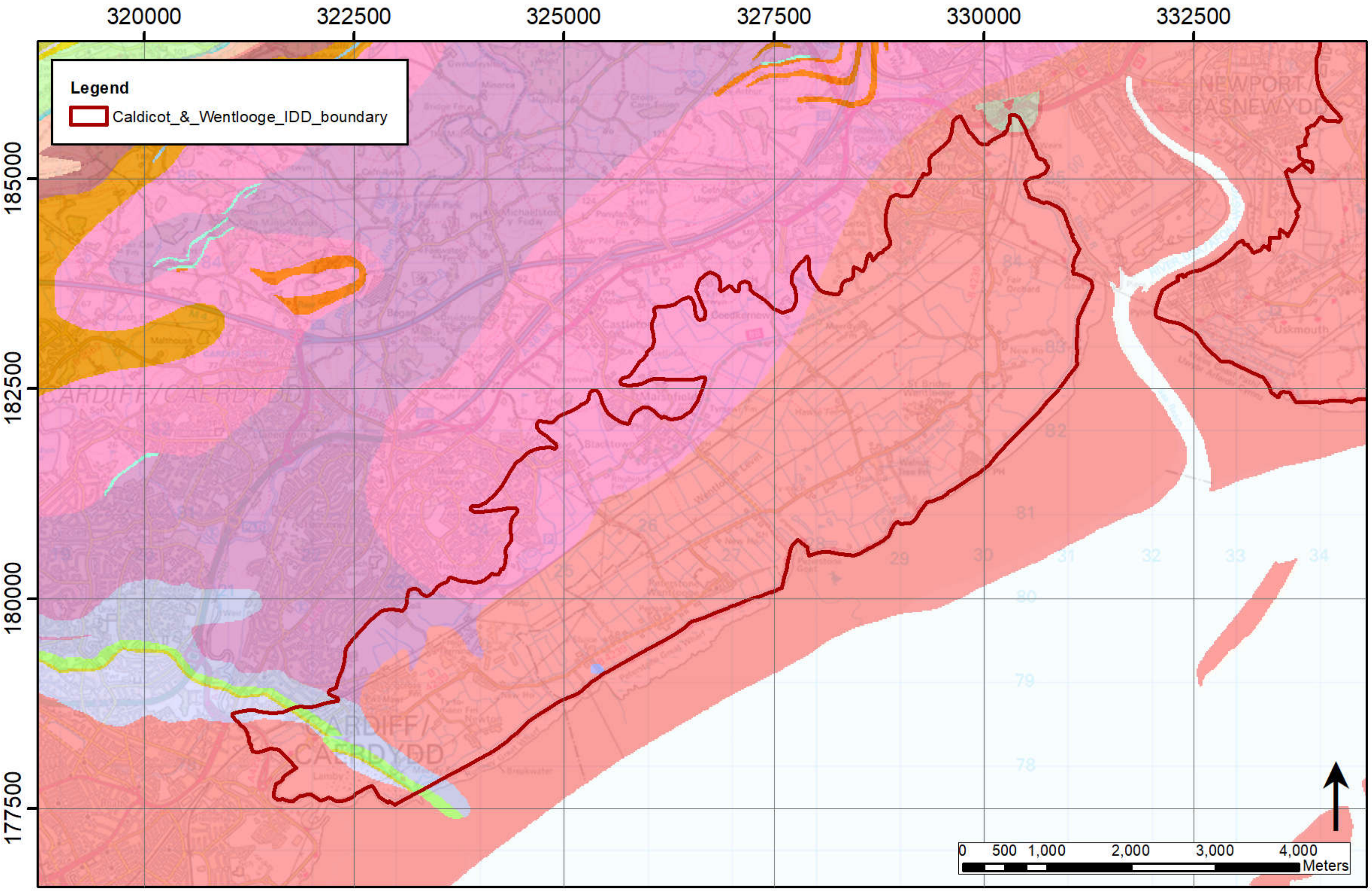

Figure 2.3-1. An extract from the BGS 1:50,000-scale bedrock geology mapping; Wentlooge Level and vicinity. Key: Red = Mercia Mudstone Group (Triassic); Pink = St. Maughan's Formation (Devonian); Purple = Raglan Mudstone Formation (Devonian).

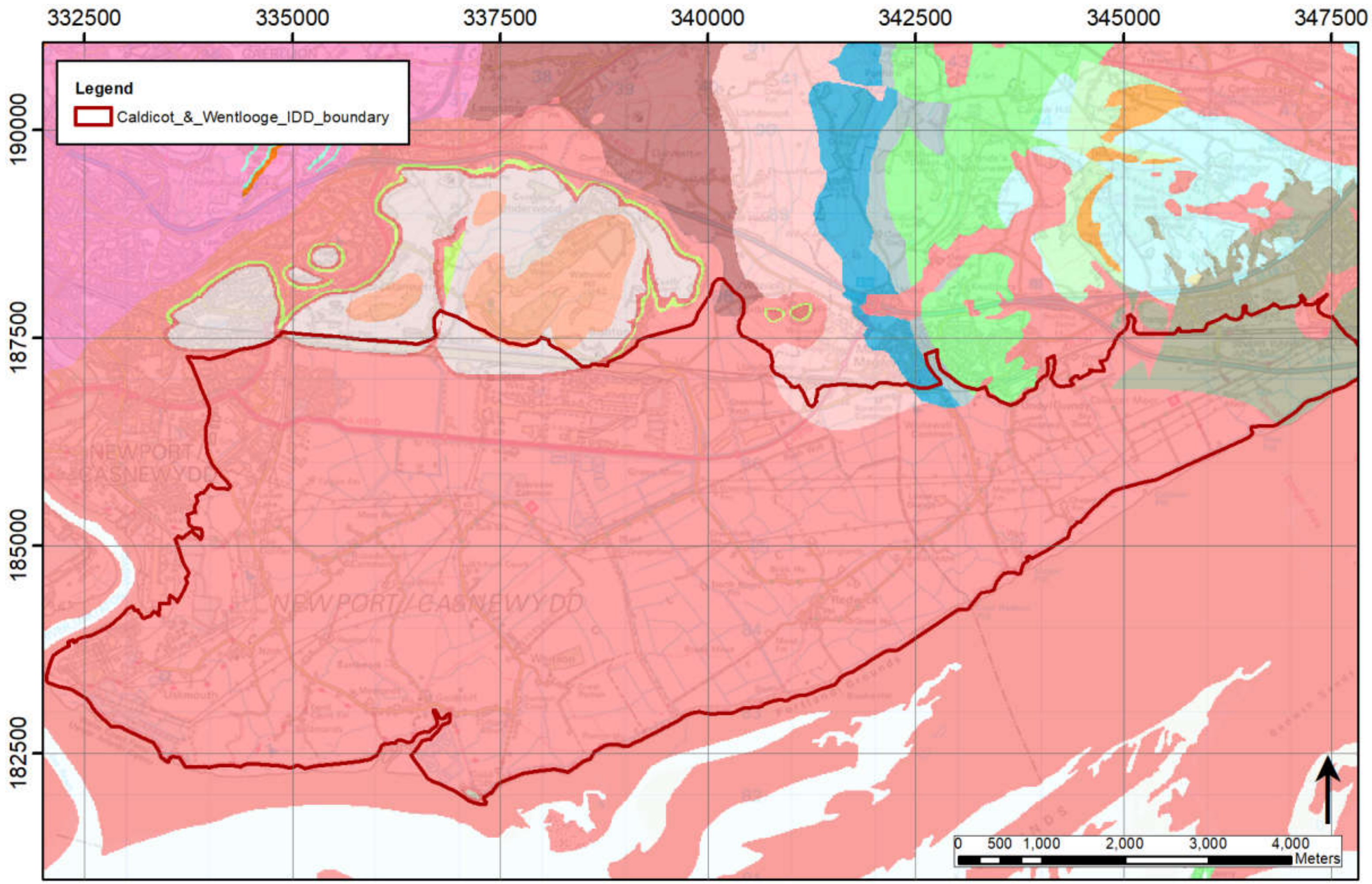

Figure 2.3-2. An extract from the BGS 1:50,000-scale bedrock geology mapping; Caldicot Level and vicinity. Key: Red (and other colours surrounded by red, e.g. grey, salmon, etc) = Mercia Mudstone Group (Triassic); Dark red= Brownstone's Formation (Devonian), Pink = St. Maughan's Formation (Devonian); Blues/Greens/Grey to the north-east = Carboniferous Limestone.

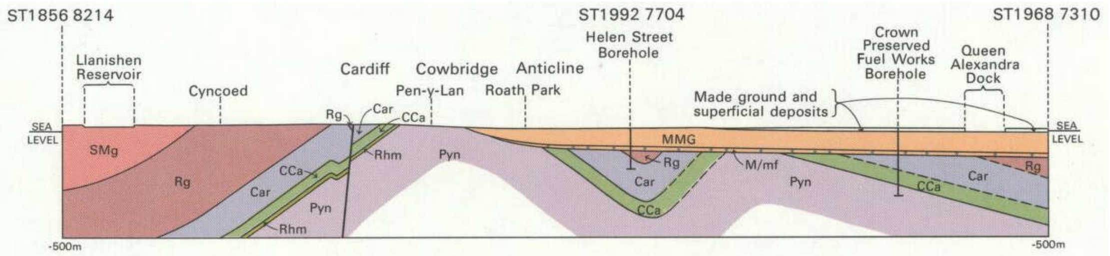

Figure 2.3-3. Illustrative geological cross-section running north (left) to south (right) through Cardiff, immediately to the west of the study area. The unconformable nature of the Mercia Mudstone rocks (MMG), above the older (Devonian, coloured red, purple and green) rocks can be seen. This general north-south arrangement extends over most of the Gwent Levels.

An extremely useful description of the Late Quaternary stratigraphy (i.e. the superficial deposits) within the Gwent Levels is given by Allen (2011), developed from collation and analysis of 882 borehole records and other information. To summarise:

- The Gwent Levels are underlain by a (Mercia Mudstone – see above) rockhead platform at -5 to -7.5 maOD, which is intricately dissected by river valleys. The cutting of the river valleys is assigned to the pre-Ipswichian (i.e. older than 127,000 years), and they are infilled with sands and gravels.
- The infill deposits occur along the inner margins of the Levels, where they mark a former coastal zone.
- The overlying Holocene (11,650 years to present) deposits consist of alternating estuarine silts and peats, are typically 10-15 m thick, and are very variable stratigraphically.

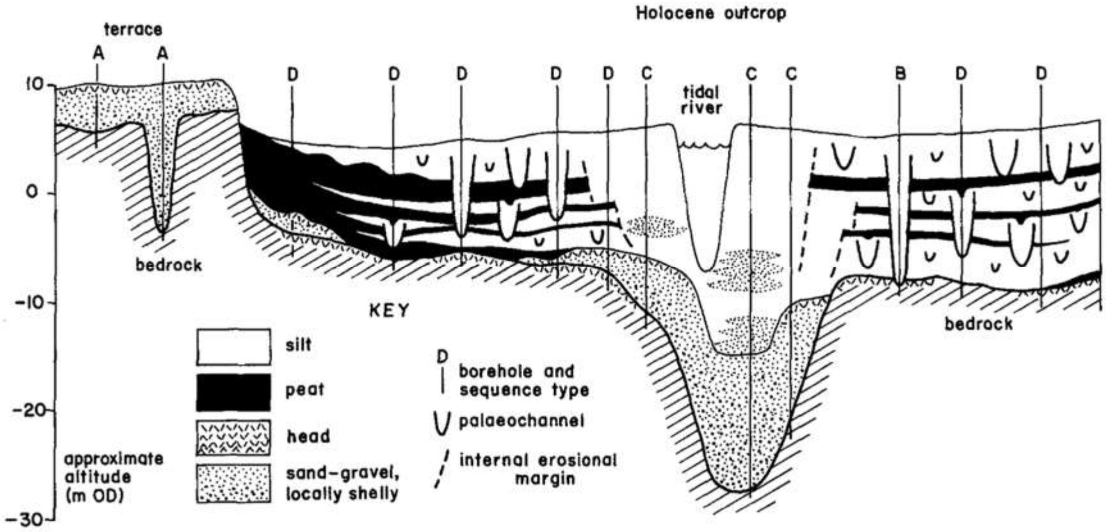

Figure 2.3-4. Figure 2 of Allen (2001) which is titled; "Highly schematic cross-section illustrating late-Quaternary stratigraphy in the Gwent Levels....".

- Near the rivers that cross the Levels the Holocene deposits are dominated by thick silts, commonly with basal or intercalated, fine- to medium-grained, grey sands in the lower half, accompanied by similar sequences that include a basal peat. These outcrops probably represent the zones within which streams and rivers wandered over the duration of the Holocene.
- Remote from lines of drainage, the Holocene deposits are a highly variable succession of alternating silts (salt marshes and mudflats) and peats (highest intertidal-terrestrial marshes). The peats tend to thicken inland, but individual beds appear and disappear locally as a result of the dynamic, coastal depositional environment.

## 2.4 Groundwater hydrology

### 2.4.1 *Hydraulic properties*

Jones *et al* (2000) notes that the permeability of the Old Red Sandstone is limited, in part because of the variety of lithologies encountered. Siltstone, mudstones and marls are all prominently interbedded with sandstones, and these fine-grained rocks provide a lithological barrier to horizontal and vertical groundwater flow. In general, the predominant Old Red Sandstone flow mechanism is via fractures, with much of the storage likely to occur in joint- and fault-related fracture systems.

The strata of the Old Red Sandstone appear to behave as a complex, multi-layered aquifer, with sandstone bands being hydraulically isolated by intervening mudstones. The effective saturated thickness is taken as 40 m, owing to the effect of fracture closure with depth.

Allen *et al* (1997) notes that the Carboniferous Limestone, which crops out immediately to the north of the eastern part of the Caldicot Level, is recognised as a highly permeable aquifer as a result of a pervasive network of productive fractures in the otherwise dense crystalline rock.

The lithological descriptions of the Mercia Mudstone Group rocks, and the overlying Tidal Flat Deposits imply that they are poorly permeable.

### 2.4.2 *Groundwater levels and groundwater flow*

Since the Old Red Sandstone which forms the higher ground to the north of the Gwent Levels is, at the larger-scale, poorly permeable, it can be assumed that its water table is generally close to the ground surface. Groundwater will discharge from the Old Red Sandstone:

1. At higher elevations on the outcrop, where the water table intersects the ground surface; this discharge can sometimes be *stratigraphically controlled*, meaning that groundwater within a more permeable sandstone layer is forced to the surface by the presence of a poorly permeable layer of marl.
2. At or close to the break of slope between the higher ground to the north, and the Gwent Levels to the south. The assumption here is that the permeability of the bedrock beneath the Gwent Levels is relatively low, and therefore that southwards groundwater flow within the bedrock and in the superficial deposits is limited. 'Excess' groundwater is forced out along the break of slope; there are a small number of springs marked along this break of slope on the OS 1:25,000-scale mapping, but it is thought likely that many of the reens which extend into this area are spring-fed to some degree; the large cross-sectional area combined with relatively low springflows often make it difficult to detect water movement.
3. The aggregate volume of the Old Red Sandstone within catchments which drain south towards the Gwent Levels is large. This means that, despite its being generally poorly permeable, it represents a significant upgradient store of water at the end of the winter/spring groundwater recharge season, and that gradual depletion of the store of water during the warmer months will mean that springflows are generally maintained; this is important in relation to the management of the Gwent Levels (see Section 4).

NRW has no observation boreholes within the Gwent Levels, but a large number were drilled during environmental baseline studies (e.g. Welsh Government, 2016) for the proposed M4 relief road, the line of which is shown in Figure 1.1-1. Figure 3 of Welsh Government (2016) is reproduced as Figure 2.4-1 and shows groundwater levels along the line of the proposed road. It is important to remember that the line of the proposed road passes through the northern margins of the Gwent Levels, which explains the significant relief when compared with the wider Levels. Figure 2.4-1 shows:

1. Generally, groundwater levels in the Tidal Flat and Glaciofluvial Deposits are above those in the underlying bedrock, demonstrating a downwards hydraulic gradient; whether this downwards hydraulic gradient condition extends widely, further south within the Levels, is uncertain.
2. Groundwater levels in the Glaciofluvial Deposits and the bedrock are lower in the vicinity of the Rivers Usk and Ebbw, probably indicating hydraulic continuity with the rivers.

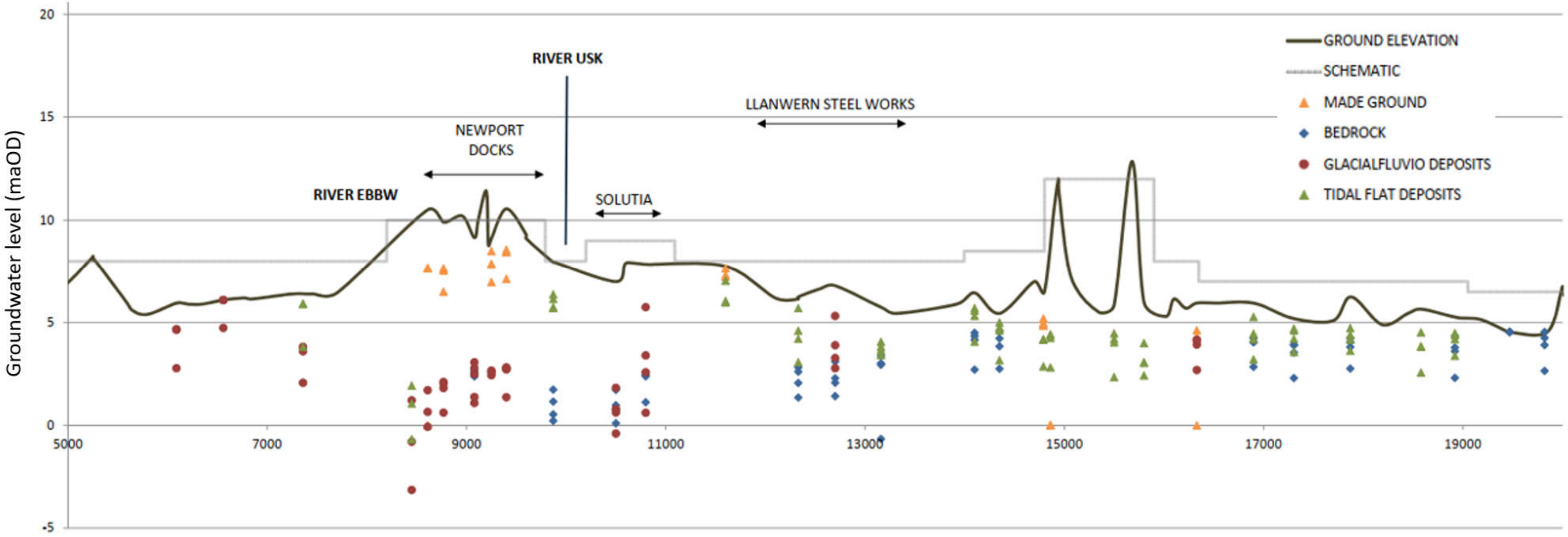

Figure 2.4-1. Groundwater levels in various formations along the line of the proposed M4 relief road (Figure 3, Welsh Government [2016]). The line of the road is shown in Figure 1.1-1, and this figure runs from west (left) to east (right) along that line.

Vertical groundwater flow within the Gwent Levels, potentially upwards or downwards between the Tidal Flat Deposits and the bedrock, is controlled by vertical conductance of the substrate and the hydraulic gradient. Vertical hydraulic gradients over the Levels, as noted above, are somewhat uncertain, although it is considered unlikely that they are anywhere very steep, either upwards or downwards. The main influence on vertical flows is likely to be the vertical conductance of the Tidal Flat Deposits, which from the published descriptions in Sections 2.3, and the lithological descriptions of auger hole arisings in Section 5, is considered likely to be very low.

This combination of weak vertical hydraulic gradients and low vertical conductance through the Tidal Flat Deposits, means that vertical flows of groundwater, between the surface and the underlying bedrock, are unlikely to be significant in terms of the Gwent Levels water balance.

The hydrogeology of the Chepstow Block of the Carboniferous Limestone is dominated by the continuous abstraction of, on average, 5,500 $m^3$/d of groundwater from the Severn railway tunnel, which is necessary to keep it dry. Groundwater levels are drawn down extensively by the abstraction, and the distribution of springs and sinks (losses of groundwater to the subsurface) was changed fundamentally when the abstraction began in the late nineteenth century.

## 2.5 Surface water hydrology

The surface water hydrological functioning of the Gwent Levels is entirely managed, reflecting its status as land which has been reclaimed from the sea in stages since at least the Roman period. The hydrology is managed by NRW, through the Internal Drainage District (IDD) function, based at Pye Corner, near Nash.

The primary aims of hydrological management are:

- At all times, maintain sufficient throughflow capacity to manage flood risk.
- During the colder months, maintain sufficiently low water levels to allow land drainage.
- During the warmer months, maintain sufficiently high water levels in the drainage ditches to support the SSSI interest feature ditch plant and invertebrate communities, and for agricultural uses.

These aims must be achieved in the context of conducting groundwater and surface water discharge which flows into the Levels from higher ground along their north-western (Wentlooge) and northern (Caldicot) boundaries to the Severn Estuary and, where and when appropriate, making it useful during its passage through the Levels.

The surface water influences beyond the Gwent Levels are:

- Major rivers. The Afon Rhymney flows along the western boundary of the Wentlooge Level into the Severn Estuary, and the combined Afon Usk and Afon Ebbw flows between the Wentlooge and Caldicot Levels, again into the Severn Estuary (Figure 1.1-1). These rivers are essentially hydraulically disconnected from the Levels, and have little or no influence over their hydrological functioning.
- Northern feeders. These are the surface water channels which flow across the northern boundary of the Gwent Levels and become major reens (see below). Examples include (see Figure 1.1-1) the St.Mellons spring (323300 181100) which feeds into the Faendre Reen at the western end of the Wentlooge Level, and the stream which becomes Julian's Reen at the western end of the Caldicot Level. These natural feeds are supplemented by at least one licensed water transfer; abstraction from the Afon Ebbw into the eastern end of the Wentlooge Level.

Within the Levels a hierarchical channel network has evolved; Figure 2.5-1 shows the Chapel Road/Chapel Reen area of the Gwent Levels as an example of this hierarchy:

- Main (carrier) reens[5]. These are the main carriers for the water entering the Levels from higher ground to the Severn Estuary. During the colder months water levels in these

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[5] Reen – a local term in SW Britain for a ditch.

channels are lowered to facilitate rapid conveyance of water towards the tidal gates along the southern margin of the Levels. During the summer water levels are raised to allow lateral discharge of water into the Levels (see below), via sluices or 'noggles[6]'.

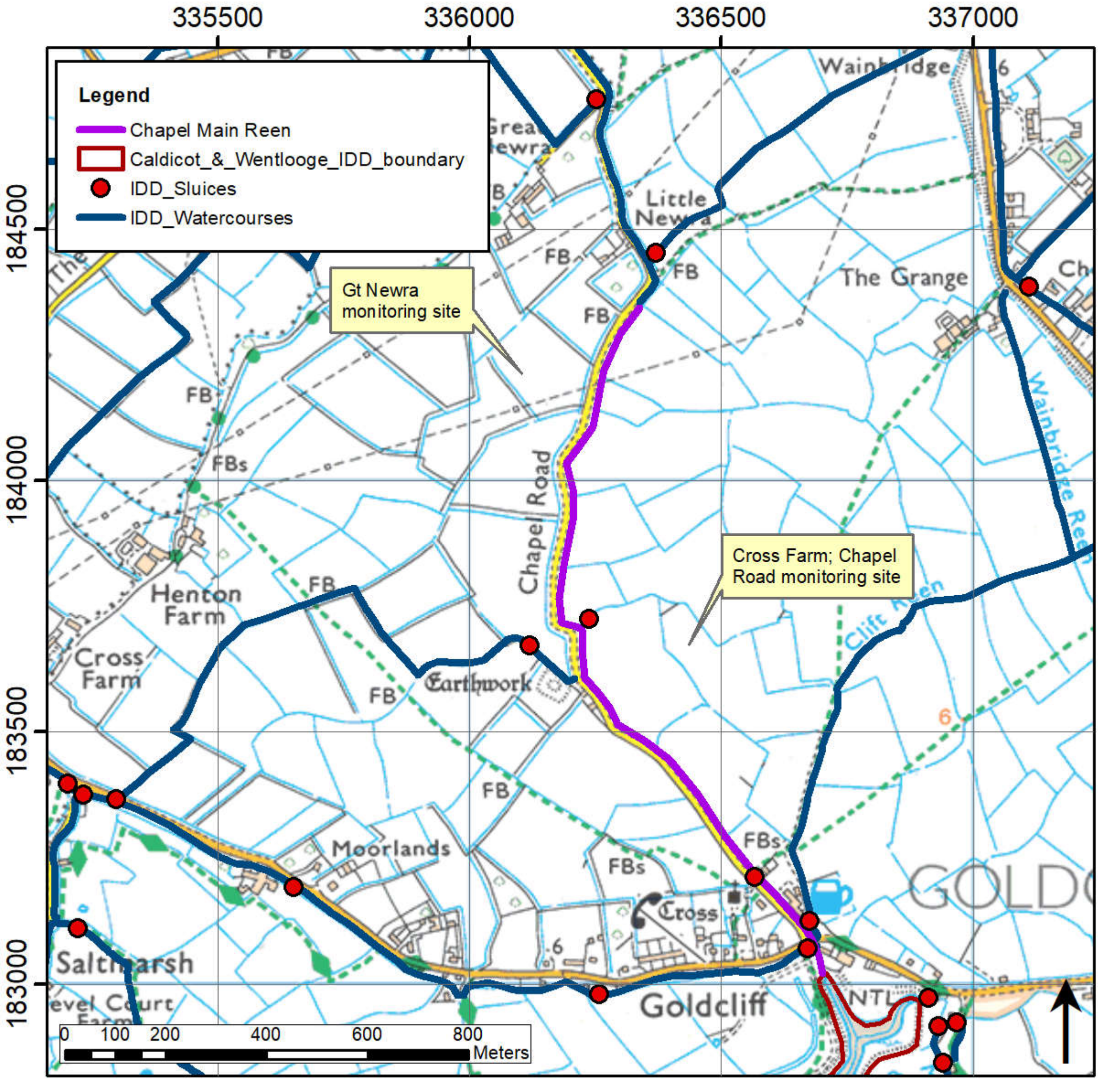

Figure 2.5-1. An example of the functional hierarchy of surface water channels within the Gwent Levels, showing the Chapel Road/Chapel Reen area. Chapel Main Reen and the IDD watercourses are marked explicitly, whilst the lowest level of drainage, field-side ditches, are marked by the blue lines on the 1:25,000-scale basemap.

- IDD reens. These form a network of named (and coded) smaller reens which during the warmer months allow distribution of water through the Levels, into the field ditch systems, to maintain high ditch water levels. During the colder months the water levels in the IDD reens are lowered to facilitate a reversal of flow, from the field drains, via the IDD drains, to the main drains, to effect land drainage. The operation of the IDD reens is controlled by a series of c. 240 sluices (e.g. Figure 2.5-2), which have recently been automated. Details of the maximum, minimum and target control levels are included in the latest Water Level Management Plan (WLMP) for the Levels (Pickup, 2011), but it is known that the reen system is managed in an adaptive and, where necessary, reactive manner (*pers comm.*, John Southall), and that therefore that some of these levels have been changed.

- Field drains. These are the interconnected ditches which run along the boundaries of most of the fields within the Levels. During the warmer months they allow diffusion of water from the IDD reens into the local Levels landscape to maintain high water levels, and during the

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[6] Valves which control water flow from main reens to IDD reens.

colder months they allow collection and transport of water into the reen system to effect drainage and flood risk management.

Figure 2.5-2. Sluice W11 on the Rhosog Fawr IDD reen, near to Sluice House Farm in the western part of the Wentlooge Level. The photograph was taken in January 2020, and the sluice is in its lower, colder month position, with flow towards the tidal gate c. 360 m downstream.

It is important to note that management of the hydrology of the Levels is highly complex with, for example, the manipulation of networks of sluices (e.g. Figure 2.5-1) to effect significant east-west movement of water during the warmer months, from zones of water surplus to zones of water deficit. Reactive management, for example to mitigate hazards during periods of acute water shortage or water surplus, also relies on a detailed understanding of the functioning of the system. During the current project it became apparent that the detailed management of the system is largely non-formalised, with relatively little being on record about how the system functions and related management-decision criteria. The author would suggest urgent consideration by NRW of a programme to formalise such knowledge, to ensure that effective management can continue in the longer-term (Section 13); this would facilitate an update of the WLMP.

# 3 Ecohydrological aspects

## 3.1 SSSIs and their interest features

As noted in Section 1.1, much of the Gwent Levels is designated via a suite of eight SSSIs; these were notified between 1988 and 2010, largely because of the range of aquatic plants and invertebrates associated with the water in the reens and field ditches of the drainage system. The survival of the aquatic plants and invertebrates is dependent on the sympathetic management of the surrounding land, which is also included within the SSSI boundaries. The SSSIs are, from west to east (see Figure 1.1-1 for their geographical extents):

- Rumney & Peterstone SSSI; 969.3 ha.
- St. Brides SSSI; 1312.0 ha.
- Newport Wetlands SSSI; 374.2 ha.
- Nash & Goldcliff SSSI; 760.7 ha.
- Whitson SSSI; 891.3 ha.
- Redwick & Llandevenny SSSI; 940.0 ha.
- Magor Marsh SSSI; 21.9 ha.
- Magor & Undy SSSI; 586.6 ha.

Magor Marsh is by far the smallest SSSI; whilst it contains interconnecting ditches it was not surveyed as a part of NRW's ecological surveys of 2010-2013 (Murton *et al*, 2017), and is not considered explicitly here.

The notified reen and field ditch habitat features, and aquatic plant features, within the seven main SSSIs are summarised usefully as Section 1.2 of Murton *et al* (2019), which is reproduced as follows, in full, to avoid the need for cross-referencing.

### 3.1.1 *Habitat features*

Standing water is an independent notified feature for all seven of the SSSIs, and essentially refers to the reens and ditches in the SSSIs.

### 3.1.2 *Plant features*

It is indicated in Table 3.1-1 whether the plant feature is an independently notified feature of the SSSI or an independently qualifying feature. An independently notified feature was recognised at the time of notification. Where a feature is qualifying, its significance on site was only recognised after notification, but it would be added to the formal list of SSSI features at any future re-notification.

The independently notified aquatic plant features of the Gwent Levels SSSIs are:

- Fine-leaved pondweed *Potamogeton trichoides (Pota tri).*
- Rootless duckweed *Wolffia arrhiza (Wolf arr).*

*P. trichoides* is an independently notified feature listed on the SSSI citation for each of the seven SSSIs, and *W.arrhiza* was an independently notified feature for the Nash & Goldcliff and Newport Wetlands SSSIs. *W.arrhiza* is a qualifying feature but was not notified on four of the SSSIs as its presence was recorded after the SSSI notification process (see Table 3.1-1).

In addition, an 'Assemblage of Aquatic and Marginal Red Data Book and Nationally Scarce Vascular Plants' are a notified assemblage feature on the SSSIs, and includes:

- Frogbit *Hydrocharis morsus-ranae (Hydr mor).*
- Tubular Water-dropwort *Oenanthe fistulosa (Oenan fis).*
- Soft Hornwort *Ceratophyllum submersum (Cera sub).*
- Arrowhead *Sagittaria sagittifolia (Sagi).*

Table 3.1-1. Plants features (independent and assemblage) on each of the Gwent Levels SSSIs.

| | **Plant species** | | | | | |
|---|---|---|---|---|---|---|
| **Sites** | *Pota tri* | *Wolf arr* | *Hydr mor* | *Oenan fis* | *Sagi* | *Cera sub* |
| Rumney & Peterstone | I & A | i & A | A | A | A | |
| St. Brides | I & A | i & A | A | A | A | |
| Nash & Goldcliff | I & A | I & A | A | A | | A |
| Whitson | I & A | i & A | A | A | A | |
| Redwick & Llandevenny | I & A | i & A | A | A | A | |
| Magor & Undy | I & A | | A | | | |
| Newport Wetlands | I & A | I & A | | | | |

I = Independently notified feature

i = not currently notified independently but qualifies and at any future re-notification would be added as an individually qualifying species

A = part of notified plant assemblage feature

## 3.2 Summary of the results of the ditch plant and invertebrate communities survey

As a part of the current project, Jonathan Graham (plants) and Martin Hammond (aquatic macro-invertebrates) were commissioned to undertake ecological assessments of ditches at the five monitoring sites; the assessment is reported under separate cover as Graham and Hammond (2020). A general summary of the work is provided in the remainder of this section; the reader is directed to the report for much more detail.

### 3.2.1 *General*

At each of the five sites a minimum of three watercourses (either field drain or IDD reen) were selected for ecological assessment. Where possible, drains were selected which had a least 10 cm of water so that both aquatic invertebrates and plants could be assessed together. However, assessment of aquatic invertebrates was limited to only two sample points at Cross Farm; Nash and Fair Orchard Farm, and a single sample point at Sluice House Farm, because drains were completely drawn down at the time of survey (5th August 2020). A total of 16 drains were surveyed for plants and 11 drains surveyed for aquatic invertebrates.

All flowering plants, bryophytes, Charophytes, macro green algae (Chlorophyta)(when prominent) and aquatic macro-invertebrates were recorded. Also, basic water chemistry: water temperature, pH and conductivity were measured for each sample drain using a Hanna H1 9811-5 meter.

In analysing the data, particular attention was given to water beetles (Coleoptera). In still and slow-moving waters, aquatic Coleoptera are by far the most speciose group of aquatic macro-invertebrates which can be sampled readily using a pond-net. Moreover, the distribution, ecology and conservation status of individual species is well-documented in Britain (e.g. Foster *et al* 2016, 2019, 2020). Assemblages of aquatic Coleoptera are thus particularly useful in constructing species quality metrics (Foster & Eyre, 1992), the most frequently used being the Species Quality Index (SQI).

### 3.2.2 *Plants*

One hundred and twelve plant species were recorded, comprising 60 bank species (including hedge species and some epiphytic bryophytes), 33 emergent species of the water's edge, seven floating aquatic species (including the alga Ulva), and 12 submerged aquatic species.

The emergent flora of the water's edge is dominated by Common Reed *Phragmites australis* and Lesser Water-parsnip *Berula erecta* (>10 out of 16 ditch sample points) with frequent Floating Sweet-grass *Glyceria fluitans*, Gypsywort *Lycopus europaeus*, Common Water-plantain *Alisma plantago-aquatica*, Reed Sweet-grass *Glyceria maxima*, Woody Nightshade *Solanum dulcamara*, Hard Rush *Juncus inflexus*, Soft Rush *Juncus effusus*, Celery-leaved Buttercup *Ranunculus sceleratus* and Clustered Dock *Rumex conglomeratus* (between 6 and

10 out of 16 ditch sample points). Twenty other emergent species occurred in <5 out of 16 ditch sample points including species of conservation note such as Tufted Forget-me-not *Myosotis laxa subsp. caespitosa*, Tubular Water-dropwort *Oenanthe fistulosa*, Water Dock Rumex *hydrolapathum* and Brookweed *Samolus valerandi*.

The vegetation of the more species-rich drains surveyed, those with a cover of duckweed and at least 2-3 submerged aquatic plants belong to the National Vegetation Classification (NVC) type A3 Spirodela polyrhiza - Hydrocharis morsus-ranae community following Rodwell (1995).

### 3.2.3 *Aquatic macro-invertebrates and vertebrates*

Eighty-two taxa of aquatic macro-invertebrates were recorded, including one which is categorised as Near Threatened in Great Britain (the Great Silver Water Beetle *Hydrophilus piceus*) and four which are listed as Nationally Scarce (the diving beetles *Agabus conspersus* and *Hydaticus transversalis*, the Pink Water Speedwell Weevil *Gymnetron villosulum* and the Ornate Brigadier soldierfly *Odontomyia ornata*). With the exception of the ubiquitous amphipod *Crangonyx pseudogracilis*, which is of North American origin, there was no evidence of non-native species. Invertebrates usually associated with brackish water included the amphipod *Gammarus duebeni* at one site, the diving beetle *Agabus conspersus* at one site and the Caspian Whirligig *Gyrinus caspius* at two.

Nine-spined and/or Three-spined Sticklebacks were present in most of the drains sampled. Single elvers were found in GN-EA27 and CF1-IDB71. Smooth and/or Palmate Newt tadpoles were present in the ditches at Great Newra Farm.

### 3.2.4 *Conclusions*

Table 3.2-1 summarises the occurrence of independent plant and invertebrate SSSI qualifying species features for the Gwent Levels occurring at the five survey sites; Great Newra Farm has by far the most qualifying features.

Table 3.2-1. Independent plant and invertebrate SSSI qualifying features for the Gwent Levels (orange shading indicates presence).

| Feature | | Nash & Goldcliff SSSI | | | St. Brides SSSI | Rumney & Peterstone SSSI |
|---|---|---|---|---|---|---|
| English Name | Latin name | Great Newra Farm | Cross Farm (site 1) | Cross Farm (site 2) | Fair Orchard Farm | Sluice House Farm |
| Hairlike Pondweed | *Potamogeton trichoides* | 🟧 | 🟧 | 🟧 | | |
| Rootless Duckweed | *Wolffia arrhiza* | 🟧 | 🟧 | | | |
| A diving beetle | *Hydaticus transversalis* | 🟧 | | | | |
| Great Silver Water Beetle | *Hydrophilus piceus* | 🟧 | | | | |
| Ornate Brigadier soldierfly | *Odontomyia ornata* | 🟧 | | | | |

In addition, the following species are considered notable: Frogbit *Hydrocharis morsus-ranae* (Great Newra Farm, Cross Farm; Chapel Road, Cross Farm; Nash, Fair Orchard Farm), Lesser Pondweed *Potamogeton pusillus* (Cross Farm; Chapel Road), Smooth Hornwort *Ceratophyllum submersum* (Cross Farm; Nash), Great Water Dock *Rumex hydrolapathum* and Tubular Water-dropwort *Oenanthe fistulosa* (Fair Orchard Farm), Moss Bladder Snail *Aplexa hypnorum* (Fair Orchard Farm), the diving beetle *Agabus conspersus* (Cross Farm site 2), the diving beetle *Nartus grapii* (Great Newra Farm and Fair Orchard Farm), the scavenger water beetle *Berosus* *signaticollis* (Great Newra Farm), Pink Water Speedwell Weevil *Gymnetron villosulum* (Cross Farm; Chapel Road).

The vast majority of drains (all sites) with open water were dominated by a very high cover of duckweed (*Lemna gibba, Lemna minuta, Spirodela polyrhiza*), often to 100% surface cover. Such high cover of duckweed is linked to eutrophication (particularly concentration of phosphate). A recent briefing note by NRW (2016) states that there are “widespread chronic failures” in relation to the Ortho-phosphate target for the Gwent Levels.

High cover of duckweed inhibits growth of submerged aquatics by shading and can, in some cases, negatively affect fauna by causing sudden low oxygen levels in late summer. Although the SSSI qualifying submerged aquatic plant Hairlike Pondweed *Potamogeton trichoides* was locally frequent under duckweed mats at three of the survey sites, plants were already breaking up and forming over-wintering turions by 5th August 2020 in response to the high duckweed cover. In drains with a low nutrient status, and no or very low duckweed cover, this species has been observed to continue growing into September (Mountford & Graham, *A Fenland Flora* - in preparation). In this way, eutrophication has an indirect negative impact on the growing season of such submerged aquatics.

All five survey sites were grazed (mainly by cattle) and the resulting poaching of drain margins, along with routine cleaning out of drains, is considered to be very important for both drain plants and invertebrates. The restriction of hedges to one side only of ditches is also important in allowing light penetration of the water column and recent positive conservation work to address this was evident at Cross Farm; Chapel Road.

The number of sites for which ditch ecological surveys were carried out was too small to allow confident testing of ecological differences in relation to field drainage types.

## 3.3 Hydrological supporting conditions

### 3.3.1 *Introduction*

Wetland plant communities can be associated with more-or-less specific hydrological supporting conditions (HSCs) which allow survival and competitive advantage of constituent species, often through functional adaptations (e.g. Mitsch and Gosselink, 2000). A significant effort was made to collate information on hydrological supporting conditions for a wide range of wetland and other habitats in the UK (~2000-2010), in order to support hydrological impact assessments under the EU Habitats and Water Framework Directives; the resulting information was reported primarily in a series of Ecohydrological Guideline publications, e.g. Environment Agency (2010).

Three elements can be considered in order to define HSCs:

- A variable, which describes a fundamental property of the incident hydrological regime, such as the depth of the water table below the ground surface, the rate or velocity of flow in a channel, or the pH of soil water.
- A metric (or metrics) which describe important characteristics of the behaviour of the variable, such as the annual range of water level, and the lowest or highest annual water levels.
- Thresholds or bounds which describe the limits within which the metric(s) should fall in relation to favourable or unfavourable supporting conditions.

Whilst some progress has been made in defining hydrological supporting conditions, there are still many and significant uncertainties in relation to all three elements above, and in relation to most wetland communities[7].

### 3.3.2 *For ditch plant and invertebrate communities of the Gwent Levels*

Literature reviews and analysis relating to the plant assemblages surveyed during the current project (Section 3.2), which are a fair representation of the ditch plant communities within the

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[7] This is perhaps reflective of ecohydrology being a relatively young interdisciplinary field.

Gwent Levels as a whole (Section 3.2.5), has shown that information relating to HSCs is available as follows:

- Wet zone groups, defined partly by water level range; Drake *et al* (2010).
- Species trophic status, pH range and water level range; Mountford and Arnold (2006).
- Ellenburg values for nitrogen and salt tolerance; Hill *et al* (2004).

From the above it is proposed that the variables through which HSCs for ditch plant communities can best be defined, which are also, importantly, potentially (directly or indirectly) sensitive to field drainage technique, are:

- Ditch water depth regime; maintenance of a stable summer water level is critical as this is when plants are most actively growing, flowering and setting seed, a guide to preferred water depths for emergent and aquatic plant species occurring within the different drainage channel types of the Gwent Levels can be inferred by reference to Newbold & Mountford (1997) and Benstead *et al.* (1997). These suggest a preferred summer water level of 0.30-1.25 m (average = 0.40 m) for field drains and 0.60-2.0 m (average = 1.25 m) for larger reens.
- Ditch water nutrient concentration; the most widespread cause of degradation in freshwater ecosystems is eutrophication in relation to elevated concentrations of nitrate and phosphate (UK Government, 2009), a guide to target levels for these two key nutrients for drainage channels within the Gwent Levels can be inferred by reference to Mainstone and Parr (2002) and Mountford and Arnold (2006). These suggest targets of <0.1mg/l (maximum 0.2) for total phosphorus and <0.7mg/l (maximum 1.6) for total nitrogen.

  NRW also has a suite of water quality determinand trigger levels, which indicate the concentration above which it becomes concerned that damage could be occurring to the SSSI features, and which therefore needs to trigger follow-up monitoring and implementation of remedial action. The trigger levels in relation to nutrients are; nitrate (as $NO_3$) = 1 mg/l, nitrite (as $NO_2$) = 1 mg/l, total oxidised nitrogen (as N) = 2 mg/l, orthophosphate (as P) = 1 mg/l.

Assessment of the sensitivity of these variables to field drainage techniques has been carried out at a qualitative level for the current project, and therefore the metrics and thresholds/bounds which define HSCs through the above variables, apart from the above, are not discussed here.

No specific information has been found on HSCs for ditch invertebrate communities.

## 3.4 Conservation objectives and performance indicators for the SSSI interest features

Conservation objectives and performance indicators (PIs) for the SSSIs are specified in Murton *et al* (2019). PIs are developed by identifying the key attributes which make up or support the feature, and setting targets for them. Each attribute is then measured and compared against the target set. If all the targets are met, the feature is in favourable condition.

It is useful to cross-reference the PIs against the HSCs discussed in Section 3.3.2 above. Most of the PIs specified in Murton *et al* (2019) relate to biotic indicators, such as presence of submerged vascular plants within a target percentage of channel sample points, or abiotic non-hydrological indicators such as ditch/reen shading.

The hydrology-related PIs are as follows.

### 3.4.1 *Extent of standing water*

The objective in relation to this PI is to maintain the extent of the standing water feature (reen and field ditch habitat feature) of the Gwent Levels as that mapped at the time of SSSI notification, to guard against loss of ditch to infilling, development or successional changes from neglect.

### 3.4.2 *Field Block Units/Field Ditches*

Ditches are categorised as follows:

1. Hedge on one side of the ditch.

2. Hedges on two sides (double hedged) of the ditch.
3. No hedge alongside the ditch but the ditch appears to be dry.
4. Intermittent hedge (note this one is split into three sub categories). (4a intermittent/gappy hedge on one side, open on other, 4b intermittent hedge on both sides, 4c one side of ditch has an intermittent hedge, other side of ditch is hedged).
5. No hedge on either side of the ditch and the ditch appears to be holding water.

Of these, category numbers 3 and 5 are explicitly hydrological. These categories are used within the PIs by setting minimum and maximum percentage representations, as follows:

- For each field block unit (where ditches present), no more than 50% of ditches to be in categories 2, 2d, 3 or 4c.
- Over a whole SSSI, at least 15% of ditches to be category 4a or 5.

# 4 Large-scale ecohydrological conceptual model

## 4.1 Introduction

*Conceptual model* (or *conceptual understanding*) is a term which has historically been used, *inter alia*, in the discipline of hydrogeology, but which is also useful in an ecohydrological context. A conceptual model essentially describes how a system works, by identifying the significant forcing variables and mechanisms, and describing how these combine to result in key aspects of system behaviour.

An ecohydrological conceptual model for a wetland usually identifies the primary variables and mechanisms which combine to control the variables through which hydrological supporting conditions (Section 3.3) are defined, within specific areas of a site. The simplest conceptual model will identify the mechanisms of water supply to, water retention within, and water loss from, a wetland. Refinements can address, for example, spatial and temporal variations in these processes at various relevant scales, as the understanding of a site progresses.

Conceptual models should be context-specific, and should follow Einstein's maxim that *everything should be made as simple as possible, but not simpler*. They are usually conveyed through diagrams, maps and narrative text.

Conceptual models are needed to support site management decision-making, and should be refined in a context-specific way according to the site management question at hand. For example, if an assessment of the possible impact of a planned nearby groundwater abstraction on groundwater discharge to a wetland is required, the conceptual model should describe the variables and processes which form the potential impact pathway(s) in appropriate detail.

For this report, the ecohydrological conceptual model has been considered at two scales:

1. The large- or SSSI-scale. This is to allow an understanding of how the Gwent Levels function ecohydrologically as a whole; what are the important large-scale water inputs, modes of water retention, and water losses. The large-scale conceptual model is presented in this section.
2. The small- or field-scale. This is to allow an understanding of ecohydrological functioning at the smallest useful scale within the Gwent Levels, which is coincident with the scale of the project monitoring plots. This is covered in Section 7.

It is worth noting that whilst the ecohydrological functioning of the Gwent Levels has been considered at two scales for clarity of explanation, the small-scale functioning of the system (2. above) is embedded within, and therefore clearly a part of, the large-scale functioning (1. above).

## 4.2 Key hydrological variable

As noted in Section 3.3.2, the variable through which hydrological supporting conditions for the ditch community interest features can be defined is the depth of water in the ditches during the warmer month period. The following conceptual model therefore seeks to identify the forcing variables and mechanisms which have a significant influence on this variable.

## 4.3 Year-round

Water supplies:

- Direct rainfall, assumed to be universal across the site.
- Streamflow entering along the northern margin of the Levels, consisting of groundwater baseflow, with supplemental surface runoff to streams during and after rainfall events.
- The evidence suggests (Section 2.4.2) that there is unlikely to be significant diffuse, upwards groundwater flow from the bedrock to the surface within the Levels.

Water retention:

Water flow through the Levels is generally slow because the area is flat at a regional scale and related hydraulic gradients are shallow. The intense network of ditches (Section 2.5) means that the bulk hydraulic conductance of the landscape is high, such that despite the shallow hydraulic gradients water can still be conducted efficiently, north-south through the Levels, whilst maintaining relatively low water levels in the channels.

Water is also retained within the Levels transiently (twice daily) by high tides, with saline backflow largely prevented by tidal gates.

Water loss:

- Evapotranspiration, universal across the site.
- The evidence suggests (Section 2.4.2) that there is unlikely to be significant diffuse, downwards groundwater flow from the surface into the bedrock within the Levels.
- Flow through the tidal gates into the Severn Estuary.

## 4.4 Colder months

The seasonal hydrological functioning of the Gwent Levels during the colder month period is illustrated in the simplified schematic cross-section given as Figure 4.4-1. The main objective of hydrological management is to minimise flood risk. The key features are:

- Flows in the streams which enter the Levels along their northern boundary are relatively high during this period as:
    1. Groundwater levels over the higher ground catchments increase, in response to rainfall-derived groundwater recharge which is heavily concentrated between October and April, meaning that groundwater discharge (baseflow) is seasonally high.
    2. Surface water runoff over the higher ground occurs more readily as soil moisture deficits are low.

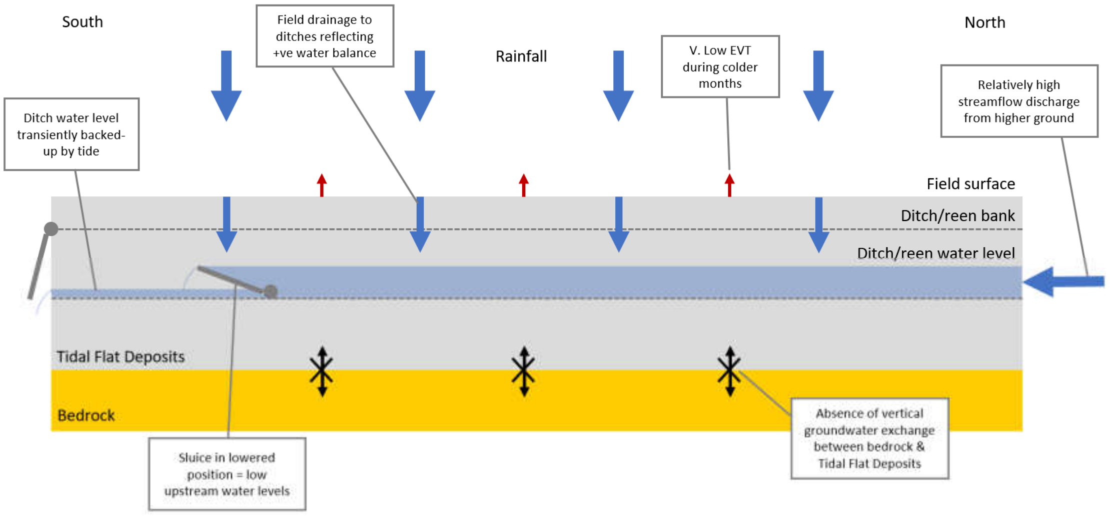

Figure 4.4-1. Schematic, simplified cross-section illustrating the larger-scale hydrological functioning of the Gwent Levels; colder months condition.

- Loss of water to evapotranspiration is relatively low during the colder months. This means that the local water balance within the Levels is positive, and water drains from the fields into the ditch system; this is covered in more detail below.
- The control water levels (sluices) in ditches are relatively low, such that hydraulic conductance is high, and storage capacity is available, to mitigate flood risk. However, ditch water levels tend to be maintained by continuous flows in incoming streams and from field drainage.

## 4.5 Warmer months

The seasonal hydrological functioning of the Gwent Levels during the warmer month period is illustrated in the simplified schematic cross-section given as Figure 4.5-1. The key features are:

- Flows in the streams which enter the Levels along their northern boundary are relatively low during this period as:
    1. Groundwater levels over the higher ground catchments are in recession since rainfall-derived groundwater recharge is much less frequent; this means that groundwater discharge (baseflow) reduces during the summer. Importantly though, because of the aggregate volume of upstream aquifer storage, groundwater discharge (springflow) is maintained, providing the water necessary to effect the hydrological management objectives within the Levels.
    2. Surface water runoff over the higher ground catchments occurs less readily as soil moisture deficits are high, soil water levels are low, and rainfall tends to evaporate or infiltrate into the soil, usually, subsequently, to be transpired by plants.

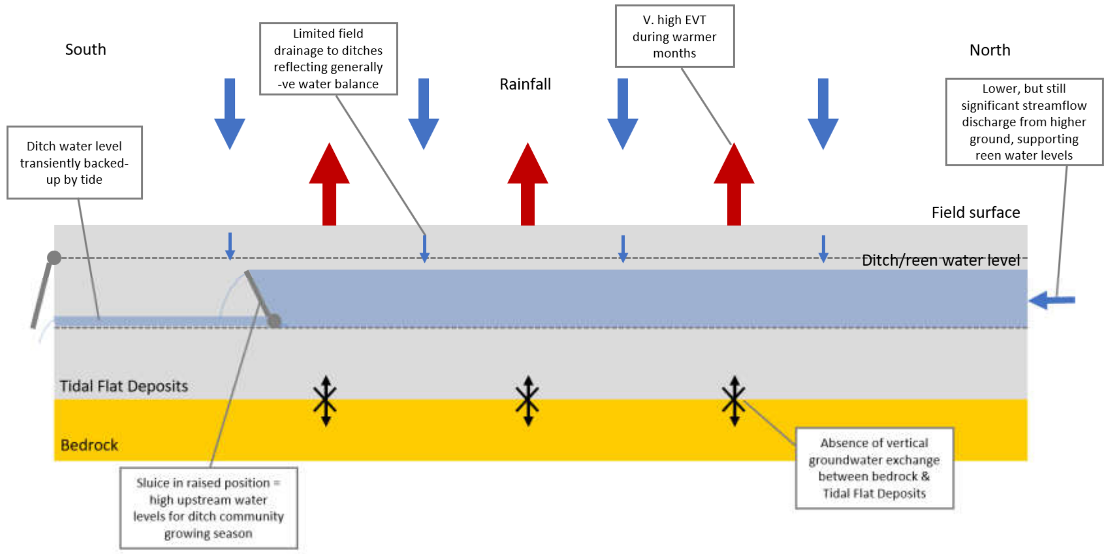

Figure 4.5-1. Schematic, simplified cross-section illustrating the larger-scale hydrological functioning of the Gwent Levels; warmer months condition.

- Loss of water to evapotranspiration is relatively high during the warmer months. This means that the local water balance within the Levels is mostly negative, and that very little water drains from the fields into the ditch system; this is covered in more detail below.
- The control water levels (sluices) in ditches are high, meaning that high water levels are maintained in ditches to maintain favourable hydrological supporting conditions for ditch communities. The sluice and ditch system are managed such that groundwater-dominated incoming stream flows can be directed through the ditch system, with the direction of water movement often having a significant lateral (east-west) component, to allow levels to be maintained more widely.

## 4.6 Hydrological variation within the Gwent Levels

One of the requirements of Part One of this project (Section 1.3) was to *provide a qualitative conceptual assessment of the current hydrological regime of the Gwent Levels as a whole* (see above)*, and the seven Gwent Levels SSSIs in particular*. Regarding the separate SSSIs, it is worth noting that the larger-scale determinants of their hydrological functioning are common:

- The SSSIs are arranged east-west across the Gwent Levels, and therefore they are all similar in hosting the hydrological progression, from water entering from the higher ground to the north, via discharge through the reen systems, to discharge into the Severn Estuary via the tidal gates.
- The nature of the drainage infrastructure, and its management (aims and practical operation) are very similar across the Levels.
- The stream length from the furthest extent to the outlet points shows little variation given the similar-sized hydrological compartments.

One source of variation between the SSSIs is the availability of water crossing the northern boundary of the Levels (in the *northern feeders*, Section 2.5), for distribution within the sites to support ditch water levels during the warmer months. During the current project John Southall (*pers comm.*) has noted that:

- The main flows into the Levels are non-linearly distributed across the northern boundary.
- There is variation between these main flows in relation to both their average discharges, and the degree to which they are sustained during the warmer month period.
- The water management system within the Levels has been developed over time to cope with the limitations of water supply, to fulfil its aim of supporting ditch water levels, often by moving water laterally (east-west).

By design, it has not been possible to capture any detailed information about the above during the current project, but it is recommended that further work is carried out to characterise the hydrological management of the Gwent Levels in more detail (as noted in Section 2.5) and for a number of reasons, as discussed in Section 13.

At the level of characterisation allowed during the current project then, it is concluded that:

1. The larger-scale hydrological functioning of the Gwent Levels SSSIs is very similar.
2. There is spatial and temporal variation in the availability of water from the northern feeders for support of ditch water levels during the warmer months. Water management within the Levels has evolved to cope, apparently successfully, with these variations.

# 5 Field data collection – method and sites

## 5.1 Equipment and methods

### 5.1.1 *Dipwells and stilling wells*

Soil water table elevation has been measured during the project through installation of dipwells. These were 2 m long, 42 mm outside diameter, 36 mm inside diameter PVC tubing with a threaded cap at the top and a threaded plug at the base. It was decided to use 2 m, rather than 1 m, long dipwells as the lowest likely soil water levels relative to the ground surface were uncertain; in hindsight this was vindicated as soil water levels fell below 1 metre below ground level (mbGL) extensively. The dipwell tubes have 1 mm wide transverse slots cut at 7 mm centres along their whole length to allow easy water ingress, and are covered with 120 µm filter fabric to reduce sediment ingress. The dipwells were pushed into, and fit snugly in, 50 mm diameter hand-augered holes, with the top of the tube being 30-50 mm below ground level to avoid interference with farming operations (Figure 5.1-1). This arrangement allows easy exchange of water between the dipwell and the surrounding formation, and therefore water levels measured in the dipwell are a good reflection of water table elevation in the adjacent soil and lower substrate. The dipwells were covered with 400 x 400 mm concrete slabs where allowed.

The shallow sedimentary sequence was carefully logged during augering of the dipwell pilot holes.

Figure 5.1-1. Dipwell (at Fair Orchard Farm) completed c. 30 mm below ground level to allow unencumbered farming operations.

Four or five dipwells were installed at each of the five monitoring sites in various spatial configurations, as discussed below.

The stilling wells were essentially dipwells (i.e. the same hardware) installed within the ditches to allow measurement of ditch water levels. The stilling wells were attached to 25 mm galvanised steel poles using stainless-steel worm-drive clips. At each site, one stilling well was installed adjacent to the dipwell array. Another stilling well was installed c. 100-200 m away from the dipwell array, to assess the direction of the hydraulic gradient, and also longitudinal differences in ditch water level response.

### 5.1.2 *Automatic water level recorders*

Water levels were measured using Solinst Levelogger Edge automatic water level recorders (AWLRs). The instruments were suspended at the bases of the dipwells and stilling wells, below the water surface, using stainless-steel fittings and rope. They measure the sum of the pressure exerted by the water column and atmospheric pressure. Atmospheric pressure was measured at coincident times using a Solinst Barologger (ABPR, deployed at the top of one of the stilling wells at the Cross Farm, Chapel Road site[8]), and was subtracted from the data from the Leveloggers to obtain measurements for the height of the water column above the sensor. The water level data were further processed to be expressed in both *metres relative to Local Datum* (mrLD) and metres below Ground Level (mbGL[9]). Measurements were taken hourly by the AWLR network.

### 5.1.3 *Surveying*

The spatial position of each dipwell was recorded using an Arrow GNSS receiver linked to the MapIt GPS app on an Android phone, with coordinates recorded when the reported error fell below 0.3 m. The relative elevations of the installations were surveyed (+/- c. 5 mm) using a Leica Rugby laser level and associated receiver. The elevations were then calculated and related to Ordnance Datum through the LIDAR-derived elevation of the dipwell within the widest expanse of flattest ground.

## 5.2 Overview of sites

The five monitoring sites were chosen to represent the two main types of field drainage; traditional ridge-and-furrow, and under-drained. Initial visits were made to the sites during January 2020, and in all cases the farmers agreed to installation of monitoring equipment. The short duration of the project meant that there was limited time to find and compare other sites as monitoring plots, but it was agreed amongst the project team that the adopted sites gave a good representation of drainage practice.

Table 5.2-1. Summary details of the hydrological monitoring sites.

| | **NGR** | **Drainage** | **# Dipwells** | **# Stilling wells** | **Monitoring period** |
|---|---|---|---|---|---|
| Great Newra Farm | 336100 184200 | Traditional | 5 | 2 | 19/3/20-4/8/21 |
| Cross Farm – Chapel Road | 336430 183650 | Traditional & under-drained | 4 | 2 | 19/3/20-4/8/21 |
| Cross Farm – Nash | 334900 183676 | Under-drained | 4 | 2 | 20/8/20-4/8/21 |
| Fair Orchard Farm | 329850 183900 | Traditional | 4 | 2 | 1/8/20-16/6/21 |
| Sluice House Farm | 324900 179320 | Under-drained | 4 | 2 (1 lost) | 19/3/20-4/8/21 |

General details for the sites are given in Table 5.2-1, whilst the locations of the sites are illustrated in Figure 1.1-1.

The larger-scale hydrological settings of each of the sites, with regard to their positions within the reen network, and directions of flow within that network, were discussed with John Southall

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[8] A second ABPR was installed in one of the stilling wells at Sluice House Farm, but it, along with the AWLR, was lost during ditch maintenance operations.

[9] It is worth noting that +ve values show that the water level is <u>below</u> the ground surface.

(NRW). It is worth noting, however, that (as noted in Section 2.5) the hydrology of the Gwent Levels has always been managed empirically, adaptively and reactively, and there has never been a requirement for a detailed process-level understanding of the system, i.e. flow directions and water levels at the field scale (see Section 2.4); this is reflected in the descriptions below.

The shallow lithostratigraphic sequences were recorded during augering of the holes for the dipwells. As might be expected in relation to the relatively small monitoring plots, all of the recorded sequences at each site were very similar. Hence, the sequence for only one auger hole is reported for each site in the following sections.

### 5.3 Site 1; Great Newra Farm, Broadstreet Common

The site within Great Newra Farm was located immediate to the west of Chapel Road (and Chapel Reen), and is recognised as a good example of traditional ridge-and-furrow drainage. The completion details of the dipwells and stilling wells are given in Table 5.3-1. The locations of the installations are shown over the 2020 aerial photograph in Figure 5.3-1, and over colour-coded ground-elevation LIDAR data in Figure 5.3-2. An annotated photograph of the study site is provided as Figure 5.3-3.

Figure 5.3-1. Hydrometric installations at Great Newra, displayed over the 2020 aerial photograph. SW 2 lies 120 m SSW of SW1, or 190 m along the connecting ditch. Some offsetting of the spatial mapping is to be expected at the scale of inspection here[10].

It can be seen most easily from Figure 5.3-1 that there is a two-order furrow system at the Great Newra site, with:

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[10] It is worth noting that, where possible, the colour-coding of the dipwells on the maps is the same as the colour-coding of the water level hydrograph lines in later chapters, facilitating cross-referencing.

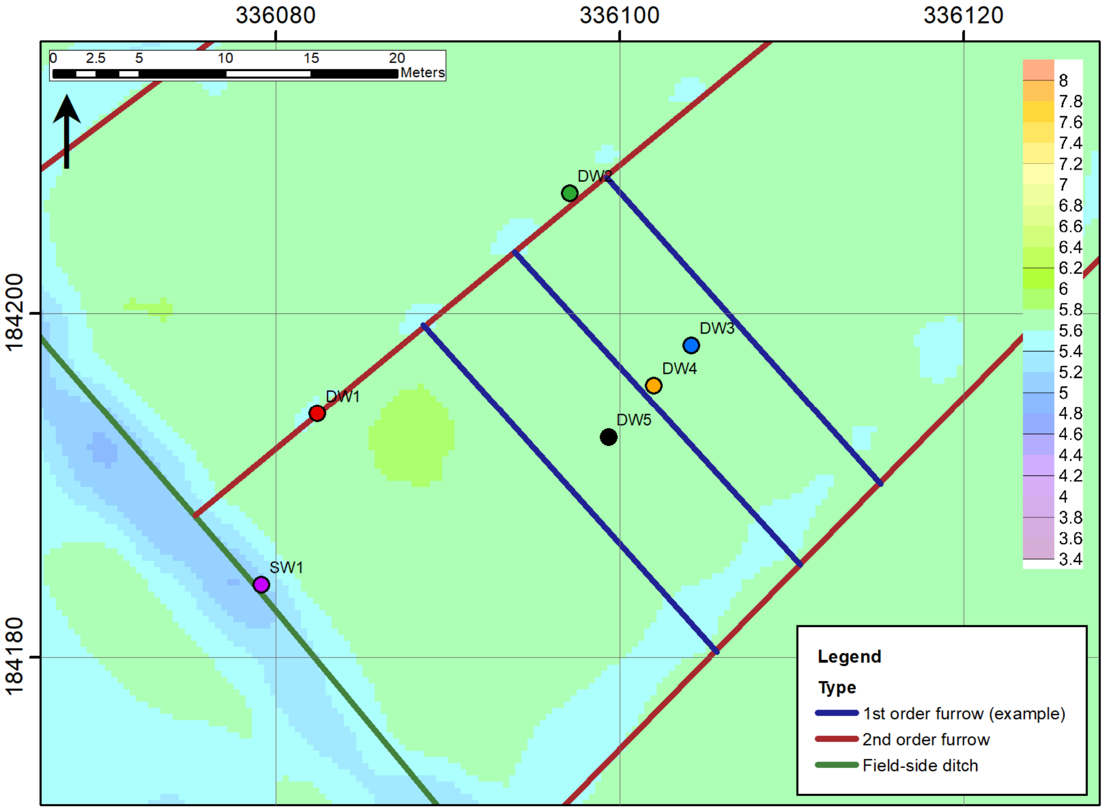

Figure 5.3-2. Hydrometric installations at Great Newra, displayed over colour-coded 1 m resolution LIDAR data. SW 2 lies 120 m SSW of SW1, or 190 m along the connecting ditch.

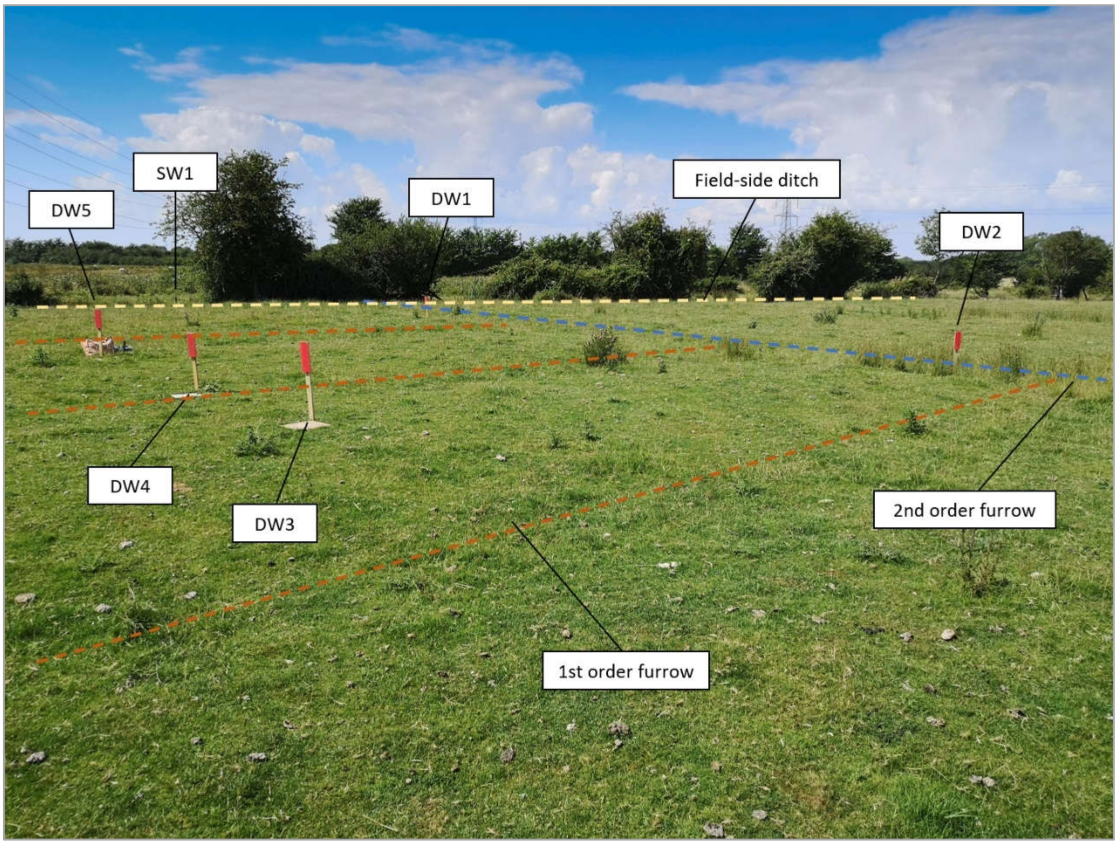

Figure 5.3-3. Annotated photograph showing the hydrometric plot at Great Newra Farm.

- Second-order furrows at ninety-degrees to, and discharging into, the field-side ditches; these have centre-to-centre spacing of c. 20 m. From Table 5.3-1 it can be seen that the base of the second-order furrow which was monitored fell by 0.10 m over 20 m.
- First-order ditches at ninety-degrees to, and draining into, the second-order ditches; these ditches facilitate drainage of the areas between the second-order furrows, and are spaced at c. 7-8 m. The topographic base of the first-order ditch which was monitored fell by 0.14 m over 11 m. The ground levels at the dipwell at the crests either side of the monitored first-order furrow were 0.036 and 0.064 m higher than the base of the first-order furrow.
- The second-order ditch was connected hydraulically to the ditch through a pipe passing through the raised headland area, which appeared to be flowing freely during reconnaissance visit in January 2020.

John Southall (*pers. comm.*, August 2021) noted that it is known to be difficult to get water to the area within which the Great Newra Farm monitoring site is located, and therefore that ditch water levels can fall to lower levels than is ideal. Water is fed into this area from Chapel Reen (immediately to the east) in the summer, and discharge is to Chapel Reen during the winter.

The closest sluices on the western side of Chapel Reen to the monitoring site are C11 (600 m NNE) and C15 (530 m S). The penning levels included in the WLMP (Pickup, 2011) are provided in Table 5.3-2.

The shallow lithostratigraphic sequence for DW1 was as follows:

- 0-20 cm; wet, dark-brown, silty, clayey TOPSOIL.
- 20-70 cm; wet, orange-grey, firm, silty CLAY.
- 70-160 cm; wet, light-grey with orange mottle, firm, laminated, slightly silty CLAY.
- 160-200 cm; wet, mid-grey, medium-soft CLAY.

## 5.4 Site 2; Cross Farm; Chapel Road

Cross Farm; Chapel Road was chosen as a site where there is both traditional drainage and under-drainage; under-drains had been installed beneath the second-order[11] furrows, but the micro-topography associated with traditional drainage was still apparent.

The completion details of the dipwells and stilling wells are given in Table 5.4-1. The locations of the installations are shown over the 2020 aerial photograph in Figure 5.4-1, and over colour-coded ground-elevation LIDAR data in Figure 5.4-2. An annotated photograph of the study site is provided as Figure 5.4-3.

The traditional two-order furrow drainage system can be seen in Figures 5.4-1 and 5.4-2, and linear piles of ditches arisings, seen to be around 0.75 m high during the reconnaissance visit in January 2020, are marked on Figure 5.4-1. The piles of arisings were levelled during the project, and the traditional furrow system, which was easily discerned during installation of the dipwells (March 2020), was much more difficult to identify during visits in 2021 (e.g. Figure 5.4-3, taken in August 2021). The latter was probably because the field had been reseeded, and the micro-topography was difficult to discern through the uniform green of the new grass.

The traditional drainage system comprised:

- Second-order furrows at seventy-five-degrees to, and discharging into, the field-side ditches; these have centre-to-centre spacing of c. 20 m. From Table 5.3-1 it can be seen that the base of the second-order furrow which was monitored was approximately level over the 23 m between DW1 and DW2.
- First-order furrows at eighty-degrees to, and draining into, the second-order furrows; these ditches facilitate drainage of the areas between the second-order furrows, and are spaced at c. 6-7 m. The base of the first-order ditch which was monitored fell by 0.056 m over

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[11] With traditional drainage furrow hierarchy as defined for Great Newra Farm in Section 5.3

10.5 m. The ground levels at the crest to the side of the monitored first-order furrow was 0.129 m higher than the base of the first-order furrow.

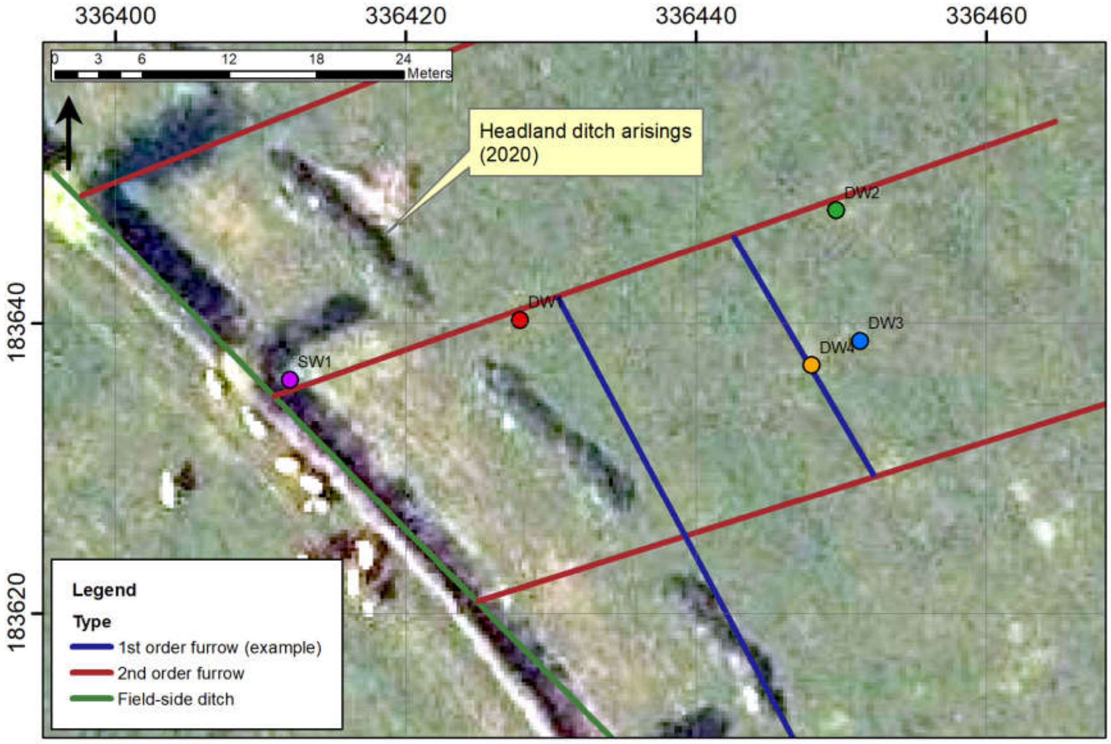

Figure 5.4-1. Hydrometric installations at Cross Farm; Chapel Road, displayed over the 2020 aerial photograph. SW 2 lies 190 m NW of SW1, or 290 m along the connecting ditch.

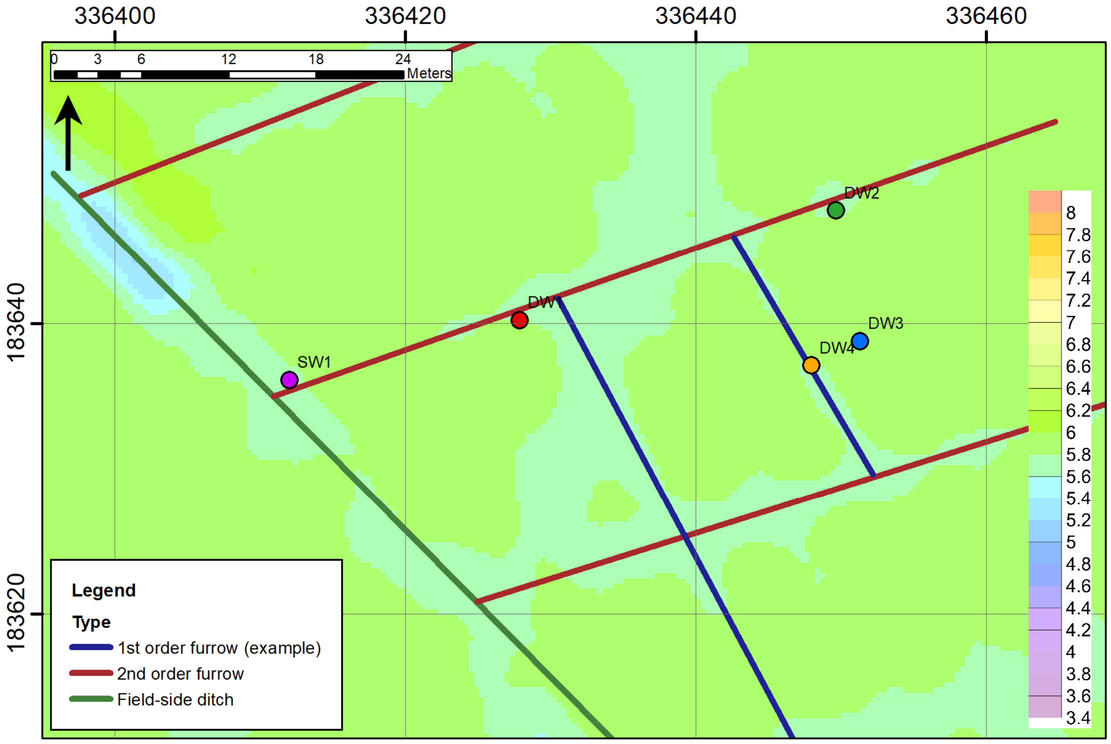

Figure 5.4-2. Hydrometric installations at Cross Farm; Chapel Road, displayed over colour-coded 1 m resolution LIDAR data.

The under-drains installed beneath the second-order furrows are perforated pipes set at c. 0.6 mbGL with a trench backfilled with gravel. The field was mole-ploughed in September 2020 (i.e. during the monitoring period), along lines at ninety-degrees to the under-drains, to a depth of 0.45 m at 2.5-3.0 m centres, but hadn't been mole ploughed for many years before (if ever).

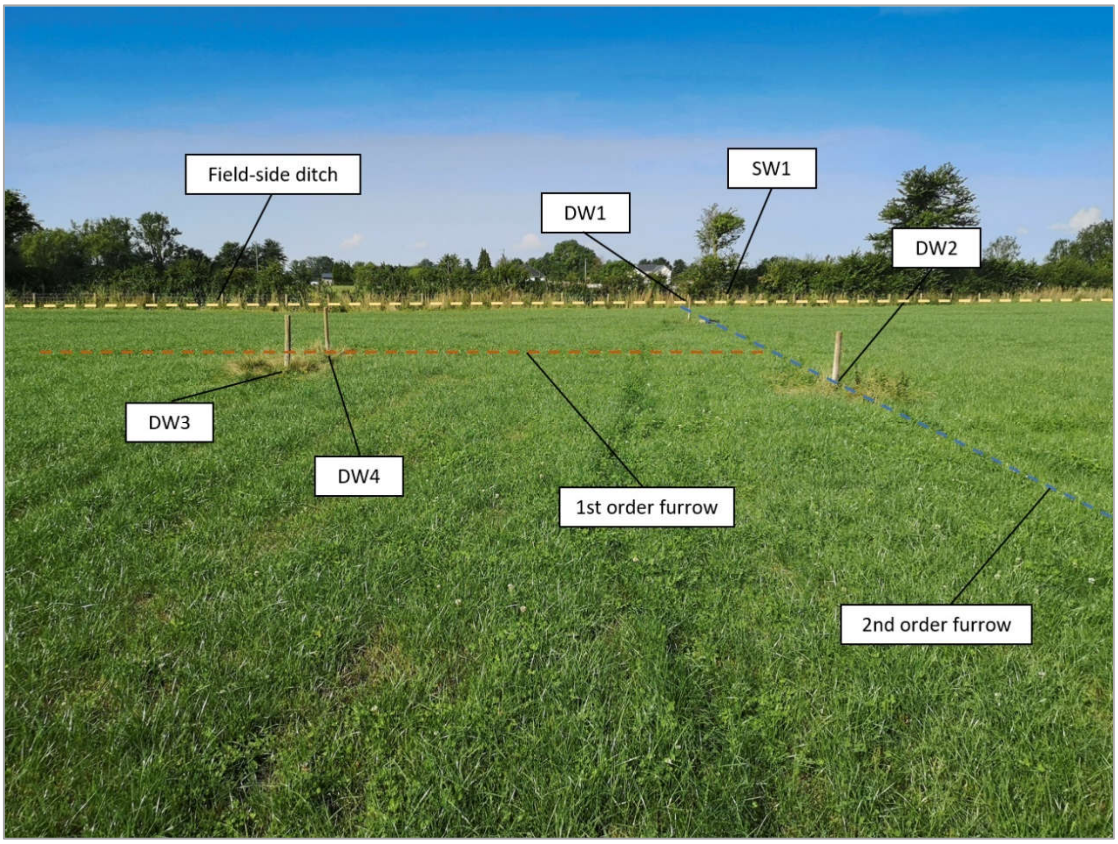

Figure 5.4-3. Annotated photograph showing the hydrometric plot at Cross Farm; Chapel Road.

John Southall (*pers. comm.*, NRW, August 2021) noted that inflows to the ditch system to maintain levels during the summer were very likely to be from the east, with water levels maintained by the sluice (C113) immediately east of SW2, also immediately upstream of the confluence with Chapel Reen. This sluice is 170 m north-west of the monitoring site, and 300 m along the lines of the ditch connection. The sluice levels for C113 are included in Table 5.3-2.

The shallow lithostratigraphic sequence for DW1 was as follows:

- 0-25 cm; wet, brown, clayey TOPSOIL.
- 25-55 cm; wet, grey with occasional orange mottle, firm, silty CLAY.
- 55-145 cm; wet, grey with orange mottle, firm, finely laminated, silty CLAY.
- 145-200 cm; wet, mid-grey, medium-soft CLAY.

## 5.5 Site 3; Cross Farm; Nash

Cross Farm; Nash was chosen as a site where drainage is effected by under-drains and mole drains. The field has been under-drained for a sufficiently long period that the micro-topography associated with the original traditional ridge-and-furrow system cannot easily be discerned visually.

The completion details of the dipwells and stilling wells are given in Table 5.5-1. The locations of the installations are shown over the 2020 aerial photograph in Figure 5.5-1, and over colour-coded ground-elevation LIDAR data in Figure 5.5-2. An annotated photograph of the study site is provided as Figure 5.5-3.

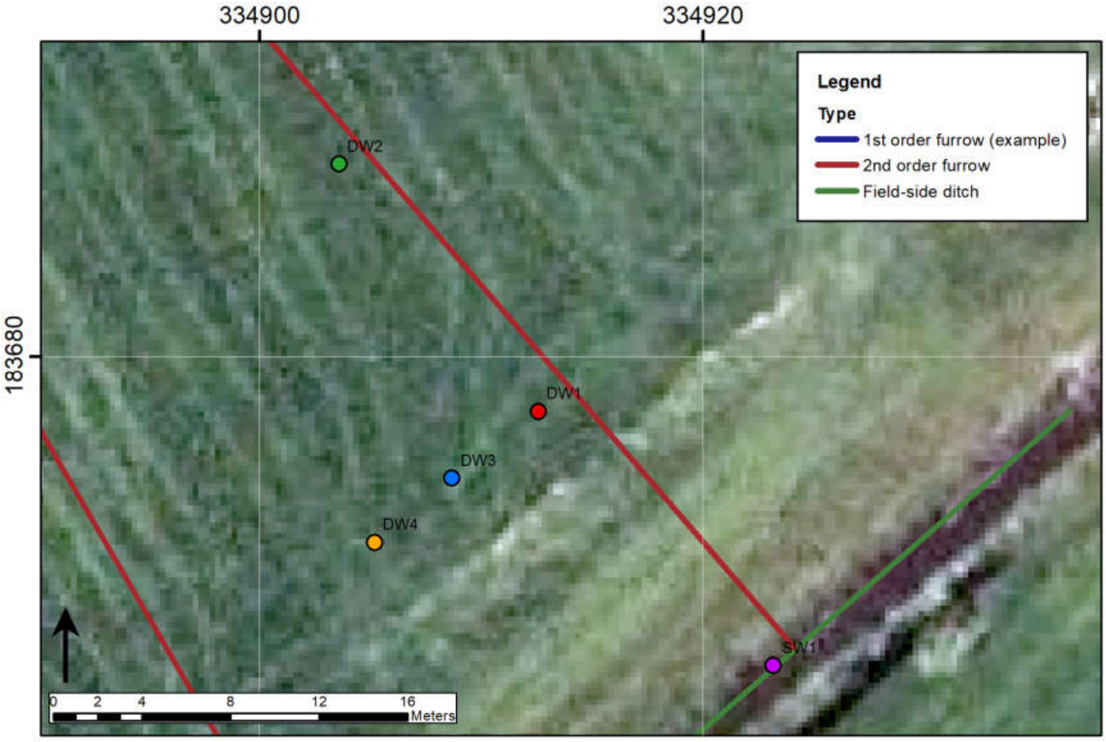

Figure 5.5-1. Hydrometric installations at Cross Farm; Nash, displayed over the 2020 aerial photograph. SW 2 lies 125 m SE of SW1, or 160 m along the connecting ditch.

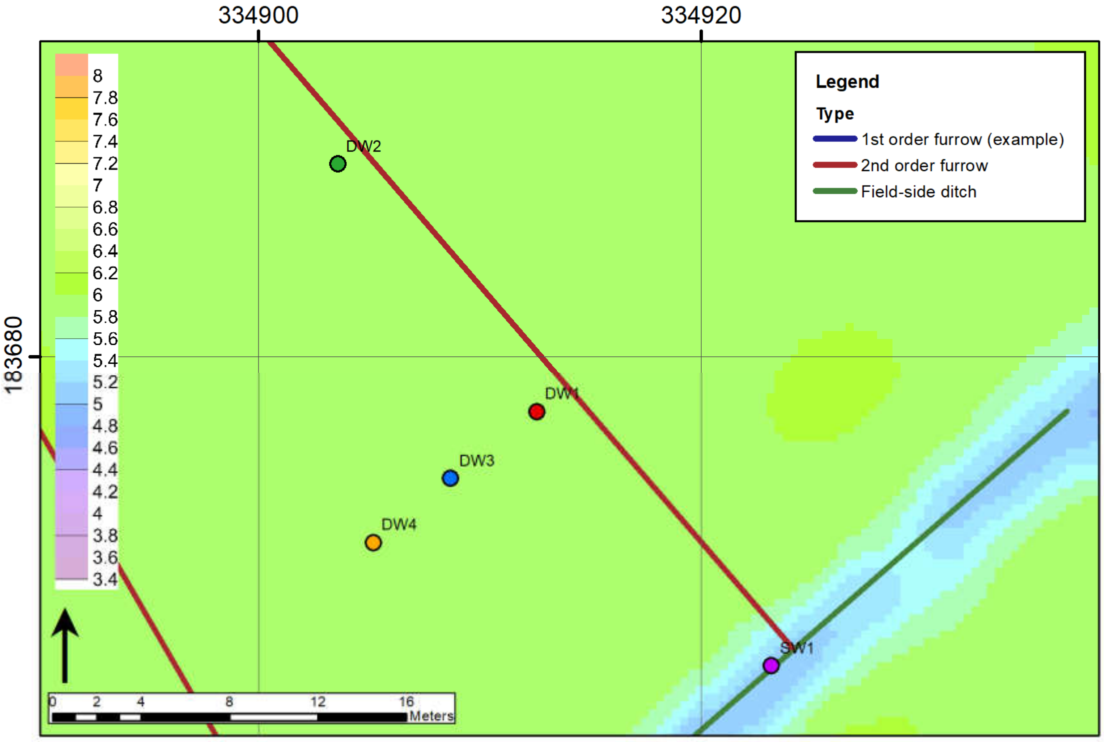

Figure 5.5-2. Hydrometric installations at Cross Farm; Nash, displayed over colour-coded 1 m resolution LIDAR data.

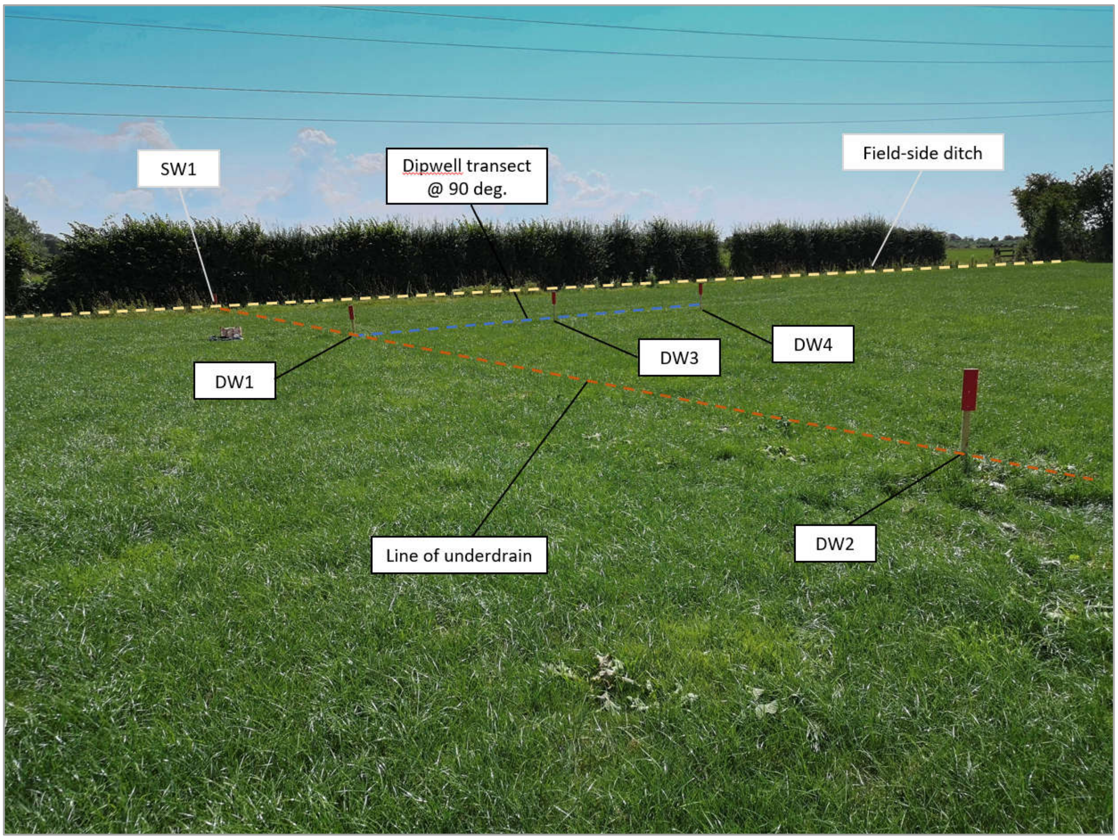

Figure 5.5-3. Annotated photograph showing the hydrometric plot at Cross Farm; Nash.

Figure 5.5-4. Mr Andrew Waters, of Cross Farm, mole-ploughing a small part of the Cross Farm; Nash monitoring site to find the lines of the under-drains.

The slight depressions associated with the lines of the under-drains (or the original second-order furrow lines) can be identified by a particular visualisation of the LIDAR data (not the one shown in Figure 5.3-2), but they were located in the field by Mr. Andrew Waters[12] using a mole plough (Figure 5.5-4) running at ninety-degrees to the under-drain, with detection through the sound as the plough passed through the stone fill of the trench.

The field was mole-ploughed in April 2013 (i.e. c. seven years before the monitoring period), along lines at ninety-degrees to the under-drains, to a depth of 0.45 m at 2.5-3 m centres.

John Southall (*pers. comm.*, NRW, August 2021) noted that inflows to the ditch system to maintain levels during the summer were very likely to be from Cross Reen, which passes immediately south of SW2, around 150 m from the monitoring site at its closest. Drainage outflows during the winter would be in the opposite direction.

The closest sluices to the monitoring site are C10 (360 m N) and C13 (420 m SE). The penning levels included in the WLMP (Pickup, 2011) are provided in Table 5.3-2. It is interesting to note that the recorded actual summer penning level for C13 is lower than the recorded preferred levels for both winter and summer.

The shallow lithostratigraphic sequence for DW1 was as follows:

- 0-20 cm; damp, brown, clay loam TOPSOIL.
- 20-45 cm; damp, grey-black, stiff, silty CLAY.
- 45-160 cm; moist, grey, medium stiff, slightly silty CLAY.
- 160-200 cm; wet, light-grey, soft CLAY.

## 5.6 Site 4; Fair Orchard Farm, St. Bride's Wentlooge

The site within Fair Orchard Farm was located between the B4239 road as it enters the eastern end of the Wentlooge Level, and the main Newport to Cardiff railway line, adjacent to the Usk estuary. It is recognised that the farm hosts good examples of traditional ridge-and-furrow drainage. The completion details of the dipwells and stilling wells are given in Table 5.6-1. The locations of the installations are shown over the 2020 aerial photograph in Figure 5.6-1, and over colour-coded ground-elevation LIDAR data in Figure 5.6-2. An annotated photograph of the study site is provided as Figure 5.6-3.

It can be seen in Figures 5.6-1 and 5.6-2 that there is a two-order furrow system at the Fair Orchard Farm site, with:

- Second-order furrows at ninety-degrees to, and discharging into, the field-side ditches; these have centre-to-centre spacing of c. 40 m, which is double the spacing for these furrows over large parts of the Levels. From Table 5.6-1 it can be seen that, taking the specific locations of the dipwells within the second-order furrow, its base falls marginally (0.16 m) over 80 m from the ditch end into the field; in practice it is essentially level over this distance.
- First-order furrows at ninety-degrees to, and draining into, the second-order furrows; these furrows facilitate drainage of the areas between the second-order furrows, and are spaced at c. 10-12 m. The base of the first-order furrow which was monitored fell by 0.265 m over 18 m. The ground level at the dipwell on the crest to the west of the monitored first-order furrow was 0.182 m higher than the base of the first-order furrow.
- As marked on Figures 5.6-1 and 5.6-2, some of the furrows on the orientation of the first-order set have the dimensions of second-order furrows. It is possible that the original traditional drainage pattern for this field was an orthogonal arrangement of second-order-sized furrows, as is evident in the field immediately to the west. This arrangement might have been augmented at a later date with shallower and more closely-spaced first-order furrows.

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[12] Particular thanks are extended to Mr. Waters for his help in this regard!

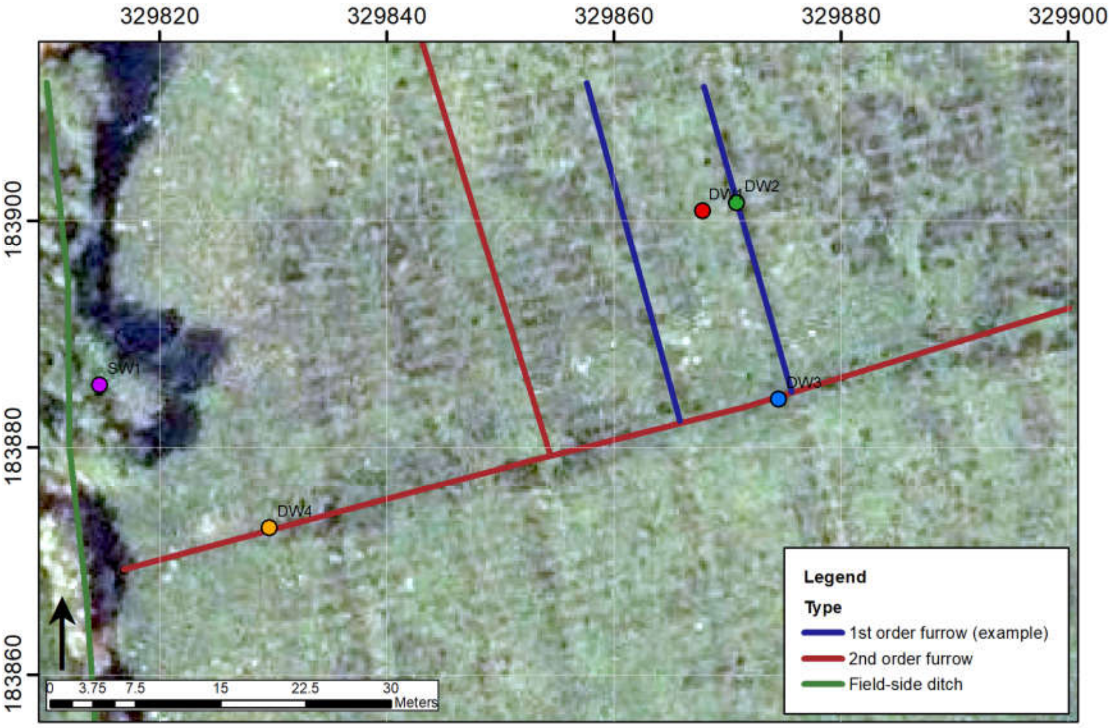

Figure 5.6-1. Hydrometric installations at Fair Orchard Farm, displayed over the 2020 aerial photograph. SW 2 lies 56 m S of SW1, in a straight line along the ditch. Some offsetting of the spatial mapping is to be expected at the scale of inspection here.

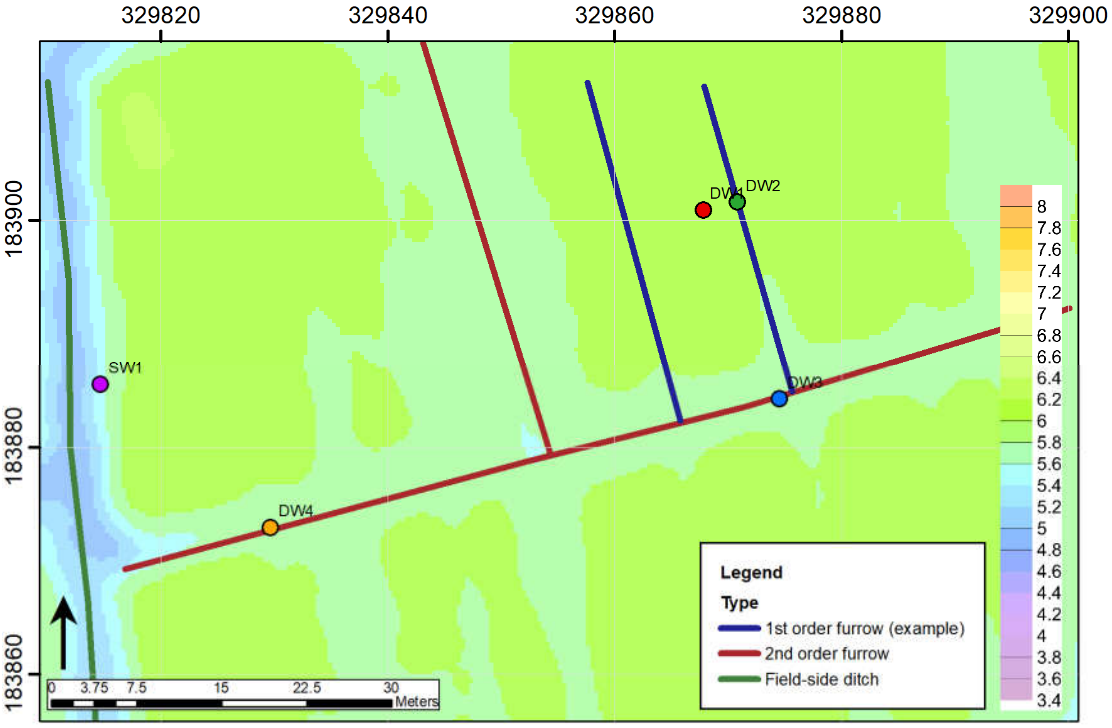

Figure 5.6-2. Hydrometric installations at Fair Orchard Farm displayed over colour-coded 1 m resolution LIDAR data.

When the dipwells and stilling well were fitted during August 2020, the second-order furrow which was monitored ran directly into the field-side ditch. During the first week of September 2020 (*pers. comm.*, Mr Andrew Prosser, contractor), the field-side ditch was cleared, with the arisings piled along the side of the ditch (usually termed a 'headland'); a pipe was installed and buried beneath the arisings to ensure hydraulic continuity between the ditch and the furrow

(Figure 5.6-4). It is not expected that this change has had any significant influence on the larger hydrological functioning of the field.

John Southall (*pers. comm.*, NRW, August 2021) noted that inflows to the ditch system to maintain levels during the summer were very likely to be from Morfa Gronw Reen, which runs east-west around 250 m south of the site. He also noted that there are large and reliable sources of water for maintenance of ditch water levels in this part of the Wentlooge Level, including the stream from the lake at Tredegar House, to the north. Drainage outflows during the winter would be in the opposite direction, to the same reen.

The closest recorded IDD sluice (W69) to the Fair Orchard Farm site is located 290 m to the south-east in a straight line, and 370 m distant by the shortest route along field-side ditches. The penning levels included in the WLMP (Pickup, 2011) are provided in Table 5.3-2.

The shallow lithostratigraphic sequence for DW1 was as follows:

- 0-15 cm; dry, grey with orange mottle, clayey TOPSOIL.
- 15-45 cm; damp, grey with orange mottle, stiff, slightly silty CLAY.
- 45-200 cm; damp, grey, stiff, slightly silty CLAY.

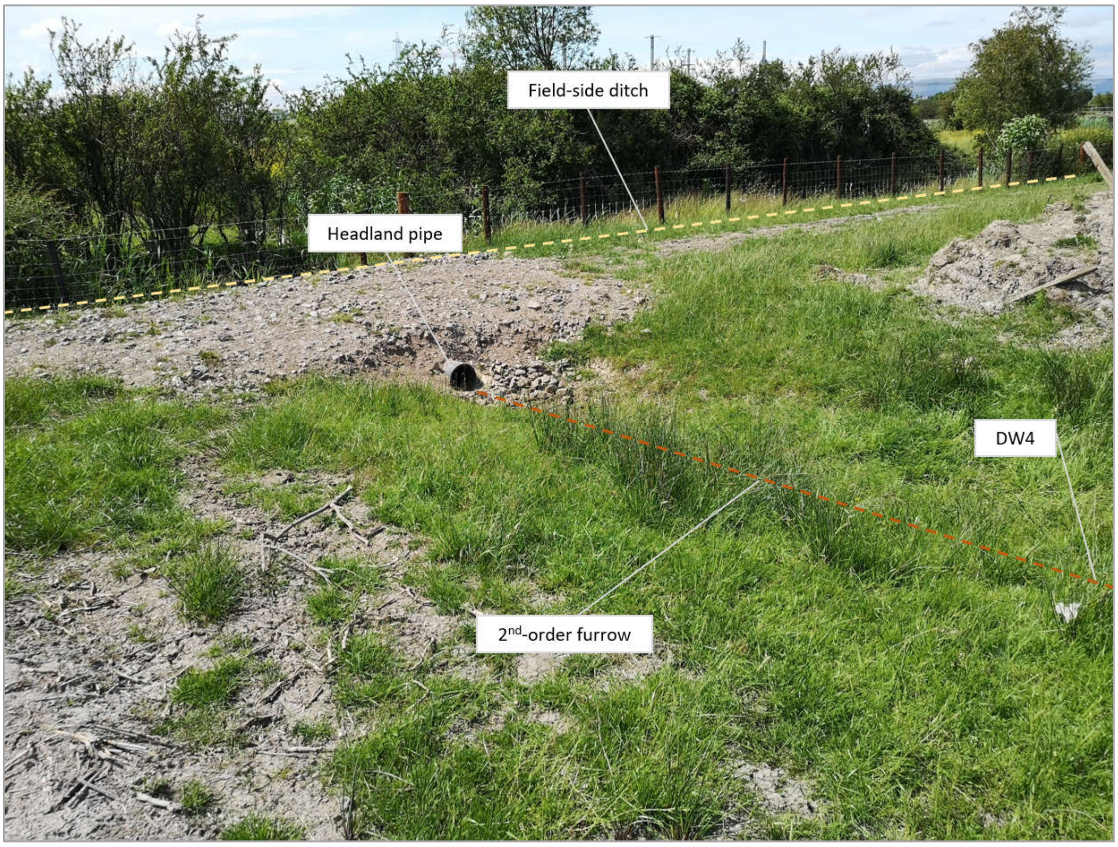

Figure 5.6-4. Annotated photograph of the recently-installed headland drainage pipe at the end of the second-order furrow monitored during the current project.

## 5.7 Site 5; Sluice House Farm, Peterstone Wentlooge

Sluice House Farm was chosen as a site where drainage is effected by under-drains. The field has been under-drained for a sufficiently long period that the micro-topography associated with the original traditional ridge-and-furrow system cannot easily be discerned visually, but can be identified through the LIDAR data (Figure 5.7-2).

The completion details of the dipwells and stilling wells are given in Table 5.7-1. The locations of the installations are shown over the 2020 aerial photograph in Figure 5.7-1, and over colour-coded ground-elevation LIDAR data in Figure 5.7-2. An annotated photograph of the study site is provided as Figure 5.7-3.

The slight linear depressions associated with the lines of the under-drains (and/or the original second-order furrow lines) can be seen in Figure 5.7-2. The field has not been mole-ploughed in the recent past, but it is planned in the next couple of years (*pers comm.*, Mr Andrew Prosser).

John Southall (*pers comm.*, NRW, August 2021) noted that inflows to the ditch system to maintain levels during the summer would be from Rhosog Fawr Reen, which has a south-west to north-east orientation, and runs along the side of the B4239 road, around 250m south-east of the site at its closest. The water for maintaining levels during the summer comes from Torwick Reen, around 250 m to the east of the site. Drainage outflows during the winter would be in the opposite direction.

The three nearest sluices, W11, W11a and W10 are all on the Rhosog Fawr Reen, respectively 300 m east-south-east, 250 m south-south-east and 360 m south-west. The penning levels for W10 and W11 are included in Table 5.3-2; there are no details for W11a which was probably added after the WLMP (Pickup, 2011) was completed.

During October 2020, the monitored field-side ditch was de-weeded, during which operation the stilling well, AWLR and ABPR were removed and lost. Fortunately, SW2 was sufficiently close to provide an alternative water level dataset for the ditch.

The shallow lithostratigraphic sequence for DW1 was as follows:

- 0-15 cm; damp, mid-brown/grey, firm, silty clay TOPSOIL.
- 15-120 cm; damp, mid-grey with orange mottle, firm, silty CLAY.
- 120-150 cm; damp, brown-black, crumbly PEAT (Von Post score = 5, i.e. medium humification).
- 150-200 cm; wet, blue-grey, soft CLAY.

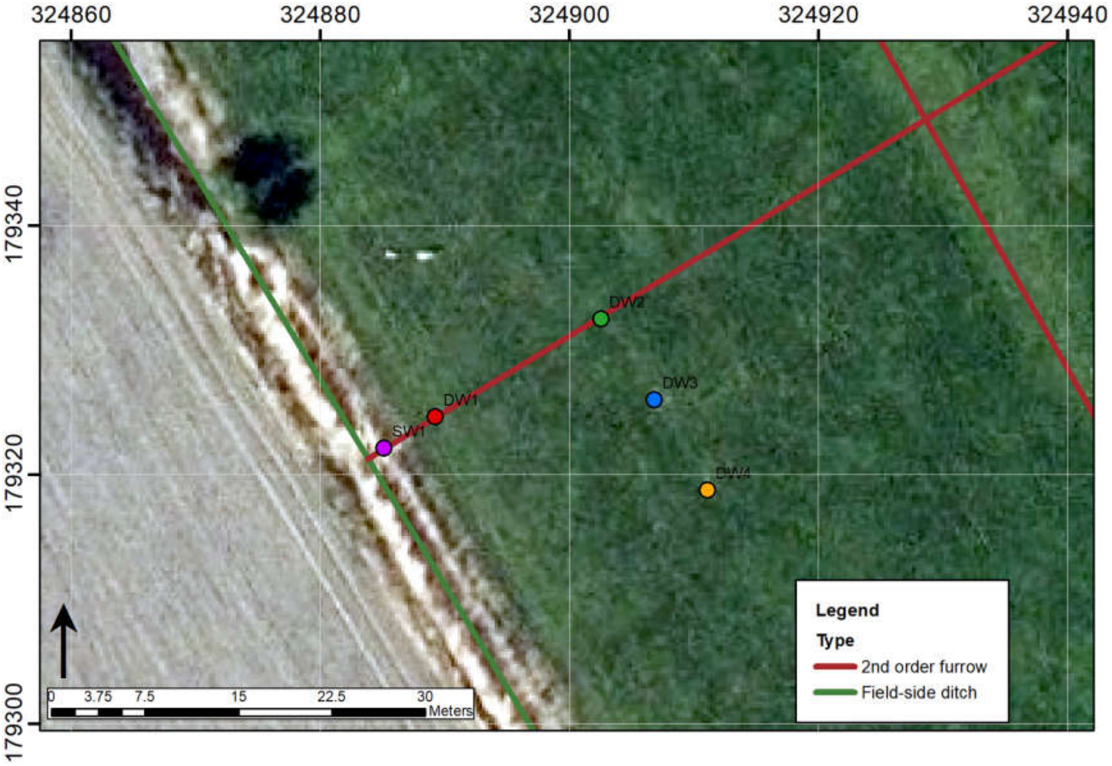

Figure 5.7-1. Hydrometric installations at Sluice House Farm, displayed over the 2020 aerial photograph. SW 2 lies 150 m SE of SW1, and 170 m along the line of the field-side ditch. Some offsetting of the spatial mapping is to be expected at the scale of inspection here.

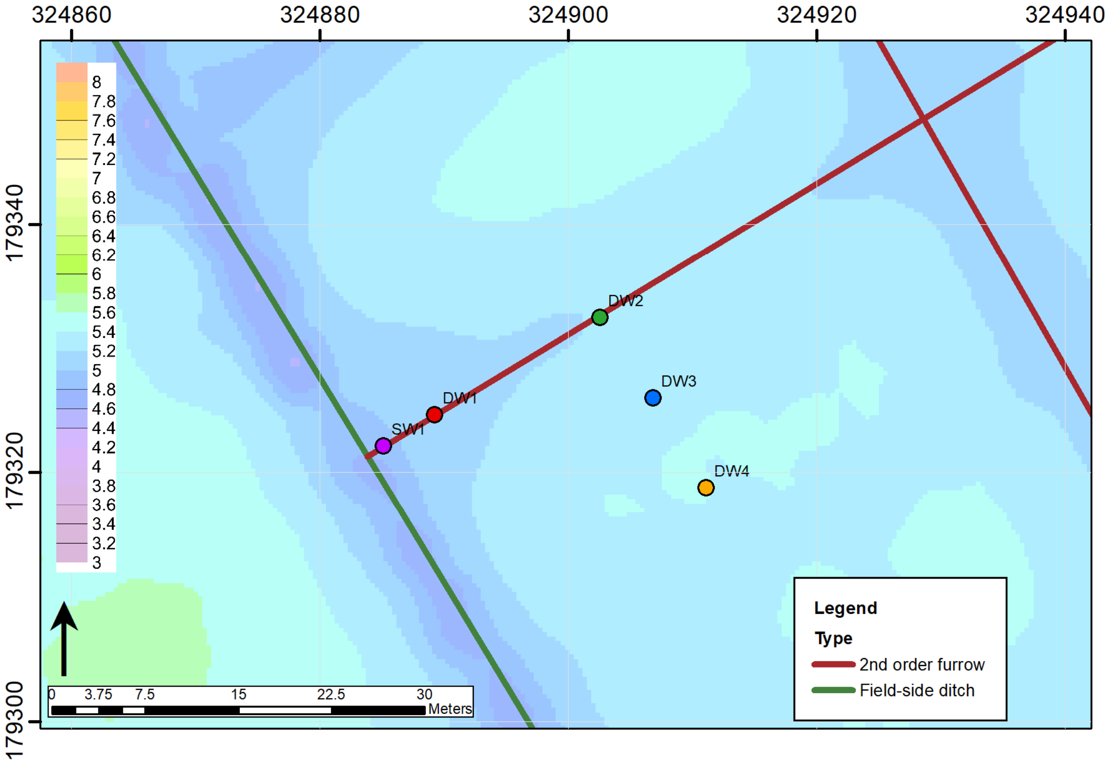

Figure 5.7-2. Hydrometric installations at Cross Farm; Nash, displayed over colour-coded 1 m resolution LIDAR data.

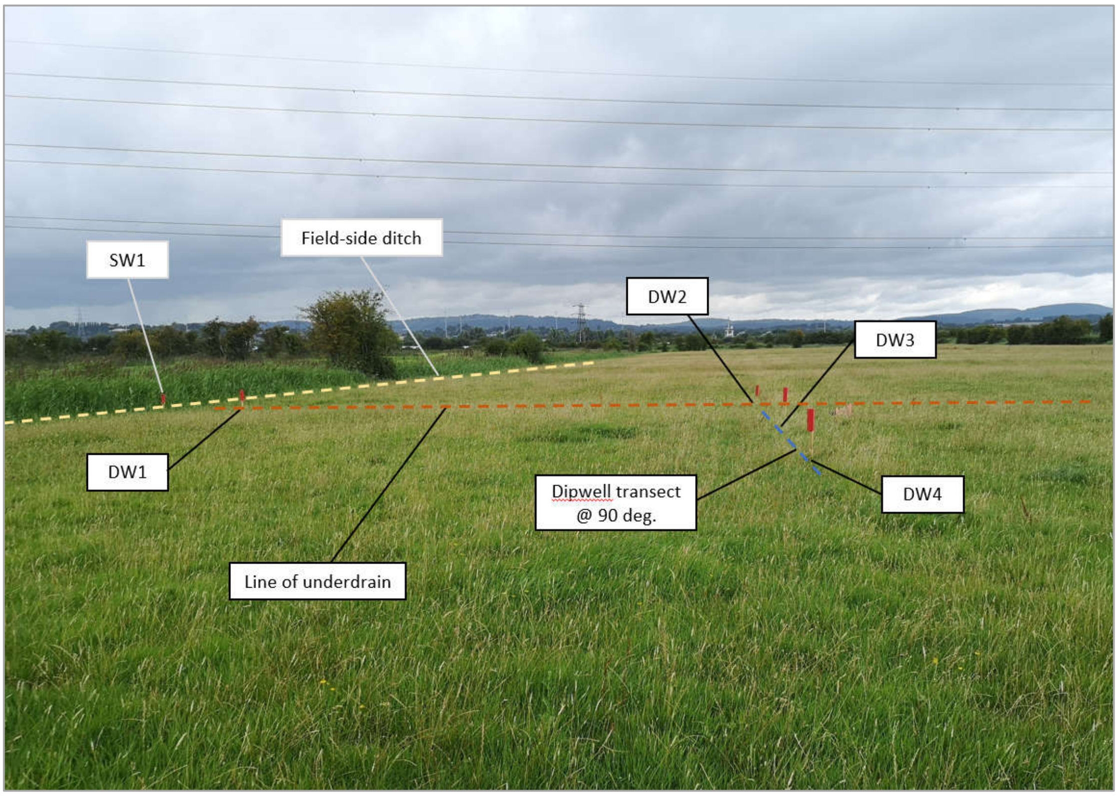

Figure 5.7-3. Annotated photograph showing the hydrometric plot at Sluice House Farm.

Table 5.3-1. Hydrometry installation details; Great Newra Farm.

| Location | Easting | Northing | Depth (m) | Extension (magl) | Datum (maOD) | GL (maOD) | P-T serial # | Relative location |
|---|---|---|---|---|---|---|---|---|
| GNDW1 | 336082.2 | 184194.9 | 2.055 | -0.055 | 5.407 | 5.462 | 2026852 | 2nd order furrow 8.8 m from ditch |
| GNDW2 | 336096.8 | 184207.9 | 2.030 | -0.03 | 5.509 | 5.539 | 2040298 | 2nd order furrow 28.5 m from ditch |
| GNDW3 | 336104.0 | 184199.6 | 2.030 | -0.03 | 5.715 | 5.745 | 2058993 | Crest between 1st order furrows |
| GNDW4 | 336101.7 | 184196.8 | 2.015 | -0.015 | 5.651 | 5.666 | 2058989 | 1st order furrow 12 m (equidistant between) 2nd order furrow |
| GNDW5 | 336099.1 | 184193.7 | 2.05 | -0.05 | 5.687 | 5.737 | 2058998 | Crest between 1st order furrows |
| GNSW1 | 336079.2 | 184184.2 | n/a | n/a | 5.985 | n/a | 2026765 | Stilling well adj. to monitoring plot |
| GNSW2 | 336041.1 | 184069.1 | n/a | n/a | 6.103 | n/a | 2059034 | Stilling well 190 m along-ditch from SW1. |

Table 5.3-2. Penning water levels for sluices close to the monitoring sites[13] (after Pickup, 2011).

| | | | | | Sluice WL limits (maOD) | | Preferred WL (maOD) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Ref** | **Reen** | **Loc'n** | **Loc'n rel. site** | **Max (1)** | **Min (2)** | **Summer (3)** | **Winter (3)** | **Actual Summer WL (maOD)(4)** |
| Gt Newra | C11 | Henton Reen | East | 600 n NNE | 4.630 | 3.045 | 4.180 | 3.725 | 4.255 |
| Gt. Newra | C15 | Red House Reen | North | 530 m S | 4.610 | 2.930 | 4.150 | 3.900 | 4.330 |
| Cross Farm; Chapel Rd | C113 | Chapel Reen (Gold) | Chestnut Street | 170 m NW | 4.330 | 2.855 | 4.500 | 3.820 | 3.860 |
| Cross Farm; Nash | C10 | Nash | Burbery | 360 m N | 5.570 | 4.325 | 5.200 | 5.100 | 4.900 |
| Cross Farm; Chapel Rd | C113 | Chapel Reen (Gold) | Chestnut Street | 170 m NW | 4.330 | 2.855 | 4.500 | 3.820 | 3.860 |
| Cross Farm; Nash | C10 | Nash | Burbery | 360 m N | 5.570 | 4.325 | 5.200 | 5.100 | 4.900 |
| Cross Farm; Nash | C13 | Cross Reen | East | 420 m SE | 6.010 | 4.685 | 5.250 | 4.915 | 5.390 |
| Fair Orchard Farm | W69 | Morfa Gronw | Ty-Hir New | 290 m SE | 6.220 | 4.725 | 5.550 | 5.550 | 5.660 |
| Sluice House Farm | W10 | Rhosog Fawr | Ty Du | 360 m SW | 4.990 | 3.915 | 4.700 | 4.250 | No entry in WLMP |
| Sluice House Farm | W11 | Rhosog Fawr | Sluice Farm | 300 m ESE | 4.980 | 3.370 | 4.200 | 4.200 | No entry in WLMP |

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[13] John Southall (*pers. comm.*) noted that: 1 – This is the top of the sluice structure, and water levels would never be penned this high; 2 – This is the base of the concrete structure, and water levels would never be lowered to this level as in most cases it would lead to a dry ditch with no protection for silt; 3 – These are the preferred respective water levels, but they are adjustable to suit local requirements; 4 – These are the actual summer penning levels, which were being recorded by CWLIDB prior to its becoming a part of NRW. This exercise was not completed, meaning that there are some gaps in the relevant table in Pickup (2011).

Table 5.4-1. Hydrometry installation details; Cross Farm; Chapel Road.

| Location | Easting | Northing | Depth (m) | Extension (magl) | Datum (maOD) | GL (maOD) | P-T serial # | Relative location |
|---|---|---|---|---|---|---|---|---|
| CF1DW1 | 336426.9 | 183641.6 | 2.030 | -0.03 | 5.808 | 5.778 | 2059033 | 2nd order furrow 17.5 m from ditch |
| CF1DW2 | 336452.3 | 183648.2 | 2.030 | -0.03 | 5.794 | 5.764 | 2079133 | 2nd order furrow 40.5 m from ditch |
| CF1DW3 | 336450.9 | 183640.1 | 2.055 | -0.055 | 5.954 | 5.899 | 2079765 | Crest between 1st order furrows |
| CF1DW4 | 336448.5 | 183638.1 | 2.030 | -0.03 | 5.850 | 5.820 | 2082122 | 1st order furrow 10 m (equidistant between) 2nd order furrow |
| CF1SW1 | 336412.0 | 183636.1 | n/a | n/a | 6.236 | n/a | 2059005 | Stilling well adj. to monitoring plot |
| CF1SW2 | 336245.6 | 183732.8 | n/a | n/a | 6.182 | n/a | 2044054 | Stilling well 290 m along-ditch from SW1. |

Table 5.5-1. Hydrometry installation details; Cross Farm; Nash.

| Location | Easting | Northing | Depth (m) | Extension (magl) | Datum (maOD) | GL (maOD) | P-T serial # | Relative location |
|---|---|---|---|---|---|---|---|---|
| CF2DW1 | 334912.6 | 183677.5 | 2.020 | -0.02 | 5.886 | 5.906 | 2117114 | Line of under-drain, 16 m from ditch |
| CF2DW2 | 334903.6 | 183688.7 | 2.010 | -0.01 | 5.894 | 5.904 | 2116632 | Line of under-drain, 30 m from ditch |
| CF2DW3 | 334908.7 | 183674.5 | 2.025 | -0.025 | 5.886 | 5.911 | 2117102 | 6 m from line of under-drain, on transect at 90 degrees |
| CF2DW4 | 334905.2 | 183671.6 | 2.020 | -0.02 | 5.914 | 5.934 | 2116629 | 11 m from line of under-drain, on transect at 90 degrees |
| CF2SW1 | 334922.2 | 183667.3 | n/a | n/a | 6.570 | n/a | 2111882 | Stilling well adj. to monitoring plot |
| CF2SW2 | 334908.3 | 183757.8 | n/a | n/a | 6.408 | n/a | 2117120 | Stilling well 160 m along-ditch from SW1. |

Table 5.6-1. Hydrometry installation details; Fair Orchard Farm.

| Location | Easting | Northing | Depth (m) | Extension (magl) | Datum (maOD) | GL (maOD) | P-T serial # | Relative location |
|---|---|---|---|---|---|---|---|---|
| FODW1 | 329867.0 | 183901.1 | 2.035 | -0.035 | 6.579 | 6.544 | 2044063 | Crest between 1st order furrows |
| FODW2 | 329872.3 | 183901.8 | 2.025 | -0.025 | 6.407 | 6.382 | 2044052 | 1st order furrow 18 m (equidistant between) 2nd order furrow |
| FODW3 | 329874.1 | 183885.6 | 2.010 | -0.01 | 6.157 | 6.147 | 2044045 | 2nd order furrow 63.5 m from ditch |
| FODW4 | 329830.6 | 183880.4 | 2.04 | -0.04 | 6.143 | 6.103 | 2044051 | 2nd order furrow 17.0 m from ditch |
| FOSW1 | 329814.7 | 183885.5 | n/a | n/a | 6.681 | n/a | 2044049 | Stilling well adj. to monitoring plot |
| FOSW2 | 329821.8 | 183830.3 | n/a | n/a | 6.756 | n/a | 2063711 | Stilling well 56 m along-ditch from SW1. |

Table 5.7-1. Hydrometry installation details; Sluice House Farm.

| Location | Easting | Northing | Depth (m) | Extension (magl) | Datum (maOD) | GL (maOD) | P-T serial # | Relative location |
|---|---|---|---|---|---|---|---|---|
| SHDW1 | 324888.800 | 179325.400 | 2.085 | -0.085 | 4.978 | 5.063 | 2044064 | Line of under-drain, 6.6 m from ditch |
| SHDW2 | 324902.300 | 179333.500 | 2.070 | -0.07 | 5.104 | 5.174 | 2044060 | Line of under-drain, 22 m from ditch |
| SHDW3 | 324906.5 | 179326.8 | 2.09 | -0.09 | 5.244 | 5.334 | 2044059 | 7.8 m from line of under-drain, on transect at 90 degrees |
| SHDW4 | 324910.700 | 179319.800 | 2.085 | -0.085 | 5.304 | 5.389 | 2044039 | 16.2 m from line of under-drain, on transect at 90 degrees |
| SHSW2 | 324979.600 | 179202.600 | n/a | n/a | 5.659 | n/a | 2044065 | Stilling well 170 m along-ditch from SW1. |

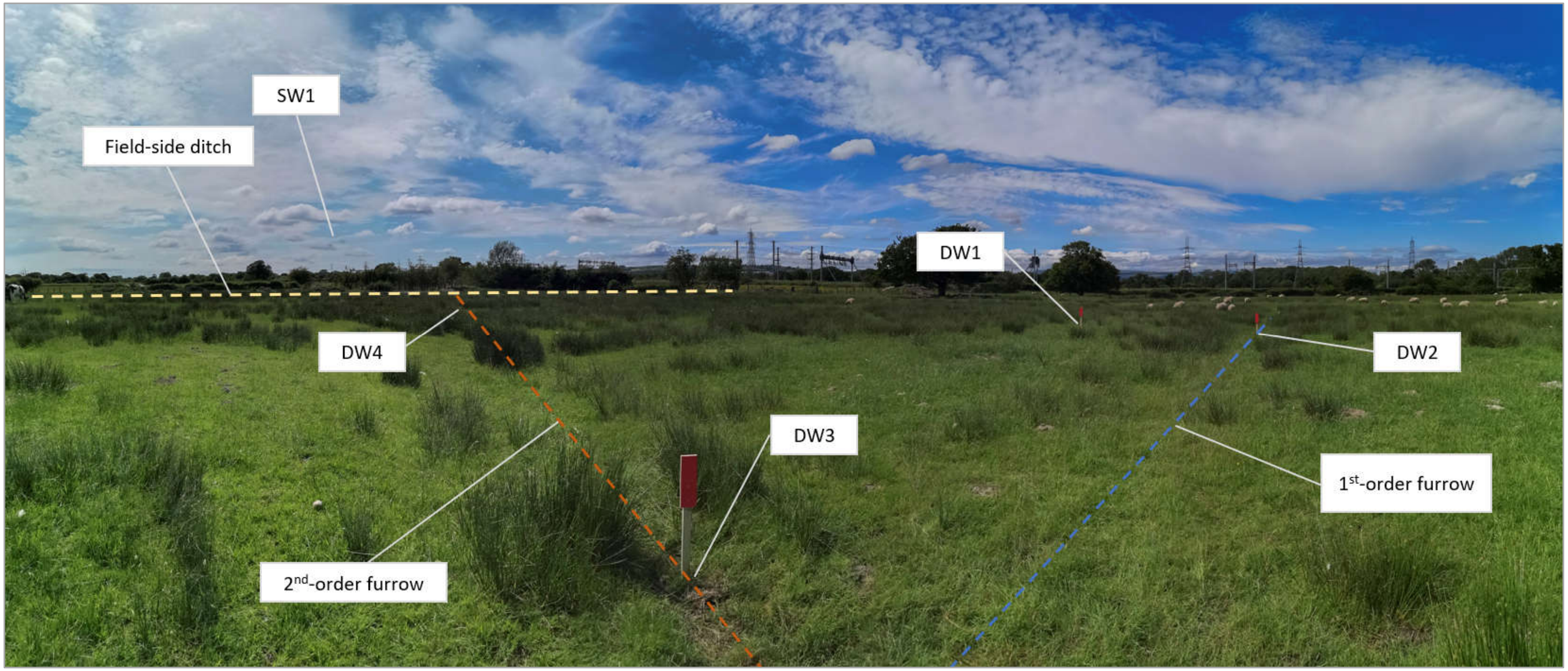

Figure 5.6-3. Annotated photograph of the hydrological monitoring plot at Fair Orchard Farm.

# 6 Qualitative interpretation of monitoring data

## 6.1 Rainfall and potential evapotranspiration

As noted in Section 2.1, rainfall data were obtained from NRW for Colister Pill raingauge (344501 186791) at the eastern end of the Caldicot Level. The average (2005-2020) annual rainfall for this gauge was 927 mm. This gauge is to the east, but within 15 km, of all of the monitoring sites. It is also the closest gauge for which data are available, and is located in the same landscape position (i.e. the coastal plain of the Levels) as the monitoring sites. For these reasons the rainfall data from Collister Pill has been used for the qualitative analysis presented in this section, and also for the groundwater modelling presented in Section 8.

It is important to set the weather conditions experienced during the project monitoring period against longer-term average conditions, in order to gauge how typical the monitoring period was in this regard.

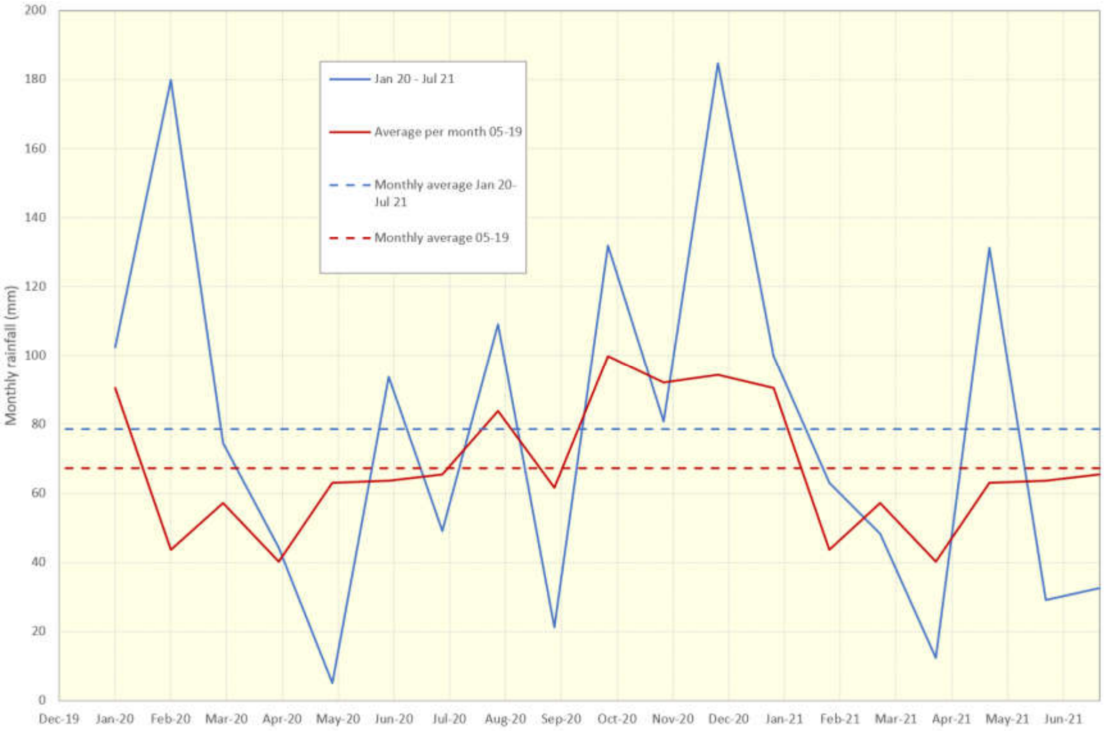

Figure 6.1-1. Time-series monthly rainfall; monitoring period and average (2005-2019) for the Collister Pill raingauge.

Figure 6.1-1 shows the time-series of:

- Monthly rainfall during the monitoring period (March 2020 to July 2021), and also the pre-monitoring period which determined the hydrological conditions at the start of monitoring (January to February 2020).
- Monthly rainfall averages (2005 to 2019).

It also includes the overall average monthly rainfall for both the monitoring period and the 2005 to 2019 period.

Figure 6.1-2 shows a time-series comparison between the monthly rainfall during the monitoring period, and over the 2005 to 2019 period, expressed as a percentage. This is calculated using the same data as Figure 6.1-1, but it allows an easier assessment of the monthly departures from the average during the monitoring period.

Considering the two figures, it can be seen that:

- Average monthly rainfall during the January 2020 to July 2021 (78.6 mm) was 16.8% higher than the longer-term monthly average (67.3 mm). This comparison is very sensitive to the large amount of rainfall during February 2020 (during the pre-monitoring period), and if only the monitoring period (March 2020 to July 2021) is considered, the average monthly rainfall (71.2 mm) was only 5.8% higher than the longer-term monthly average. The 28th February 2020 has the 6th highest daily total in the time series (37.2 mm).

- Monthly rainfall varied appreciably from the average values during the monitoring period; this is to be expected to some extent when comparing individual records against a longer-term average.

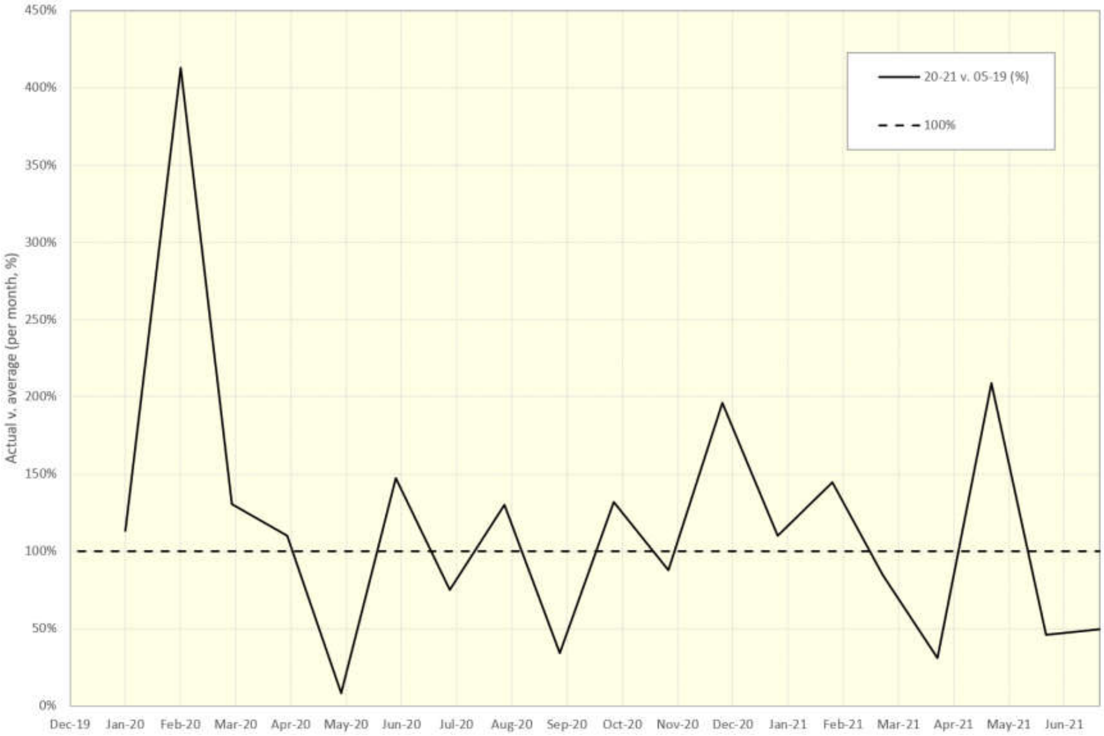

Figure 6.1-2. Time-series comparison of monthly rainfall; monitoring period and average (2005-2019), expressed as percentage difference, for the Collister Pill raingauge.

- During the monitoring period there were some significant departures from the monthly averages with, for example, only 8% of longer-term monthly average rainfall during May 2020 (this was a notable dry period[14]), and c. 200% of longer-term monthly average rainfall during December 2020 and May 2021.
- There were no sustained (i.e. two or more months) periods of significantly wetter or drier than average conditions, particularly during the monitoring period (March 2020 to July 2021).

It is therefore concluded that:

- There was exceptional rainfall during February 2020 (413% of the February average), which will have contributed to the monitoring sites being in a ‘wetted’ state at the start of monitoring in March 2020.
- Overall, rainfall during the monitoring period (March 2020 to July 2021) was slightly higher (+5.8%) than average.
- There were no sustained periods of wetter or drier than average conditions during the monitoring period.

Therefore, in terms of incident rainfall, the monitoring period was reasonably representative of longer-term average conditions, which is useful with regard to the general applicability of the results of the project.

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[14] Which is more prominent in collective memory as it coincided with the period of severely reduced activity imposed to manage the SARS-COV-2 virus.

## 6.2 Site 1; Great Newra Farm, Broadstreet Common

Soil water and ditch water level monitoring in the traditionally-drained field at Great Newra was carried out between March 2020 and August 2021. Details of the monitoring installations are provided in Section 5.3. Time-series water level hydrographs are provided as follows:

- Figure 6.2-1. This shows water levels plotted at the correct relative elevation to each other, with the elevation (maOD) based on a LIDAR elevation for the dipwell on the flattest ground, in this case DW3. The maximum and minimum ground elevations across the dipwells are also shown.
- Figure 6.2-2. This shows water levels plotted relative to the ground surface (i.e. mbGL) at each individual dipwell; the stilling wells are not included.
- For both of the figures the daily rainfall at Collister Pill (Section 6.1) is included.
- And for both of the plots, the colours used for each hydrograph line correspond with the 'dot-colour' used in the maps within Section 5, to allow easy cross-referencing.

The following, which are directly relevant to the current project, can be observed from the two figures:

Ditch water levels

The ditch water level hydrographs show clear evidence of IDD management:

- Between the end of March and the end of May 2020, ditch water levels rose by c. 0.3 m ('1' in Figure 6.2-1). This was a during a dry and warm period when soil water levels fell by up to 0.8 m, and it is clear evidence of the effects of raising sluices and re-directing water from the main carrier reens. The relatively slow rise in ditch water levels during this period demonstrates that it was solely caused by re-direction of surface water, with minimal rainfall to fill the extra ditch storage volume created by raising the sluices.
- The stable ditch water level during summer 2020 ('2') is probably a reflection of the continuous overflow across a downstream sluice or sluices. The relative ditch water levels in the stilling wells show a northwards hydraulic gradient. The actual summer penning levels (Table 5.3-2) at the two nearest sluices are 4.255 maOD (C11, 600 m NNE) and 4.330 maOD (C15, 530 m S). The retained summer 2020 level at SW1 was c. 4.79 maOD which is at least 0.46 m higher than the recorded level for the nearby sluices, which suggested that there is not a direct, highly conductive, connection between the monitoring site and either of the sluices, and/or that there is an intermediate (unrecorded) water level control.
- The effect of lowering of sluices in preparation for the colder months of 2020-21 can be seen from early September 2020 ('3'). It is thought likely that the sluices were lowered at this time, although the immediate, precipitous fall in levels was partly caused by the dry weather. It is notable after this time though that the ditch water levels do not return to summer levels during the colder months ('4'), despite significant rainfall and much lower evapotranspiration.
- It is worth noting that the ditch water levels at the monitoring site (routinely 4.5-4.7 maOD) are much higher than the recorded winter penning levels for the nearby IDD sluices (3.725 and 3.9 maOD for C11 and C15 respectively). This suggests either an error in the levels quoted for the sluices, or that the ditch water levels at the monitoring site are not directly controlled by these sluices.
- The effects of any raising of sluices during spring 2021 are more difficult to identify; there was no period of near-constant ditch water levels during the monitoring period. The marked upwards step in ditch water levels in early April 2021 ('7'), which was coincident with a very small rainfall event, was perhaps more the effect of raising sluices.
- Ditch water levels are markedly less responsive to rainfall events during the warmer months (e.g.'8') than during the colder months (e.g. '9'). This is almost certainly because high soil water levels during the winter mean that there is little available within-field water storage potential, and water runs off directly into the field-side ditches; hydrologically this is often referred to as a 'flashy' condition. In contrast, soil water levels are generally lower during

the warmer months, and this within-field storage buffers runoff, and high EVT reduces runoff, to the field-side ditches in response to rainfall.

Soil water levels

- The seasonal cycle of soil water levels can be seen, with low soil water levels during the warmer months of 2020 (down to 1.0-1.3 mbGL) and 2021, and high soil water levels during the colder months of 2020-21. During late-October 2020, the soil water level condition changed relatively rapidly ('A' in Figure 6.2-2) from a low to a high condition. This was almost certainly caused by a combination of a prolonged period of rainfall and a reduction in evapotranspiration as air temperatures fell.
- During the colder months of 2020-21, soil water levels were almost constantly within 0.3 m of the ground surface ('B'), with the differences in relative elevation ('5') being solely a function of the variation in ground surface elevation within the micro-topography of the field.
- The situation above is reversed during the warmer months. The water table becomes relatively flat ('6'), and the differences in soil water level expressed as mbGL ('C') are solely a function of the overlying micro-topography.
- During the two warm and dry periods of spring 2020, soil water levels within all five dipwells fell below (up to c. 0.4 m) the water level in the field-side ditch ('2' and '6'). This offers confirmation that one of the purposes of maintaining high ditch water levels during the warmer months, to support adjacent soil water levels, is being achieved. The degree of support that is actually achieved, i.e. the amount of water which flows from the ditches into the fields in response to the reversed hydraulic gradient, is open to question. In this regard it is worth noting that:
    - The soil water level has fallen into the interval of grey clay, which will be very poorly permeable, and;
    - The higher ditch water levels appear to have little or no effect on the dynamic behaviour of the soil water levels, i.e. there is no reduction of the rate of fall of soil water levels as they fall below the ditch water level ('10').
- With regard to agricultural access to the field during the monitoring period, soil water levels were universally below the often-quoted field access threshold of 0.4-0.5 mbGL until the end of October 2020 ('A'). They fell more consistently below this level from the end of March 2021 ('D'), although they returned briefly to higher levels in response to heavy rainfall during May 2021 ('E').

## 6.3 Site 2; Cross Farm, Chapel Road

Soil water and ditch water level monitoring within the combined under-drained and traditionally-drained field at Cross Farm; Chapel Road was carried out between March 2020 and August 2021. Details of the monitoring installations are provided in Section 5.4. Time-series water level hydrographs are provided, in the formats described at the start of Section 6.2, as Figures 6.3-1 (maOD) and 6.3-2 (mbGL). The following, which are directly relevant to the current project, can be observed from the two figures:

Ditch water levels

The ditch water level hydrographs show clear evidence of IDD management:

- The hydrographs for SW1, at the monitoring plot, and SW2, downstream of the plot and immediately upstream of sluice C113, are extremely similar, implying a very good hydrological connection along the line of the ditch. Looking closely, it appears that the hydraulic gradient along the ditch is often reversed, with the levels at SW2 being higher than those at SW1. The hydrograph for SW2 is often 'noisy' for short periods (e.g. '1' in Figure 6.3-1), which almost certainly indicates a tidal influence.
- The ditch water levels appear to show the influence of IDD management with, for example, a rise in level during a dry period in late-May 2020 ('2'), a lower base level during the colder months of 2020-21 ('3'), transitioning to a higher base level during the warmer months of 2021 ('4'). The periods of 'flat-line' response (e.g. '4') confirm local control at the overflow level of the sluice (C113).

- The actual summer penning level for sluice C113, estimated from the hydrographs (c. 4.75 maOD), is higher than the recorded preferred summer level (4.5 maOD, Table 5.3-2) and much higher than the recorded actual summer level (3.86 maOD). Similarly, the actual winter penning level (4.5-4.65 maOD) is significantly higher than the recorded winter penning level of 3.82 maOD. There is no obvious explanation for this mismatch in recorded and actual penning levels.
- Ditch water levels are markedly less responsive to rainfall events during the warmer months (e.g.'5') than during the colder months (e.g. '6')(see Section 6.2).

Soil water levels

Perhaps unsurprisingly, the hydrology of the Cross Farm; Chapel Road monitoring plot appears to be dominated by the presence of under-drains, which mask any hydrological influence of the remnants of the traditional field micro-topography. As such, the dipwells can be divided into two response-types, as for the other under-drained sites at Cross Farm; Nash (Section 6.4) and Sluice House Farm (Section 6.6).

- During the colder months the base level for soil water levels in DWs 1 and 2, which are located along the line of the under-drain, was c. 4.9 and 5.1 maOD respectively ('7'). This was 0.45-0.5 m higher than the level in the field-side ditch. This implies that the under-drain was flowing, relatively efficiently, towards the field-side ditch, and that the base level for the soil water levels is close to the invert level (the base of the pipe) for the under-drains, implying that the invert level is 0.7-0.8 mbGL.
- During the warmer months the soil water level along the line of the under-drain falls below its invert level (e.g. '8'), and therefore it becomes de-coupled from the influence of the under-drain and behaves in a very similar manner to the soil water levels over the wider field (DWs 3 and 4, see below).
- During the colder months the soil water levels away from the under-drain (DWs 3 and 4) are much higher than those along the under-drain, demonstrating a relatively steep hydraulic gradient towards the under-drain, and thus the efficiency of the under-drains. It is interesting that the soil water level behaviours in DWs 3 and 4 were very different during this time; the water levels in DW3 were very responsive to rainfall ('9') whereas those in DW4 were strongly controlled at a maximum elevation of 5.48 maOD ('10') or 0.4 mbGL ('A' in Figure 6.3-2). There is no direct evidence of an explanation for the latter, but it can reasonably be inferred that there is a highly permeable mole drain or (drying?) fracture in the soil at this level, along which water flows readily to control levels at the dipwell. The control level (0.4 mbGL) is coincident with the reported elevation of mole drains.
- During the warmer months the soil water levels in all of the dipwells fall below the invert level of the under-drain, and behave very similarly. During July and August 2020, the soil water table was at a very similar absolute level across the monitoring plot ('8'), and differences in elevation relative to the ground surface ('B') were solely a function of the overlying micro-topography.
- During the warmer months soil water levels were fairly unresponsive (e.g. 'C') to all but the largest rainfall events (e.g. 'D'), suggesting that rainfall was held in the upper soil (as partial saturation of the previously dry upper soil horizons) before being lost to evapotranspiration. Storage of rainwater as partial saturation of upper soil layers means that it does not penetrate through the unsaturated zone to the water table. Larger rainfall events appear to overwhelm the storage capacity of the upper soil zone, allowing water to flow to the water table and subsequently flow laterally to the field-side ditches.
- It is interesting to note that during the colder months relatively steep hydraulic gradients are established from the wider field to the under-drain, and from the under-drain to the field-side ditch. These hydraulic gradients become less steep during the warmer months, as the water table declines, and the hydraulic gradient between the field and the field-side ditch was reversed in the late summer of 2020.

## 6.4 Site 3; Cross Farm, Nash

Soil water and ditch water level monitoring in the under-drained field at Cross Farm; Nash was carried out between August 2020 and August 2021. Details of the monitoring installations are provided in Section 5.5. Time-series water level hydrographs are provided, in the formats described at the start of Section 6.2, as Figures 6.4-1 (maOD) and 6.4-2 (mbGL). The following, which are directly relevant to the current project, can be observed from the two figures:

<u>Ditch water levels</u>

The ditch water level hydrographs show clear evidence of IDD management:

- The effect of lowering of sluices in preparation for the colder months of 2020-21 can perhaps be seen in late-October 2020 ('1' in Figure 6.4-1), when the ditch water level fell sharply during a prolonged period of rainfall. It is notable that after this time the ditch water levels generally did not return to summer levels (between rainfall events) during the colder months ('2'), despite significant rainfall and much lower evapotranspiration. The relative ditch water levels in SW1 and SW2 show a hydraulic gradient to the south, towards C13 sluice. The ditch water level fell to a minimum of 4.9 maOD during the colder months in early March 2021, which is similar to the reported preferred winter level for C13 (4.915 maOD, Table 5.3-2), which offers tentative confirmation that this sluice controls the ditch water levels at the monitoring site.
- It would appear that the sluices were raised in preparation for the warmer months of 2021 during mid-March 2021 ('3'). After this point higher levels were maintained ('4') than the period immediately before, during a prolonged dry period. The apparent penned level was c. 5.15 maOD, which is c. 0.24 m lower than the recorded actual summer penning level at C13 (Table 5.3-2).
- Again, ditch water levels are markedly less responsive to rainfall events during the warmer months (e.g.'5') than during the colder months (e.g. '6')(see Section 6.2).

<u>Soil water levels</u>

- The expected seasonal cycle of soil water levels can be seen, with low soil water levels during the warmer months of 2020 (down to 1.0-1.1 mbGL) and 2021, and high soil water levels during the colder months of 2020-21.

The dipwells can be divided into two response-type groups:

- <u>DWs 1 and 2</u> are located along the line of an under-drain. The soil water levels in these dipwells are generally very similar to the water levels in the field-side ditch, which probably confirms the under-drainage pipe and stone-filled trench as an axis of high conductance. It is interesting to note that the soil water levels are virtually the same as the field-side ditch levels during the warmer months ('4' and '7'), with the ditch water level maintaining the level along the under-drain. It is also interesting to note that during these periods the soil water levels are below 0.8 mbGL ('G' in Figure 6.4-2), which implies that the effective base of the under-drain is lower than the c. 0.6 mbGL previously suggested (*pers. comm.*, Andrew Waters). During the colder months, with a lowered ditch water level and more water draining from the field, soil water levels are maintained at a higher level than the ditch water level (e.g. '6'). During the colder months, the soil water levels along the under-drain are generally well below the ground surface ('A'), but they are also very sensitive to rainfall, and often rise very briefly to higher levels ('B') before water is removed rapidly by the under-drain.
- <u>DWs 3 and 4</u> are in a transect at 90 degrees to the under-drain. The water levels in these dipwells were generally lower (0.1-0.2 m) than those in DWs 1 and 2, or the field-side ditch, during the warmer months of 2020 ('7'), but generally much higher (up to 0.4 m) than these comparators during the colder months of 2020-21 ('8'). This suggests that there is a relatively poor hydraulic connection between the line of the under-drain and the ground between the under-drains, causing soil water levels away from the under-drains to act somewhat independently. High evapotranspiration during the warmer months results in low soil water levels, whilst low evapotranspiration during the colder months, along with rainfall, causes the soil water level to rise to higher levels.
- The soil water level away from the under-drains, during the colder months, appears to have a 'base level' of 0.35-0.4 mbGL ('C'), but rises and falls steeply in response to rainfall ('D'). This behaviour implies a relatively transmissive shallow zone (0-0.4 m); the temptation

would be to ascribe this to the presence of mole drains; the field had last been mole-drained in April 2013 (*pers. comm.*, Mr. Andrew Waters).

- It is interesting to note that the soil water levels maintained in DWs 3 and 4 during the colder months, away from the under-drain, are lower (relative to the ground surface) than those maintained in an analogous position at Great Newra, under a traditional drainage arrangement (see Figure 6.2-2); this is thought likely to be due to increased effective soil permeability due to the presence of mole drains, as discussed further in Section 6.7.
- During late-October 2020, the soil water level condition away from the under-drains changed relatively rapidly (‘E’) from a low to a high condition. This is the same as seen at other locations (e.g. Great Newra) and was almost certainly caused by a combination of a prolonged period of rainfall and a reduction in evapotranspiration as air temperatures fell.
- During the warmer months of 2020, soil water levels away from the under-drains fell below (up to c. 0.25 m) the water level in the field-side ditch (‘F’). This offers confirmation that one of the purposes of maintaining high ditch water levels during the warmer months, to support adjacent soil water levels, is being achieved (see Section 6.2 for further discussion).
- With regard to access to the field during the monitoring period, soil water levels were below the often-quoted access threshold of 0.4-0.5 mbGL until the end of October 2020 (‘F’). They fell more consistently below this level from the end of March 2021, although they returned briefly to higher levels in response to heavy rainfall during May 2021 (‘G’).
- It is interesting to note that during the warmer months of 2020, soil water levels in DW3 were generally slightly higher than those in DW4, which means that there was a shallow hydraulic gradient away from the under-drain into the area between under-drains; this shows the potential for under-drains to help to irrigate the soil between under-drains. The reverse condition is seen during the colder months of 2020-21, when there was a shallow hydraulic gradient towards the under-drain.
- It is also interesting to note that during the colder months there is generally 0.3-0.4 m difference between the soil water levels along the under-drain (DWs 1 and 2), and those remote from the under-drains (DWs 3 and 4). This suggests that lowering the water level in the field-side ditches, which would almost certainly lower the soil water levels along the under-drain, would probably have relatively little effect on soil water levels remote from the under-drains.

## 6.5 Site 4; Fair Orchard Farm, St. Bride’s Wentlooge

Soil water and ditch water level monitoring in the traditionally-drained field at Fair Orchard Farm was carried out between August 2020 and August 2021. Details of the monitoring installations are provided in Section 5.6. Time-series water level hydrographs are provided, in the formats described at the start of Section 6.2, as Figures 6.5-1 and 6.5-2. The following, which are directly relevant to the current project, can be observed from the two figures:

Ditch water levels

In this case the ditch water level hydrographs show less clear evidence of IDD management:

- Ditch water levels fell sharply by c. 0.2 m in two stages during the last week of September 2020 (‘1’ in Figure 6.5-1). There are two possible explanations for this:
    - It was caused by IDD lowering of sluices, the closest being W69 around 370 m along the lines of ditches, to the south-east.
    - A lowering of levels caused by the clearing of ditches.

  Since a more gradual fall in water levels would be expected if sluices were lowered, as the aggregate volume of the ditches drained over the sluices, it is thought more likely that ditch-clearing was the cause. The contractor for ditch-clearing (*pers. comm,*. Mr Andrew Prosser) has suggested that the ditch-clearance occurred during the first week of September 2020, but the water level evidence suggests that they were cleared during the last week of September 2020.

- Given the above, there is no obvious indication in the water level data about when the ditch water levels were lowered during autumn 2020.
- The local sluices appear to have been raised in preparation for the warmer months of 2021 at the end of March ('2'). During the following period (April) the ditch water level rose gradually ('3'), by c. 0.2 m, even though there was virtually no rainfall; the gradual rise is caused by the ditch network gradually filling with water flowing from more distant sources.
- Ditch water levels are somewhat less responsive to rainfall events during the warmer months (e.g.'4') than during the colder months (e.g. '5'); the likely explanation is the same as that given in Section 6.2.
- The recorded levels for the local sluice (W69, 290 m SE) suggest that there is minimal seasonal management of ditch water levels in this area (Table 5.3-2) as the recorded preferred summer and winter levels are both 5.550 maOD, and the actual recorded summer penning level is 5.660 maOD (i.e. only 0.11 m higher). Given the evidence of rising ditch water levels during the dry period of April 2021, it seems likely that water level management has progressed from that recorded in the WLMP (Pickup, 2011).

Soil water levels

- The expected seasonal cycle of soil water levels can be seen, with low soil water levels during the warmer months of 2020 (down to 0.5-1.3 mbGL) and 2021, and high soil water levels during the colder months of 2020-21. During late-October 2020, the soil water level condition changed relatively rapidly ('A' in Figure 6.5-2) from a low and variable to a high and relatively constant condition. This was almost certainly caused by a combination of a prolonged period of rainfall and a reduction in evapotranspiration as air temperatures fell.
- During the colder months of 2020-21, soil water levels were universally very high, with differences in level relative to the ground surface related to the micro-topographic position of the dipwell:
    - DW1 was located on the crest between first-order furrows, and the soil water level was fairly constant at 0.02-0.20 mbGL.
    - DW2 was located in the first-order furrow adjacent to DW1, and the soil water level was more-or-less at the ground surface ('B') throughout the colder months.
    - DWs 3 and 4 were located in the second-order furrow which discharges to the field-side ditch. The water levels at these two dipwells were generally between 0.1 and 0.2 maGL (above Ground Level)('C'), showing that the second-order furrow was inundated. This is consistent with the fact that the absolute water levels were very often the same ('6').
- It is notable that during the colder months of 2020-21 the hydraulic gradient was from DW1 (crest area between first-order furrows), to DW2 (first-order furrow), to DWs 3 and 4 (second-order furrow), and to the field-side ditch. These hydraulic gradients were completely reversed during the warm, dry period of August/September 2020.
- To confirm, during the two warm and dry periods of spring 2020, soil water levels within all of the dipwells fell below (up to c. 0.4 m, '7') the water level in the field-side ditch. A similar phenomenon was seen at Great Newra Farm, and the related explanation (Section 6.2) applies here.
- The differing, but explainable soil water level responses to significant rainfall events during the warmer and colder months are interesting. Soil water levels barely respond to significant rainfall during the colder months as the ground is completely saturated, and the extra water quickly manifests as surface runoff; for example, there was virtually no soil water level response to the 39.8 mm of rainfall which fell on 23rd December 2020 ('8'), the 4th highest daily total in the 17-year rainfall record for Collister Pill. In contrast, soil water levels are very responsive to rainfall during the warmer months as the rainfall tends to infiltrate into the ground; for example, soil water levels rose c. 1.0 m in response to the 37.8 mm of rainfall which fell on 27 August 2020 (5th highest).
- With regard to access to the field during the monitoring period, soil water levels were universally below the often-quoted access threshold of 0.4-0.5 mbGL for most of the time

until the end of October 2020 ('A'). They fell below this level during April 2021 ('D'), although they returned briefly to higher levels in response to heavy rainfall during May 2021 ('E').

## 6.6 Site 5; Sluice House Farm, Peterstone Wentlooge

Soil water and ditch water level monitoring in the under-drained field at Sluice House Farm was carried out between March 2020 and August 2021. Details of the monitoring installations are provided in Section 5.7. Time-series water level hydrographs are provided, in the formats described at the start of Section 6.2, as Figures 6.6-1 and 6.6-2. The following, which are directly relevant to the current project, can be observed from the two figures:

### Ditch water levels

The ditch water level hydrographs show that:

- The ditch water level appears to have been controlled at c. 4.2 maOD between March 2020 and February 2021 (e.g. '1' in Figure 6.6-1), with transient higher levels caused by rainfall. This is consistent with the reported preferred level for sluice W11, for both winter and summer (4.2 maOD, Table 5.3-2). It is unsurprising that this sluice appears to control the ditch water levels at the monitoring site as it is located between the site and the tidal outfall immediately south of the Sluice House Farm buildings.
- The ditch water level fell steeply in early February 2021 ('2'), and appears to have been briefly controlled at c. 3.9 maOD ('3'). The sluice appears to have been raised back to 4.2 maOD after this, and the upstream ditch water level recovered back to a base level of c. 4.3 maOD during a relatively dry period ('4'); this control level appears to have persisted until the end of the monitoring period.
- Again, ditch water levels were less responsive to rainfall events during the warmer months than during the colder months (see Section 6.2).

### Soil water levels

- The expected seasonal cycle of soil water levels can be seen, with low soil water levels during the warmer months of 2020 (down to 1.5 mbGL) and 2021, and high soil water levels during the colder months of 2020-21.

Similar to the other under-drained site at Cross Farm; Nash (Section 6.4), the dipwells can be divided into two response-type groups:

- DWs 1 and 2 are located approximately (see below) along the line of an. The soil water levels in these dipwells are generally slightly higher (e.g. '5') than the water levels in the field-side ditch during the warmer months, and they behave very similarly. This confirms that there is good hydraulic continuity along the under-drainage pipe and stone-filled trench, and that the ditch water levels control the soil water levels in these dipwells during the warmer months.
- During the colder months, with a lowered ditch water level and more water draining from the field, soil water levels are maintained at a significantly higher level than the ditch water level (e.g. '6').
- Unlike at Cross Farm; Nash, during the colder months, the soil water levels along the under-drain are close to the ground surface ('A' in Figure 6.6-2), and are sensitive to rainfall; this might be because the dipwells were slightly offset from the under-drain, as noted above.
- DWs 3 and 4 are in a transect at 90 degrees to the under-drain. During the warmer months of 2020 the soil water levels in these dipwells were often below (up to 0.35 m) those in DWs 1 and 2 (the under-drain) and the ditch water levels (e.g. '7'), meaning that there is a hydraulic gradient from the under-drain into the field. The dominant control on the soil water levels away from the under-drain is evapotranspiration, whereas the levels in the under-drain are controlled by the field-side ditch.
- During the colder months, the soil water levels in DWs 3 and 4 were slightly higher than those in DWs 1 and 2 ('8'), indicating a hydraulic gradient from the wider field to the under-drain. However, largely because the soil water levels in DWs 1 and 2 were also relatively

high during the colder months (see above), this field-to-under-drain hydraulic gradient was not as steep as that at Cross Farm; Nash.

- The soil water level away from the under-drains, during the colder months, appears to have a ‘base level’ of 0.4-0.5 mbGL (‘B’), but rises and falls steeply in response to rainfall (‘C’). This behaviour implies a relatively transmissive shallow zone (at 0.0-0.5 mbGL).
- During early-October 2020, the general soil water level condition at the site changed relatively rapidly (‘D’) from a low (dry) to a high (wet) condition. This was almost certainly caused by a combination of a prolonged period of rainfall and a reduction in evapotranspiration as air temperatures fell.
- As noted above, during the warmer months of 2020, soil water levels away from the under-drains fell below (up to c. 0.35 m) the water level in the field-side ditch (‘7’). Again, this offers confirmation that one of the purposes of maintaining high ditch water levels during the warmer months, to support adjacent soil water levels, is being achieved (see Section 6.2 for further discussion).
- With regard to access to the field during the monitoring period, soil water levels were mostly well below the often-quoted access threshold of 0.4-0.5 mbGL until early October 2020 (‘E’). They fell more consistently below this level from the end of March 2021, although they returned briefly to higher levels in response to heavy rainfall during May 2021 (‘F’).
- Differences in response type between DWs 1 and 2 (under-drain) and DWs 3 and 4 (field) are less pronounced than those for the equivalent dipwell pairs at the other under-drained site at Cross Farm; Nash. There are two possible explanations for this:
    - DWs 1 and 2 at Sluice House House did not intercept the under-drain quite as effectively as DWs 1 and 2 at Cross Farm; Nash. The under-drain represents a relatively narrow ‘target’ for dipwell insertion, and the facility to find the exact line of the under-drain using a mole plough, as was available at Cross Farm; Nash, was not available at the Sluice House Farm site. It is also worth noting that because the substrate is poorly permeable, the under-drain has a relatively small zone of influence.
    - The monitored under-drain at Sluice House Farm is less effective than the equivalent under-drain at Cross Farm; Nash, i.e. it doesn’t convey water to the field-side ditch as effectively, and significant hydraulic gradients can develop along its length during the colder months.

## 6.7 Inter-site comparison of water level dynamics

Sections 6.2 to 6.6 inclusive provided commentary and interpretation on the soil and ditch water level behaviours at the individual monitoring sites, with limited cross-referencing between sites. This section provides more detailed cross-referencing, in order to highlight the key differences in hydrological behaviour across the sites.

Figure 6.7-1 shows time-series soil water levels (mbGL) for dipwells which were located between the major lines of in-field drainage, i.e. between the drainage furrows at the traditionally-drained sites, and between the under-drains at the under-drained sites. These areas represent a high proportion of the total areas of the respective fields, and therefore the water level regimes within these dipwells can be considered typical for the fields. The feasibility of field access would be determined by looking at the hydrographs from these dipwells, rather than the hydrographs for the dipwells within the major lines of in-field drainage as the latter represent a relatively small aggregate area within the fields.

The dipwells are:

- Traditionally-drained; GNDW3 at Great Newra Farm and FODW1 at Fair Orchard Farm.
- Under-drained; CF2DW3 at Cross Farm; Nash and SHDW4 at Sluice House Farm.

Monitoring at Great Newra and Sluice House Farms began in March 2020, whilst monitoring at Cross Farm; Nash and Fair Orchard Farm began in August/September 2020.

As noted above, the major controls on in-field soil water regimes, apart from the drainage system, are similar between the sites, meaning that any differences in soil water regime are likely to be related to the drainage system:

- The sites are 1.3 km apart, and therefore it can be assumed that incident rainfall and evapotranspirative potential are very similar.
- Shallow (0-2 mbGL) lithostratigraphy is very similar at all of the sites.

Considering Figure 6.7-1, the most striking and important characteristic is the similarity of water table response at all of the sites, irrespective of drainage type:

- A clear difference between water table regime during the warmer and colder month periods can be seen at all of the sites, and therefore irrespective of drainage type; the water table is generally significantly below 0.6 mbGL during the warmer month period, and almost always above 0.5 mbGL during the colder month period. The transition from the warmer month to the colder month regimes occurred at all of the sites within a seven-day period (21st October to 28th October 2020)('1' in Figure 6.7-1).
- The water table at Great Newra and Sluice House Farm was generally below 0.8 mbGL until early-August 2020, demonstrating a similarity of response between traditionally-drained and under-drained fields.
- The water table fell significantly at all of the sites during the dry period of March and April 2021 ('2'), and also rose back towards the ground surface in response to the sustained rainfall during May 2021 ('3'). It fell universally again after May 2021 ('4').

The differences between the water table hydrographs are less significant, and where they exist they don't seem to be related primarily to drainage type:

- The water table was more responsive to larger rainfall events during the warmer months of 2020 at Sluice House Farm (under-drained) and this resulted in a short period of different water table response during August 2020('5'), during which the water table was transiently 0.4-0.8 m higher (relative to the ground surface) than at Great Newra Farm (traditionally-drained).
- During early-October 2020, it can be seen that the water table at Fair Orchard Farm (traditionally-drained) was as responsive to rainfall ('6') as it was at Sluice House Farm (under-drained); this suggests that the enhanced responsiveness is not primarily related to drainage type, as might be concluded from the bullet above.

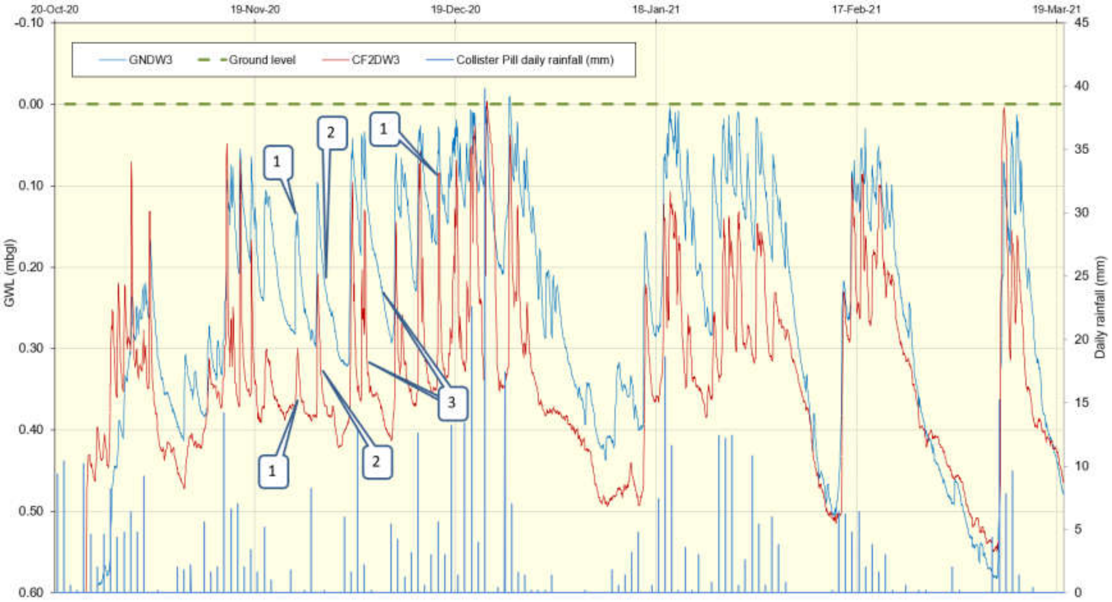

Figure 6.7-2. Time-series soil water levels (mbGL) for wider-field dipwells at the Gt. Newra and Cross Farm; Nash monitoring plots; colder month period, 2020-21.

- During the colder month period of 2020-21, the water table at the traditionally-drained sites ('7') was generally slightly higher than the water table at the under-drained sites ('8'). However, the differences in water table height relative to the ground surface between the sites rarely exceeded 0.25 m water table at all of the sites, and the water table was almost always above 0.5 mbGL, which suggests that the under-drained fields would not have been more accessible than the traditionally-drained fields during this period.

Figure 6.7-2 again shows time-series water table elevations for GNDW3 at Great Newra Farm (traditionally-drained) and CF2DW3 at Cross Farm; Nash (under-drained), but only for the colder month period, so that the differences in response can be inspected more closely. Considering the figure:

- During the colder month period of 2020-21, soil water levels at the under-drained site were consistently slightly lower than those at the traditionally-drained site, with the difference generally being between 0.1 and 0.2 m. In both cases, however, the soil water level was consistently above 0.4 mbGL.
- Soil water levels at both of the sites were responsive to rainfall, but the magnitude of response varied significantly, both through time at the individual sites, and for the same rainfall events at the two sites (e.g. ‘1’).
- The character of soil water table recession at the two sites was very different, with the recession always being more gradual at the traditionally-drained site (e.g. ‘2’ and ‘3’).

The colder month behaviour of the soil water levels at the two sites suggests that the shallow (c. 0-0.4 mbGL) zone in the under-drained case is significantly more permeable than that at the traditionally-drained site. Since lithostratigraphy at the two sites was observed to be very similar, it is likely that the difference relates to the presence of mole drains at the under-drained site.

For the sites and the monitoring periods in question, the period during which soil water levels were higher than 0.4 mbGL was practically the same for the two sites, which suggests that the period during which access to the field would cause damage was the same in both cases. Hence, whilst slightly lower soil water levels prevail during the cold month period at the under-drained site, it would seem that they are not sufficiently low to allow access to the field for a longer period, compared with the traditionally-drained site.

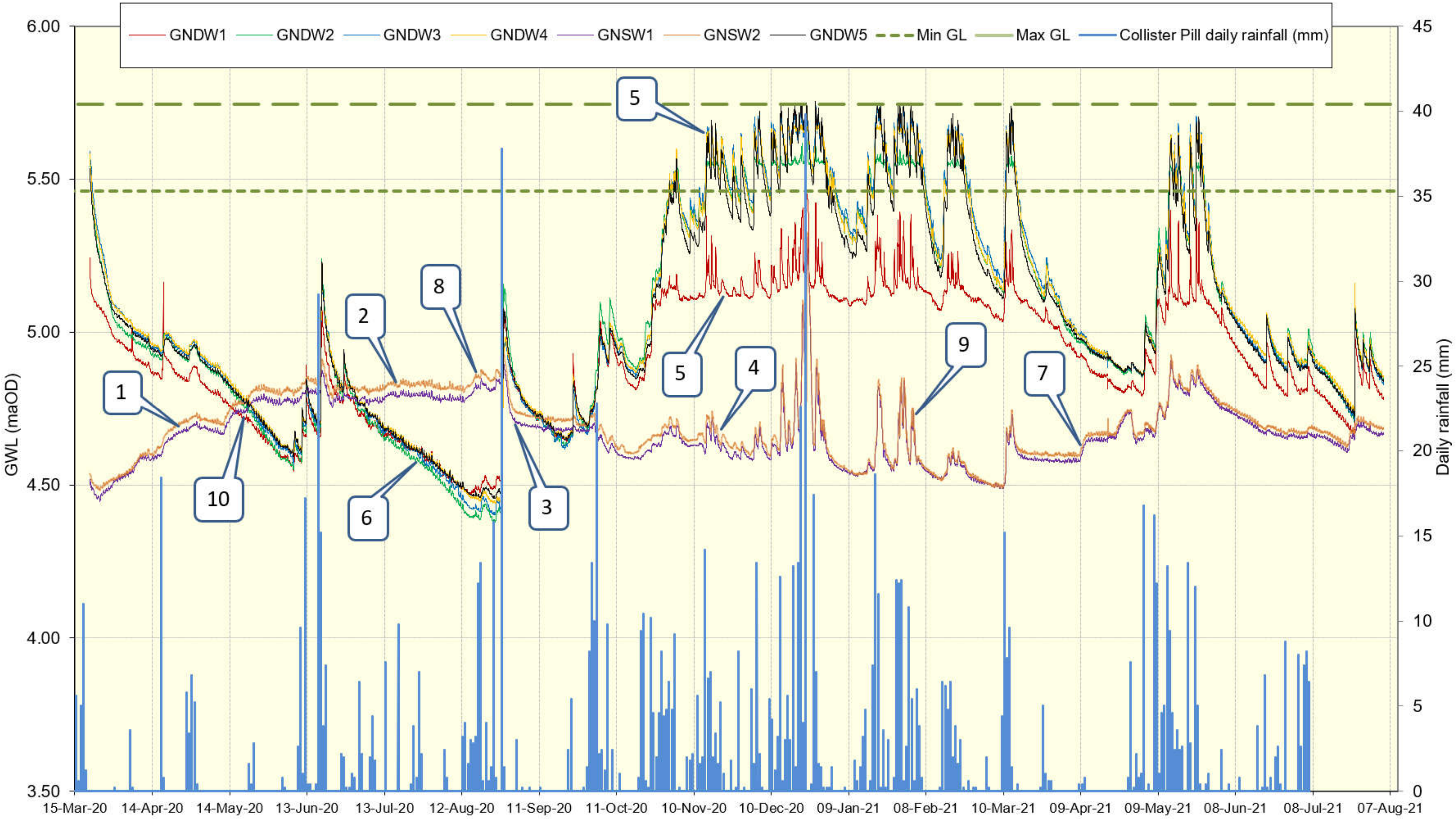

Figure 6.2-1. Time-series soil and ditch water levels (maOD) for the Gt. Newra monitoring plot.

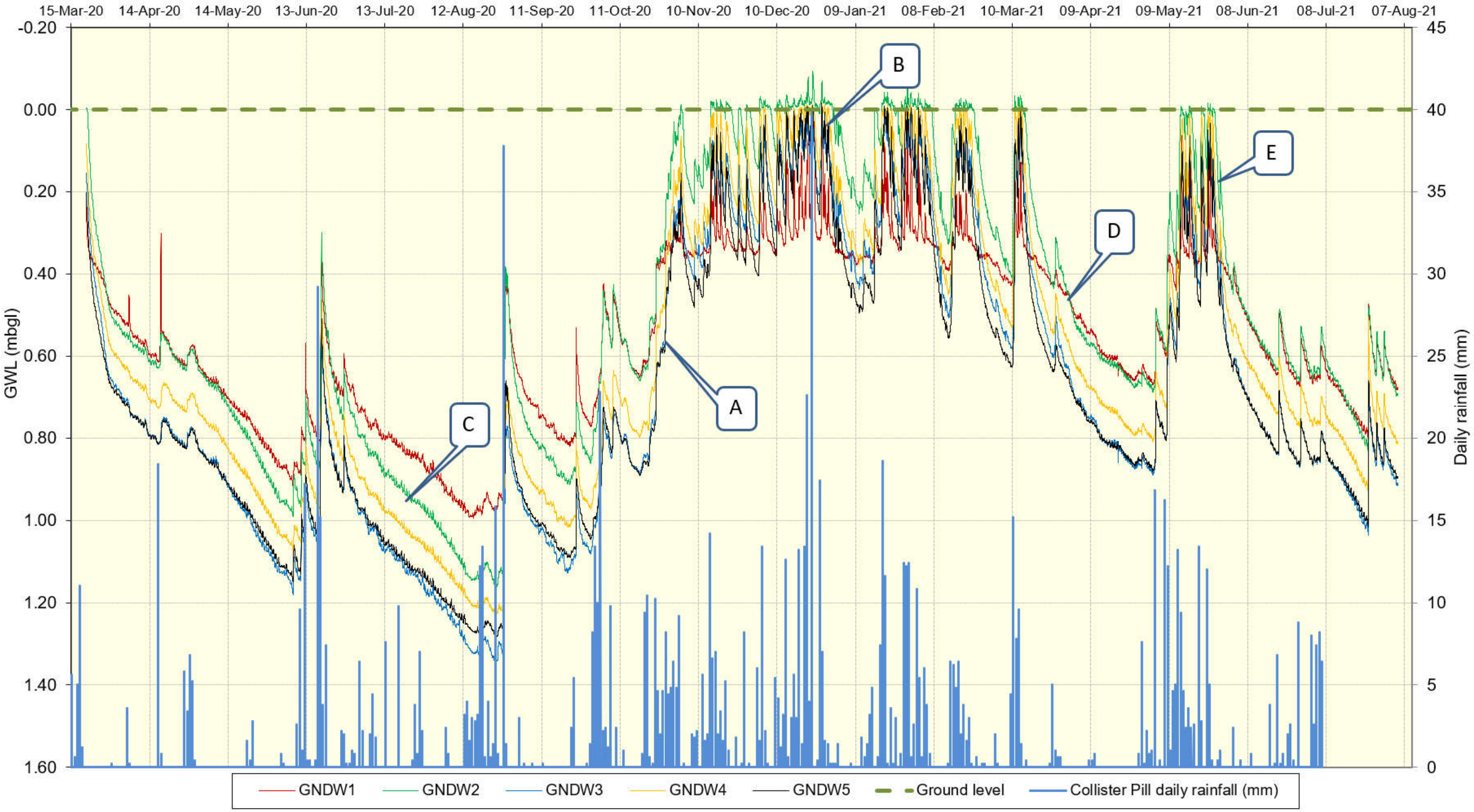

Figure 6.2-2. Time-series soil water levels (mbGL) for the Gt. Newra monitoring plot.

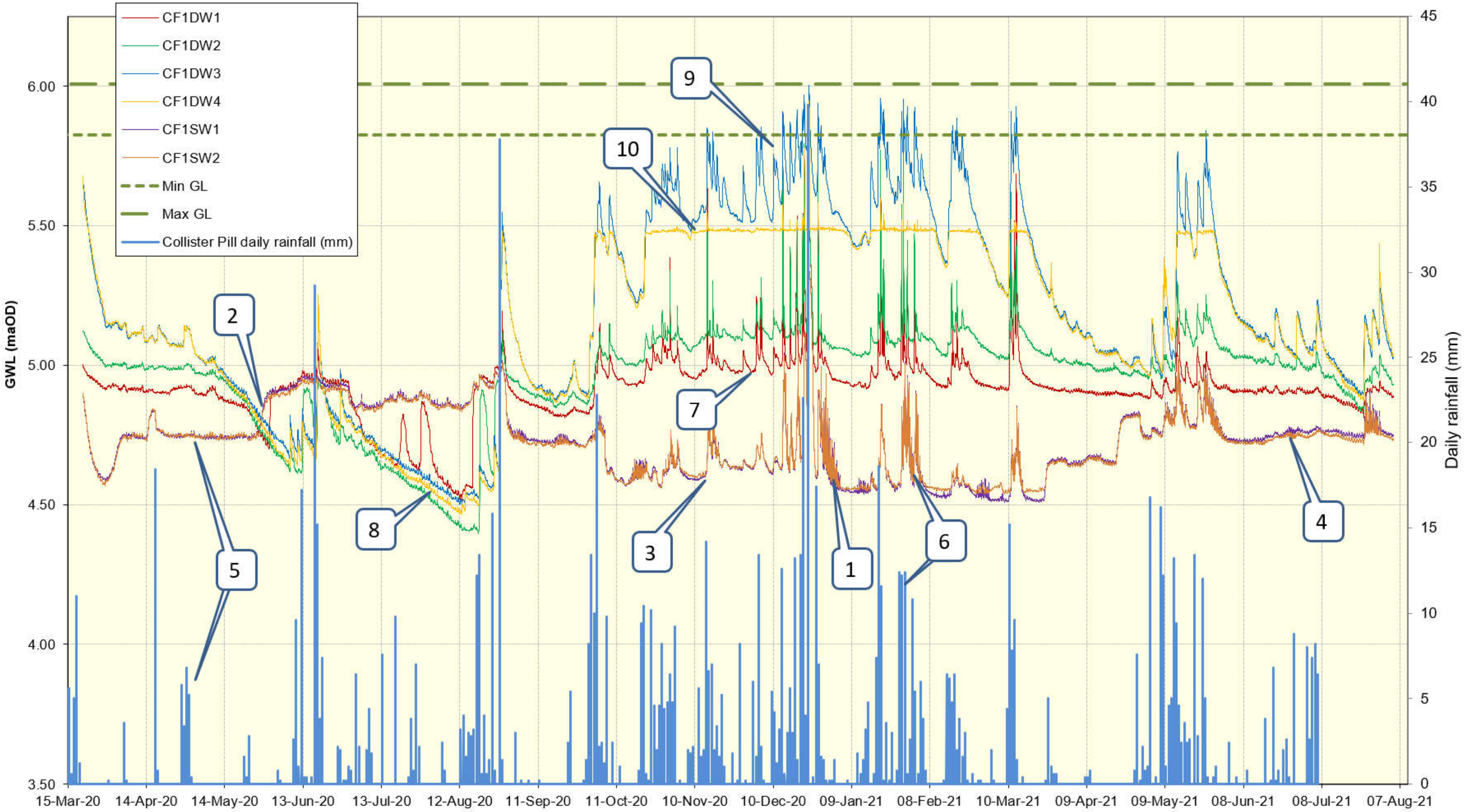

Figure 6.3-1. Time-series soil and ditch water levels (maOD) for the Cross Farm; Chapel Road monitoring plot.

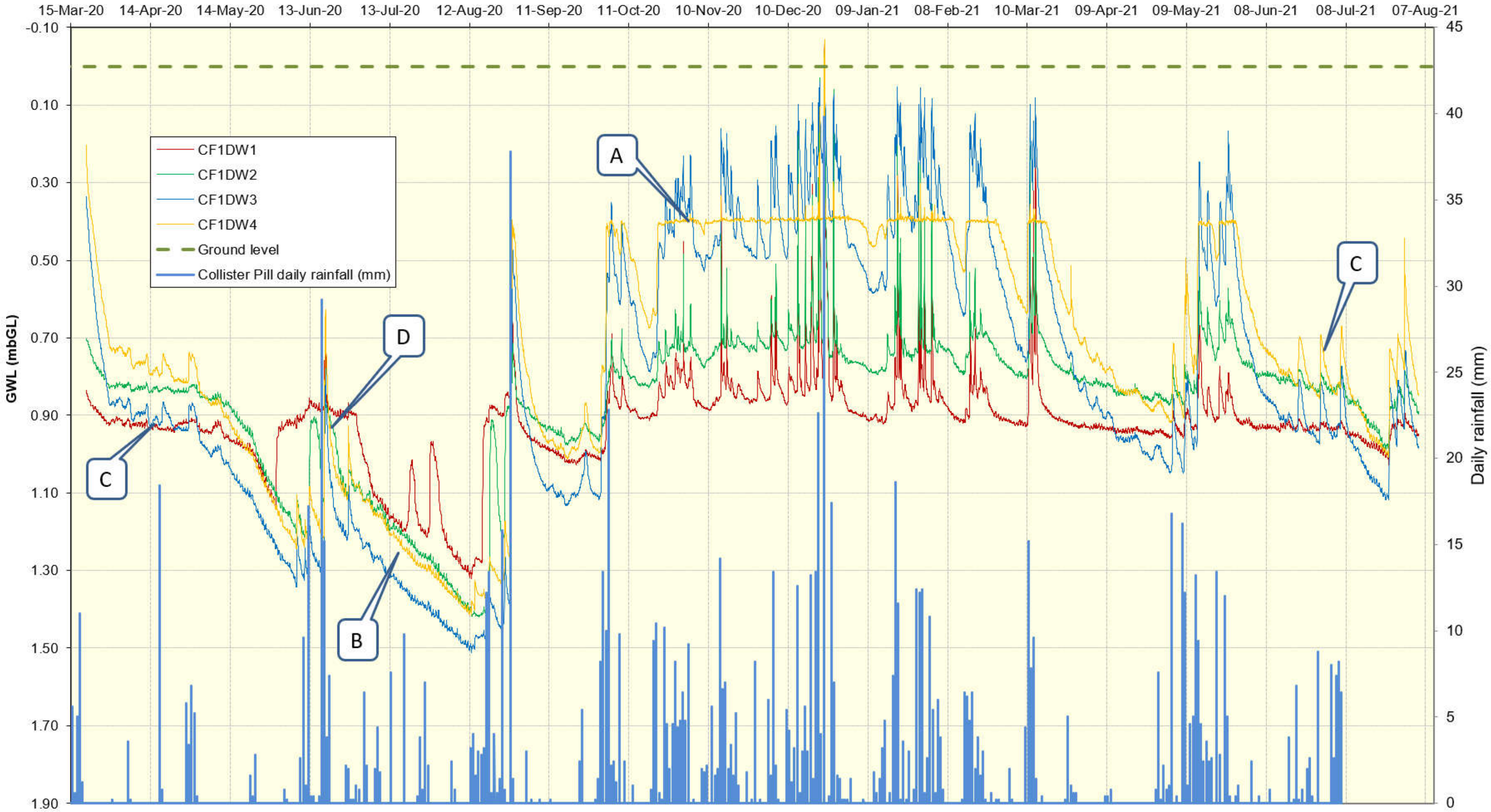

Figure 6.3-2. Time-series soil water levels (mbGL) for the Cross Farm; Chapel Road monitoring plot.

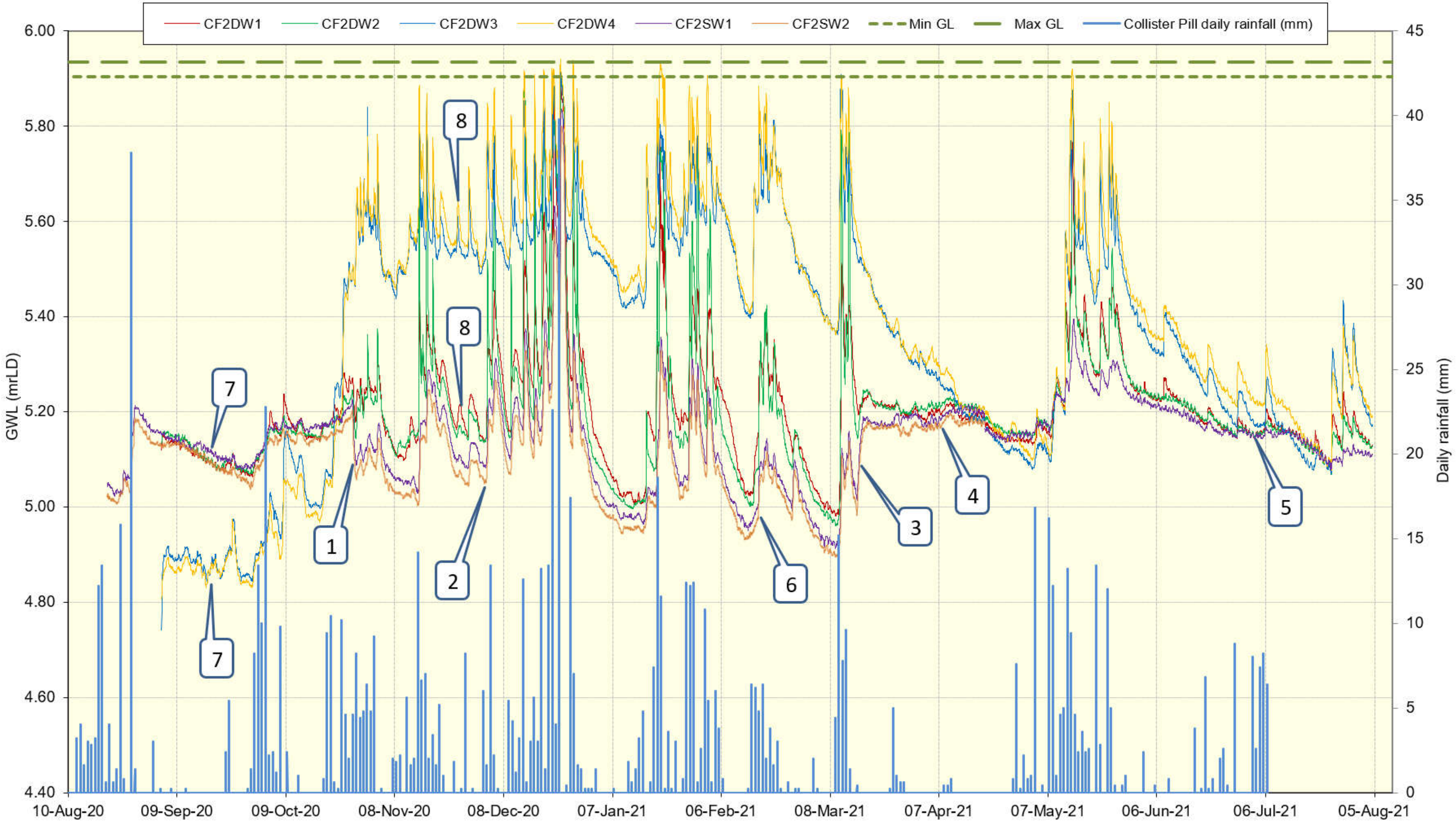

Figure 6.4-1. Time-series soil and ditch water levels (maOD) for the Cross Farm; Nash monitoring plot.

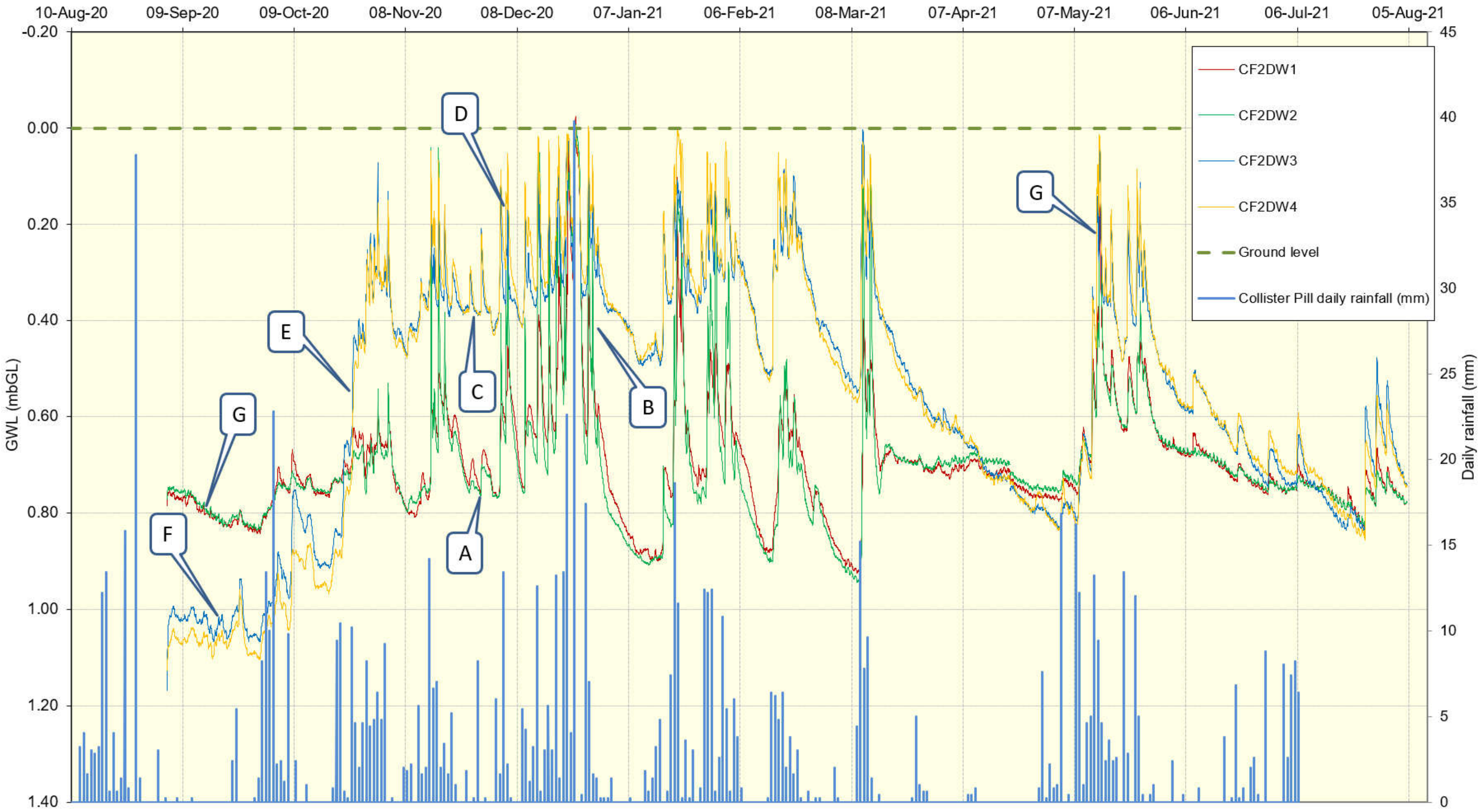

Figure 6.4-2. Time-series soil water levels (mbGL) for the Cross Farm; Nash monitoring plot.

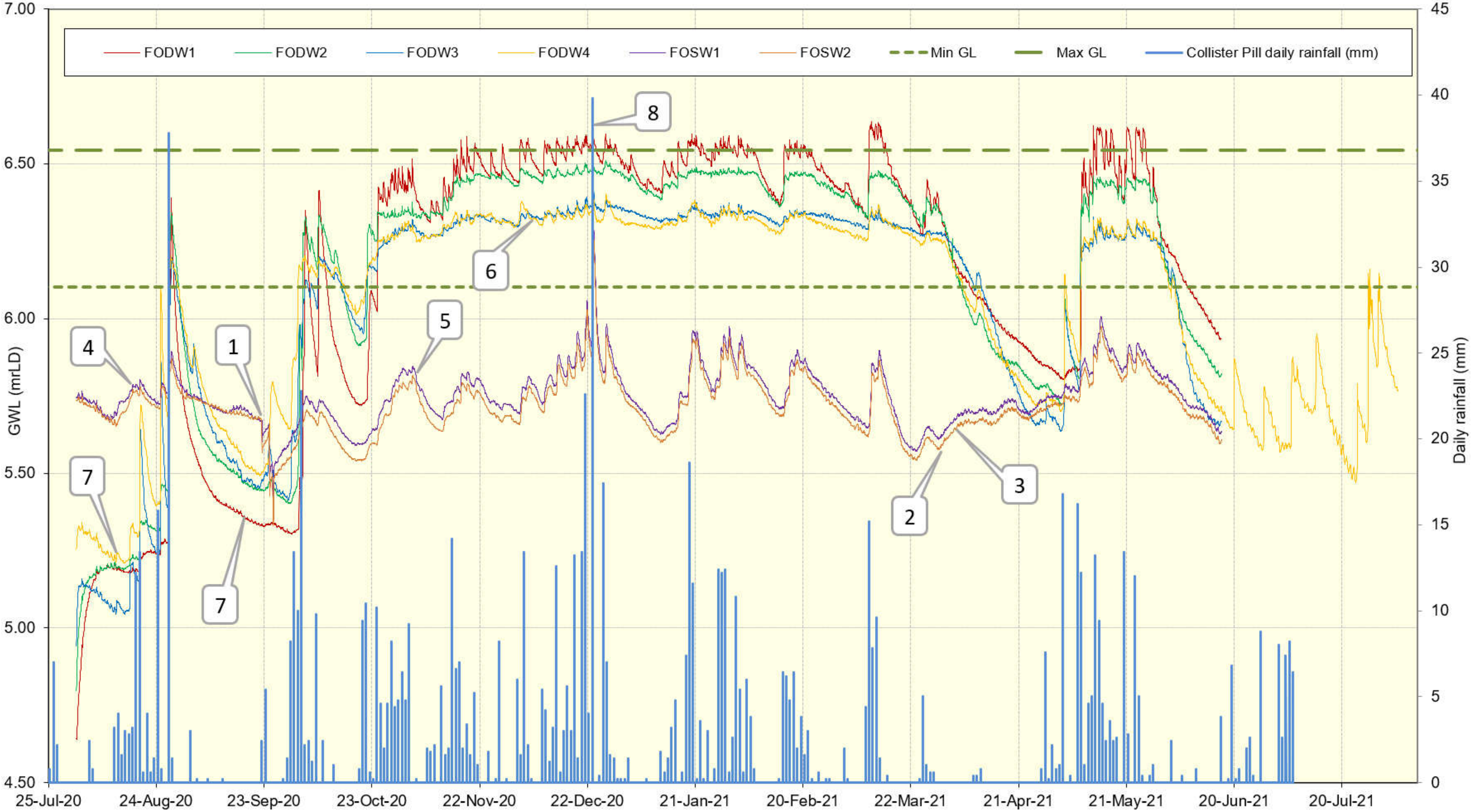

Figure 6.5-1. Time-series soil and ditch water levels (maOD) for the Fair Orchard Farm monitoring plot.

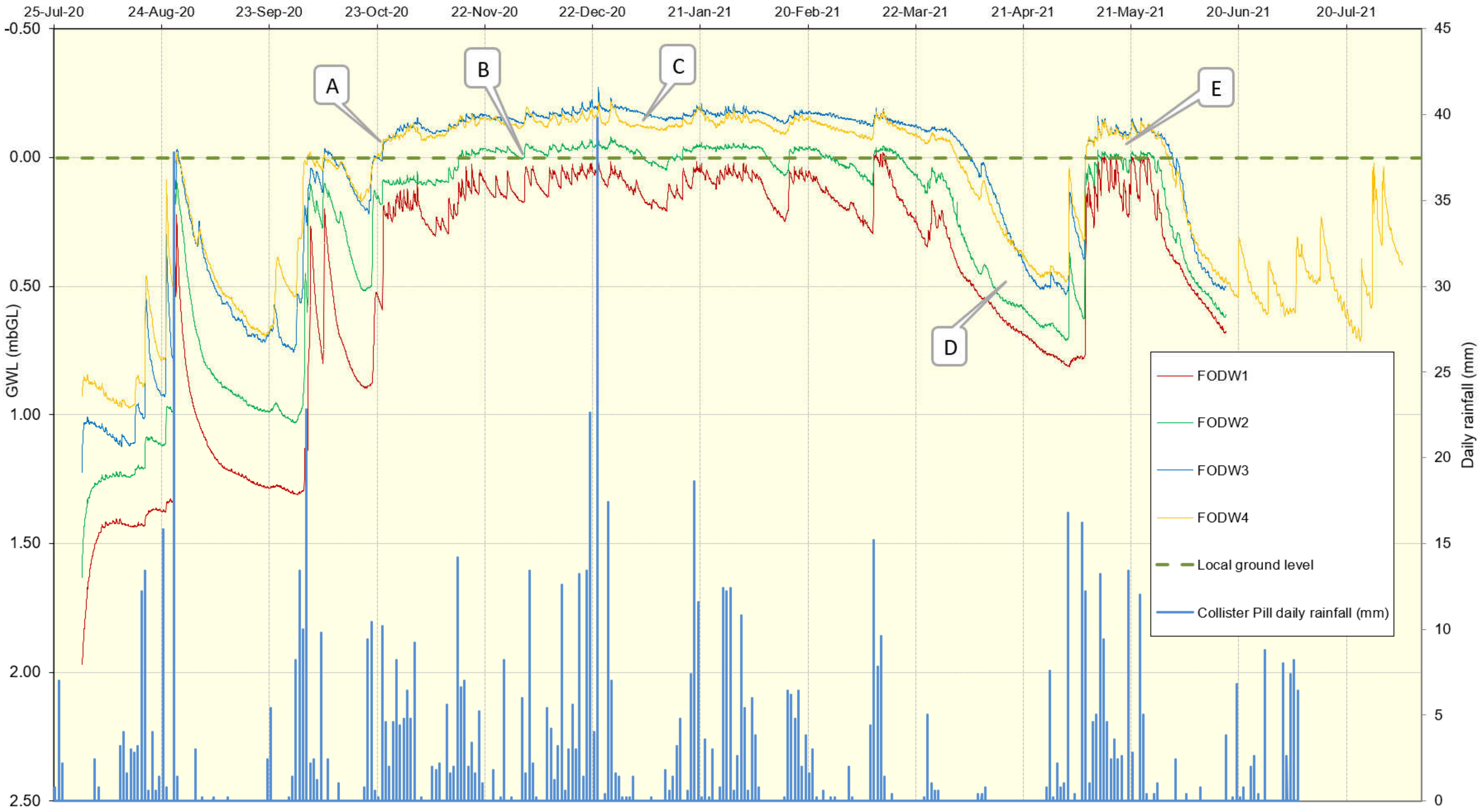

Figure 6.5-2. Time-series soil water levels (mbGL) for the Fair Orchard Farm monitoring plot.

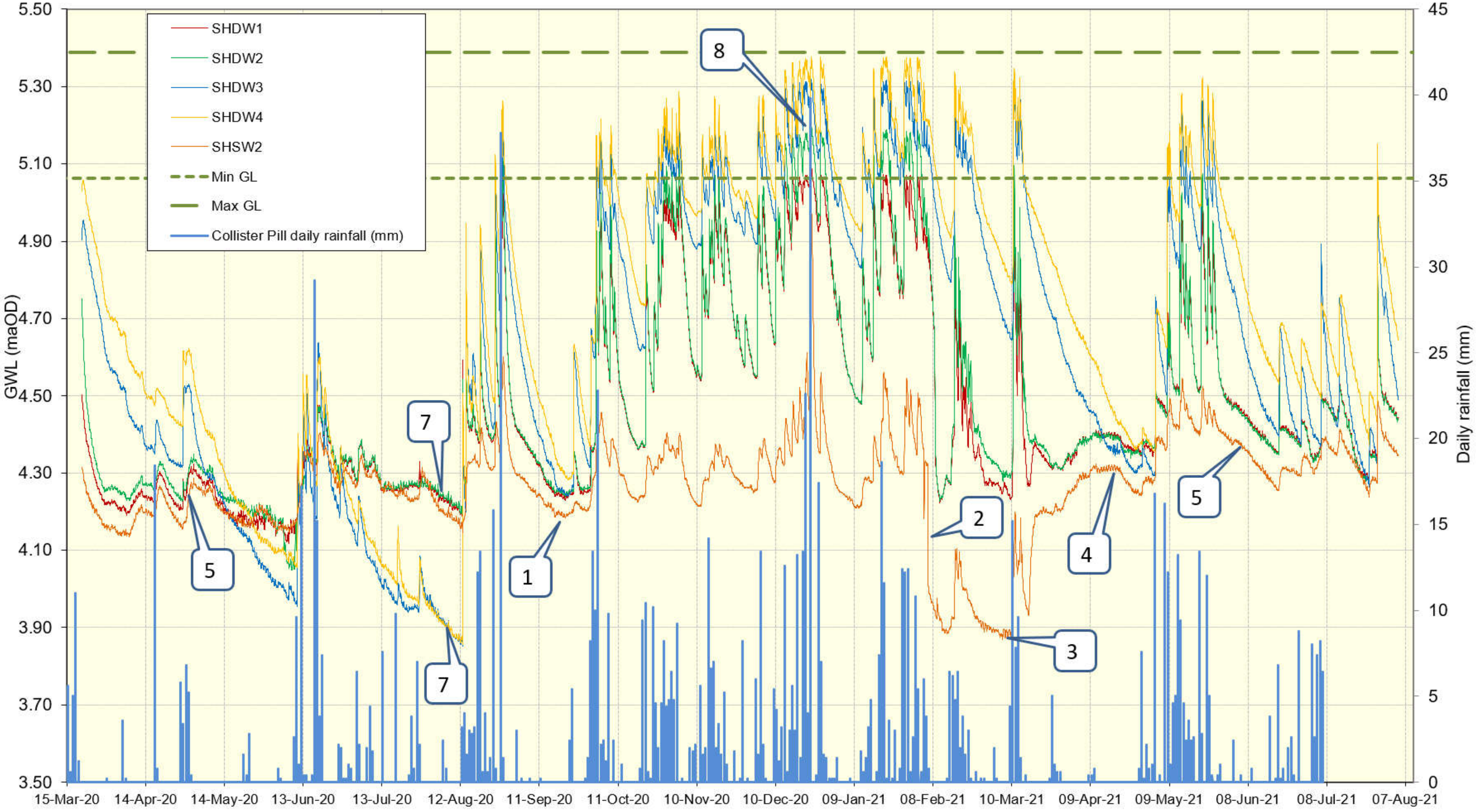

Figure 6.6-1. Time-series soil and ditch water levels (maOD) for the Sluice House Farm monitoring plot.

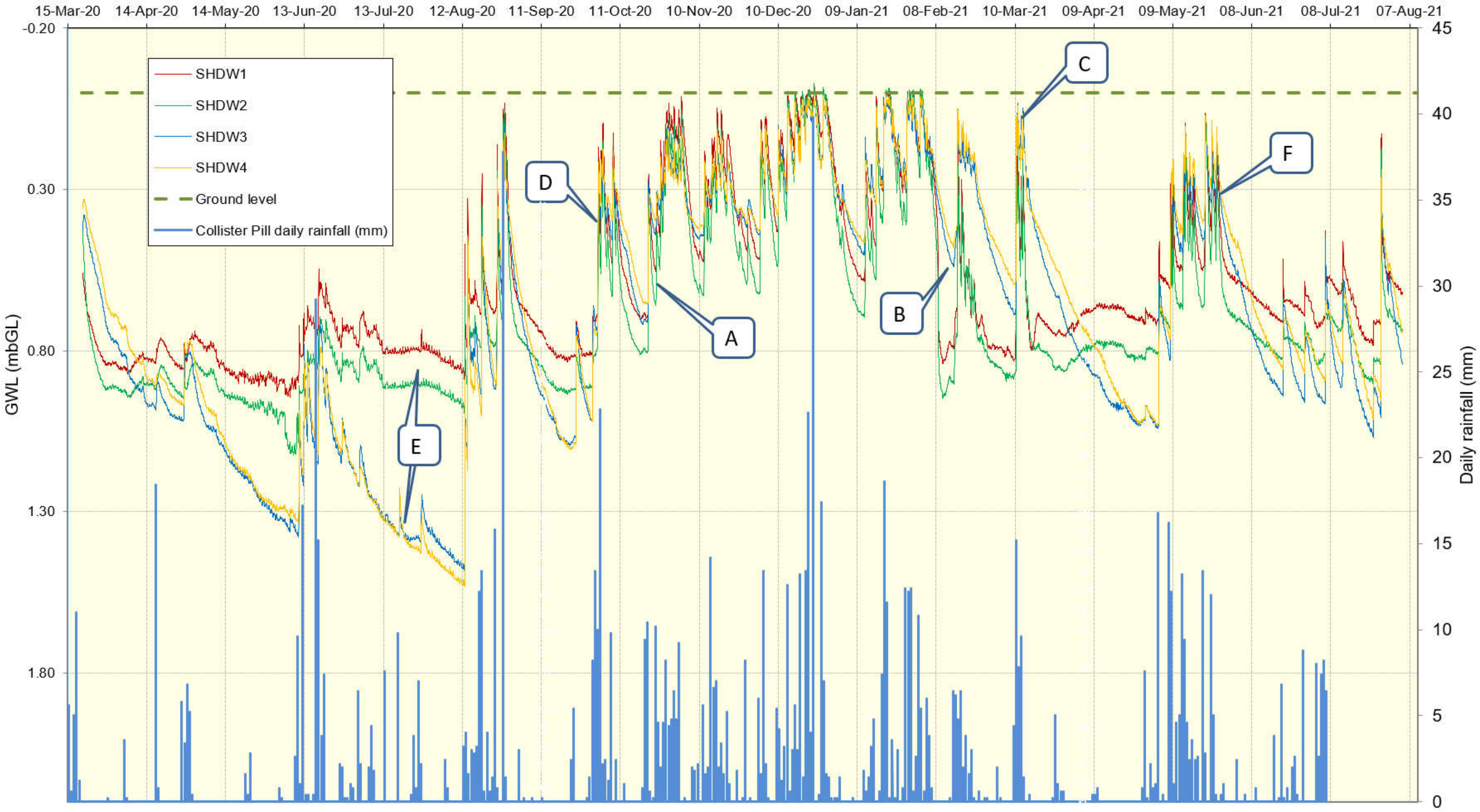

Figure 6.6-2. Time-series soil water levels (mbGL) for the Sluice House Farm monitoring plot.

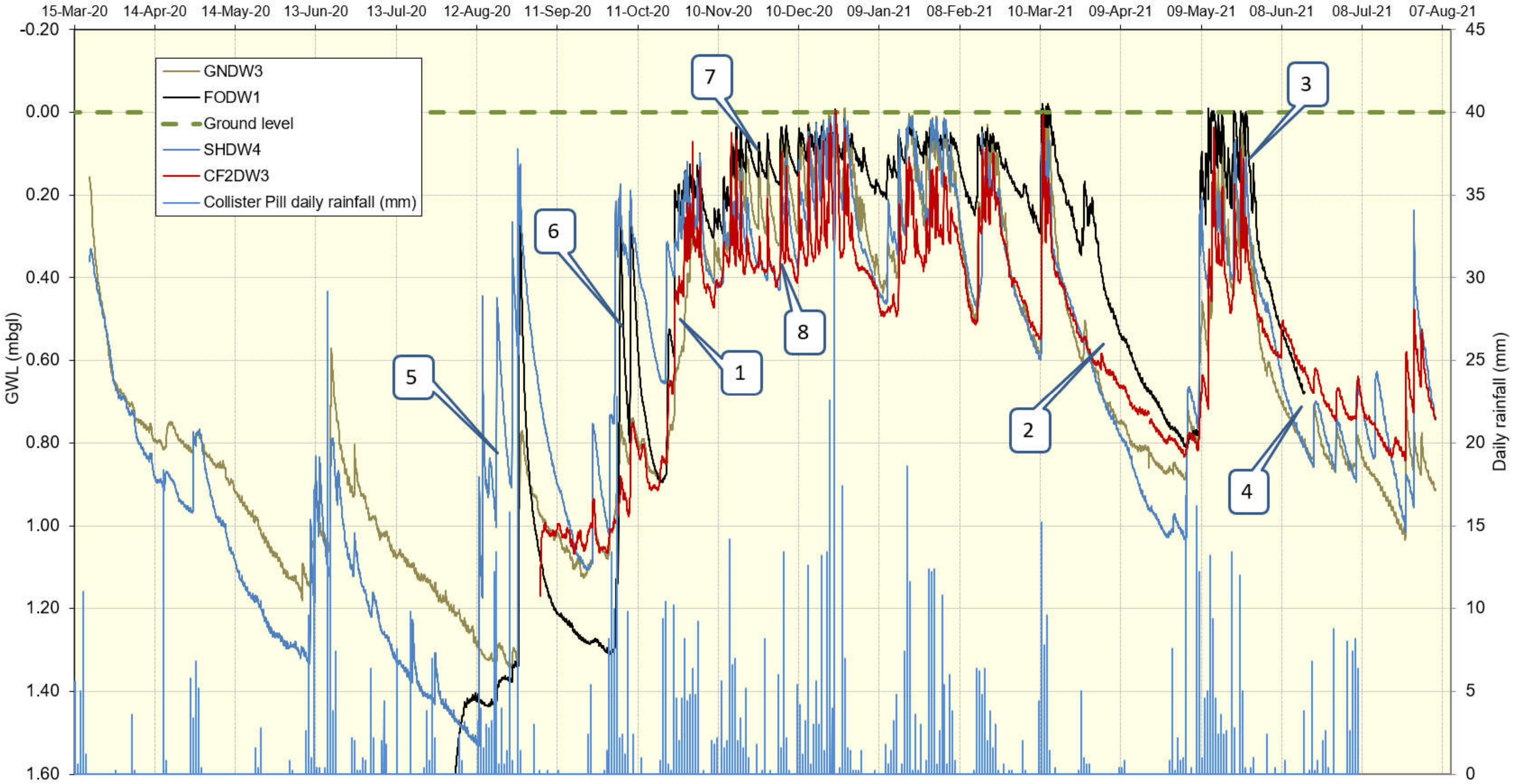

Figure 6.7-1. Time-series soil water levels (mbGL) for representative dipwells from the traditionally-drained and under-drained sites. GN – Great Newra, FO = Fair Orchard, SH = Sluice House, CF2 = Cross Farm Nash.

# 7 Summary of hydrological behaviours and ecohydrological conceptual models

## 7.1 General

### 7.1.1 *Ditch hydrology*

- The influence of IDD sluice level management was identified through ditch water level responses at all of the monitoring sites, but there were differences in ditch water responses to the management. For example, the ditch water level at Great Newra rose gradually during the dry period of spring 2020, whereas the ditch water level at Cross Farm; Chapel Road rose relatively rapidly. This variation in response is a reflection of the varying local hydrological settings of the monitoring plots, with important factors including the distance from a controlling sluice, and flow directions and water availability within the ditch network.
- The response of ditch water levels to management control will also be influenced by local runoff from fields, and therefore the rainfall/evapotranspiration balance.
- Shorter-term (i.e. dynamic) ditch water level varied between sites, almost certainly for the same reasons as above.
- Lengthy periods of relatively constant ditch water levels were often seen during the warmer months; this is probably the result of constant inflows of water (IDD management), with levels being controlled at the overflow level of local sluice(s) downstream.
- Related to the above, ditch water levels are much less responsive to rainfall events during the warmer months than they are during the colder months. This is a function of difference field drainage behaviours, as discussed below.
- The relationship between recorded ditch water levels at the monitoring sites and the recorded levels of local sluices was inconsistent. Possible explanations include; 1) errors in the recorded sluice height values, 2) the sluice being set at a different elevation than is recorded in the WLMP, and/or 3) a more complex connection through the ditch network between the monitoring site and the sluice than has been assumed. A more detailed and extensive hydrological investigation would be required to enable understanding of the wider hydrological functioning of the sites to be developed.

### 7.1.2 *Soil hydrology*

- Soil water levels exhibit very different colder and warmer month period behaviours, being:
    1. High and responsive to rainfall during the colder month period. This is because the water table is close to the ground surface, so infiltrating rainfall reaches the soil water table almost immediately.
    2. Low and mostly unresponsive to rainfall during the warmer months. This is because the water table is at greater depth, and infiltrating rainfall can be stored above (in the unsaturated zone) before being lost to transpiration or direct evaporation. Soil water levels respond to large rainfall events when they overwhelm the storage capacity of the unsaturated zone.
- Soil water levels often fall below the water level in the adjacent field-side ditch, but because of the poorly permeable deeper substrates (primarily silty clay), very little flow occurs in response to the reversed hydraulic gradient. This means that the sometimes-stated purpose of maintaining high ditch water levels, to provide water to support the water table in adjacent fields, is unlikely to be fulfilled to any large extent.
- It is also worth noting that there is relatively little flow from the fields to the field-side ditches during the warmer months. It has been suggested that such flows help to maintain higher water levels in field-side ditches during these periods; this is not the case.

## 7.2 Traditionally-drained fields

The particular aspects of the hydrological functioning of traditionally-drained fields are illustrated schematically in Figure 7.2-1. They are:

During the colder months:

- Rainfall significantly exceeds evapotranspiration; there is a positive water balance and the hydrology is runoff-dominated.
- The water table resides close to (generally within 0.3 m) the ground surface at all locations. It fluctuates at a relatively high frequency within a more permeable shallow (0.0 – c. 0.3-0.4 mbGL) zone, rising in response to rainfall, and then falling rapidly as the water flows laterally towards the lower elevation furrows. The higher permeability of this zone is thought to derive from semi-natural processes (soil structure, desiccation cracking, plant roots). The base of this zone is marked by a significant reduction in permeability, and the water table tends not to go below this level; very little lateral flow occurs below this level.

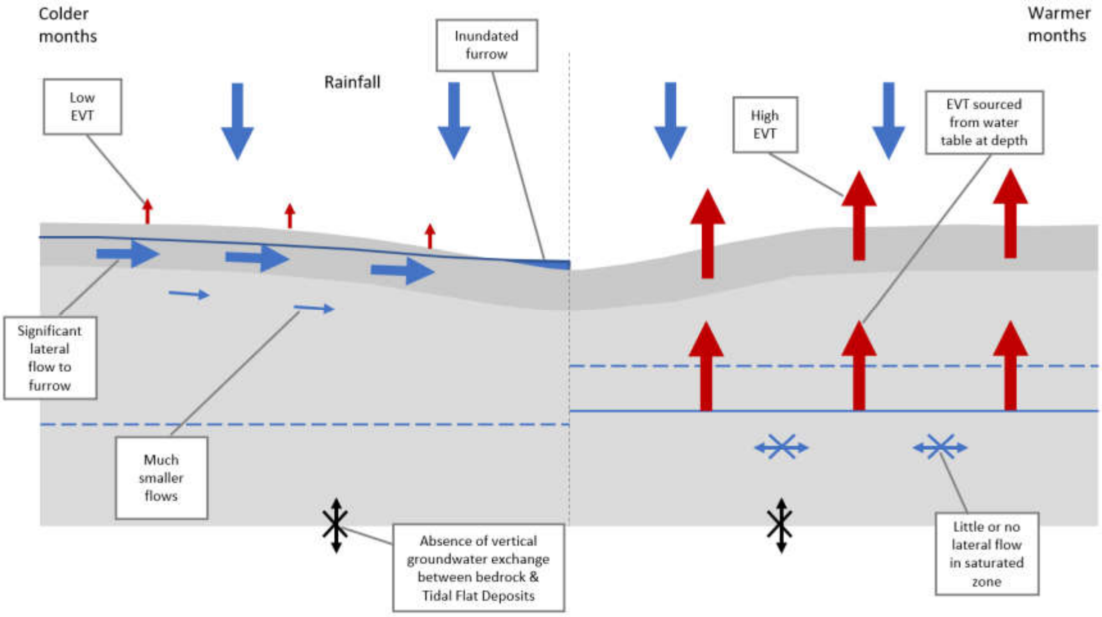

Figure 7.2-1. Schematic cross-section showing the hydrological functioning of a traditionally-drained field within the Gwent Levels, during the colder months (left) and the warmer months (right). The solid blue lines represent the time-averaged water table and the dashed blue lines represent the projected water level in the field-side ditch.

- Soil water level is often ‘controlled’ at or close to the ground surface by removal of water by flow across the ground surface, and furrows are often inundated.
- The furrows host surface flow to the field-side ditches, in which low water levels are maintained. Water levels in field-side ditches rise transiently in response to rainfall-derived runoff.

And during the warmer months:

- Evapotranspiration significantly exceeds rainfall; there is a negative water balance and the hydrology is evapotranspiration-dominated.
- The water table is generally significantly below the ground surface, within poorly permeable substrate, and there is little or no lateral groundwater flow.

## 7.3 Under-drained fields

The hydrological functioning of under-drained fields is illustrated schematically in Figure 7.3-1. The key aspects are:

- Unsurprisingly, given their construction, under-drains act as axes of very high permeability; this is reflected by the fact that soil water levels along monitored under-drains were at very similar elevations along the under-drains.
- The soil water level along the under-drain is either:
  1. The same as the ditch water level, if this is above the invert level of the under-drain, or
  2. At the invert level of the under-drain, if this is higher than the ditch water level and the under-drain is discharging freely into the ditch.

- During the colder months there is a significant difference between the soil water levels along the line of the under-drains, and the much higher levels across the wider field away from the under-drains. This steep, local hydraulic gradient is maintained by the low permeability of the lower substrate.

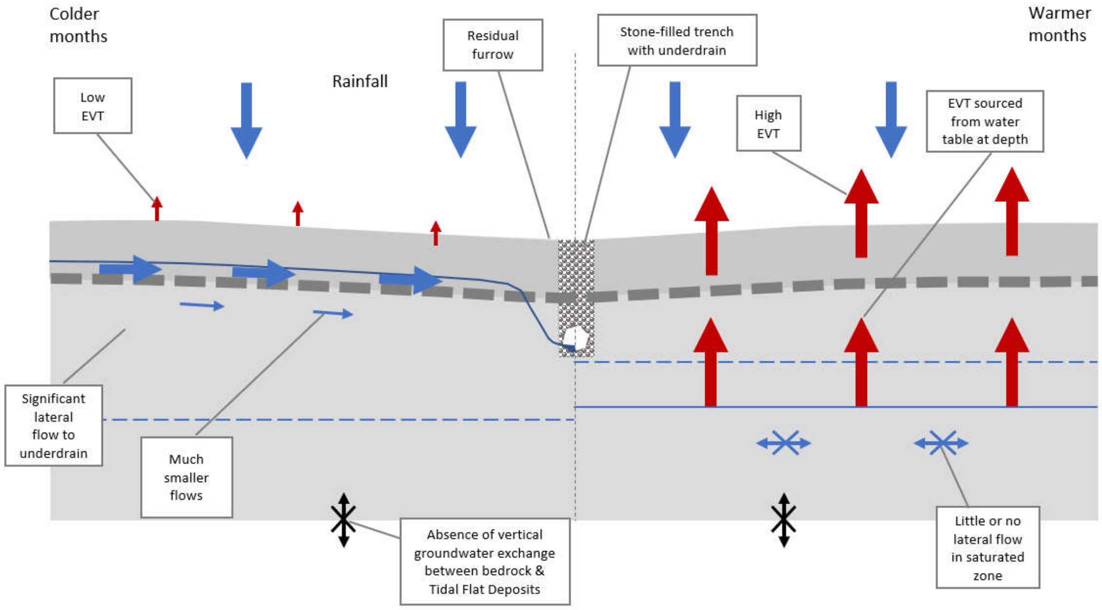

Figure 7.3-1. Schematic cross-section showing the hydrological functioning of an under-drained field within the Gwent Levels, during the colder months (left) and the warmer months (right). The solid blue lines represent the time-averaged water table and the dashed blue lines represent the projected water level in the field-side ditch. The thick dashed grey line represents a mole drain at c. 0.45 mbGL, and the under-drain lies at c. 0.60 mbGL.

- Also during the colder months, the soil water table away from the under-drains fluctuates at a relatively high frequency within a highly permeable shallow (0.0 – c. 0.45 mbGL) zone, rising in response to rainfall, and then falling rapidly as the water flows towards the under-drains. The high permeability of this zone is thought to derive from the presence of mole drains, and also semi-natural processes (soil structure, desiccation cracking). The base of this zone is marked by a significant reduction in permeability, and the water table tends not to go below this level during the colder months.

- The analyses and modelling (Section 8) undertaken as part of this project suggest that underdrains should remain effective as long as the (winter) water levels in the ditches are maintained below the base of the relatively high permeability zone in the soil, which is considered to extend to around 45cm below ground surface. This should be the case even if the outfall of the underdrains in the sides of the ditches are under water. There is unlikely to be additional drainage benefit if the ditch water levels are maintained any lower than 45cm below the field ground level. However, there may be reduction in underdrain efficiency if ditch water levels are maintained less than 45cm below field ground level. Soil water levels often fall below the invert level of the under-drain during the warmer months, becoming hydraulically decoupled from it. During these periods soil water levels along the lines of the under-drains behave similarly to those across the wider field.

# 8 Numerical hydrological modelling at the scale of the monitoring plots

Groundwater models have been constructed to simulate water levels and flow rates through the soils of two of the monitored sites, which were chosen as the most typical examples of their respective drainage types[15]:

- Great Newra Fram: traditional ridge-and-furrow drainage (Section 5.3).
- Cross Farm Nash: under-drainage (Section 5.5).

The design and construction of the models was based on the conceptual models presented in Section 7.

## 8.1 Model construction

### 8.1.1 *Modelling software*

The groundwater models have been constructed using the industry standard USGS MODFLOW 6 software (Langevin, 2017), with the initial models constructed with the aid of Groundwater Vistas modelling interface (ESI, 2017), with subsequent enhancements and pre- and post-processing utilising spreadsheets.

The MODFLOW 6 software has many advantages over previous MODFLOW software releases, with significant improvements to its representation of de-saturated conditions and associated improvements to the calculations and model stability.

### 8.1.2 *Simulation period and time discretisation*

The model simulations cover the period from the 1st of January 2020 until the 1st of July 2021 consisting of 548 daily time periods. An initial steady state period has also been included (with average rainfall and potential evaporation rates) to establish stable initial conditions for the transient part of the simulation.

This simulation period was defined due to the availability of water level measurements from March 2020 onwards at Great Newra, and from August 2020 onwards at Cross Farm Nash, and allowing for an initial model warm-up period for the simulation to stabilize from initial conditions.

### 8.1.3 *Model domains and external boundary conditions*

The model domains have been defined at the smallest reasonable scale in order to allow the flow processes in the fields to be simulated with a high degree of spatial resolution, whilst maintaining reasonably short simulation run times.

With this in mind, the boundaries of each model domain have been chosen to align with likely flow convergence lines (situated along ditches, furrows or under-drains), and along likely flow divides (situated along lines half-way between ditches, furrows or under-drains). Following the principle of symmetry within the repeating patterns of furrows, ditches and/or under-drains across the fields of the Gwent Levels, it has been assumed that the flow across the converging and diverging lines of symmetry is sufficiently small that it can be approximated as being zero, and therefore the external boundaries of the models have been defined as central no-flow boundaries.

The model domains have been rotated so that the main axes of the rectilinear model grids approximately align with the main axes of the roughly perpendicular features of the field drainage.

The spatial extent of the Great Newra model domain (traditionally-drained field) is presented along with the micro-topography and dipwell locations in Figure , and covers an area of 1,811 m$^2$. The Cross Farm Nash model (under-drained field) covers an area of 1,367 m$^2$ and its domain is presented in Figure .

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[15] Also, the soil water level responses observed at these two sites are more similar to each other than to any other combination of traditionally and under-drained sites, making them more directly comparable with each other.

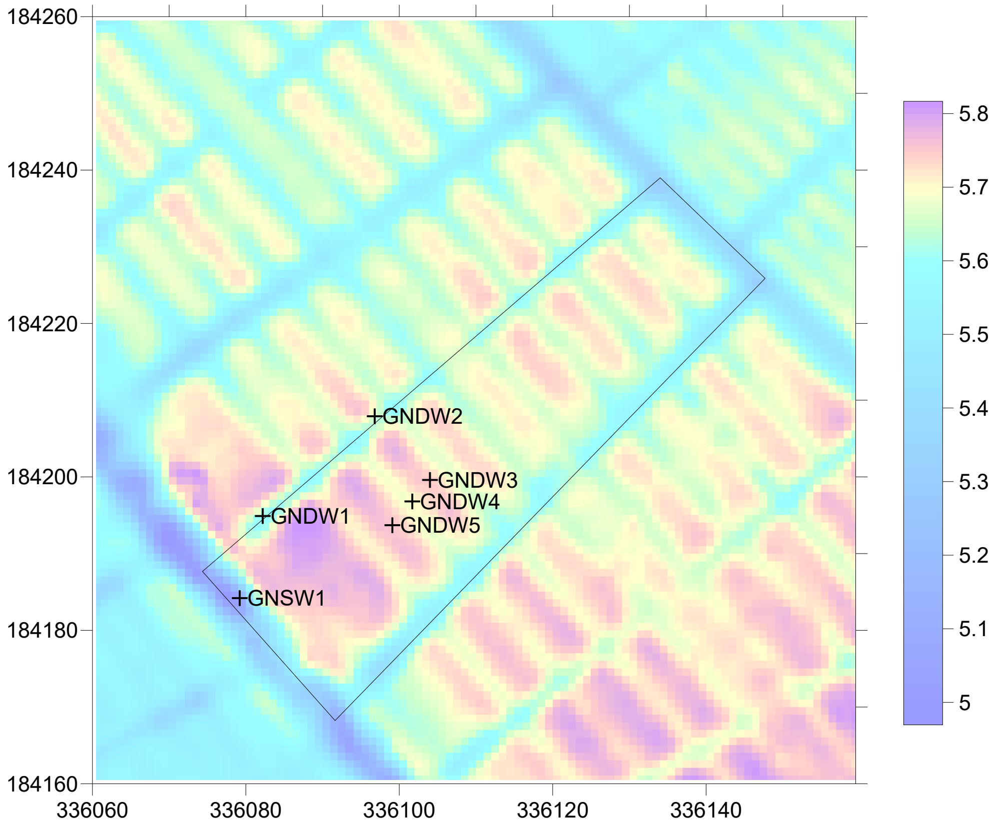

Figure 8.1-1. Model domain, micro-topography and dipwell locations for the Great Newra model (traditionally-drained).

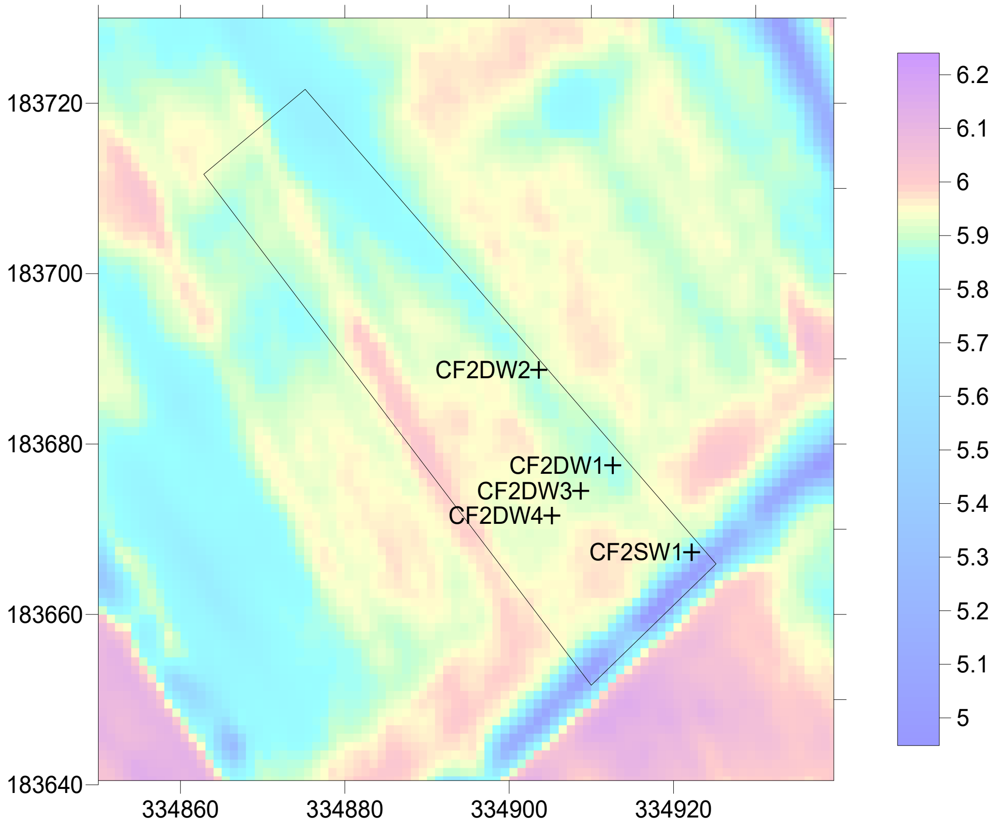

Figure 8.1-2. Model domain, micro-topography and dipwell locations for the Cross Farm Nash model (under-drained).

### 8.1.4 *Topography and model mesh*

The micro-topography of the fields has been defined from LIDAR data (Section 2.2) with 1 m spatial resolution and at least 0.01 m elevation accuracy (Figure  and 8.1-2), which has then been interpolated onto the more detailed (and rotated) 0.5 m groundwater model grid.  The rotated model domains and grids are shown in Figures 8.1-3Figure and 8.1-4.

The LIDAR data for Great Newra (Figure 8.1-1) clearly shows the perpendicular patterns of field-side ditch (in the southwest), second-order furrow (northeast), second-order furrows (running southwest to northeast) and first-order furrows (running northwest to southeast).  Also evident in both Figure  and 8.1-3 is the presence of a small headland separating the second-order furrow from the field-side ditch, through which a pipe has been placed to allow runoff to flow from the furrow to the ditch.

Over the surface of the ditches, the LIDAR elevations reflect the water level (and/or vegetation level) in each ditch on the day that data was captured.

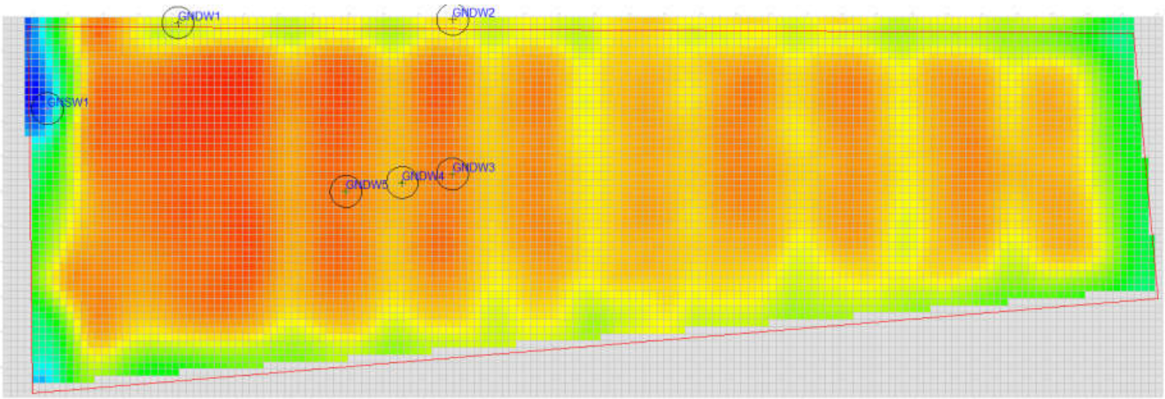

Figure 8.1-3.  Rotated model domain and grid for the Great Newra groundwater model (ditch to the left). Red are high values, grading through yellow and green, with the lowest being blue.

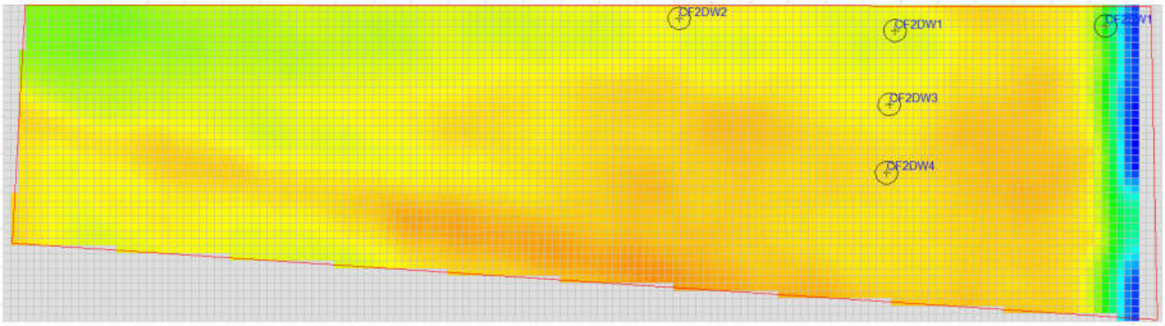

Figure 8.1-4.  Rotated model domain and grid for the Cross Farm Nash groundwater model (ditch to the right).

The groundwater models have been split up into 40 discrete model layers, representing thin intervals of the soil horizons, with thin 5 cm thick layers near the surface, gradually increasing to 40 cm thick layers at the base of the model, the bottom of which is located at 10 mbGL.  Below this level it has been assumed that groundwater flows in the underlying clay deposits are small enough to be negligible.

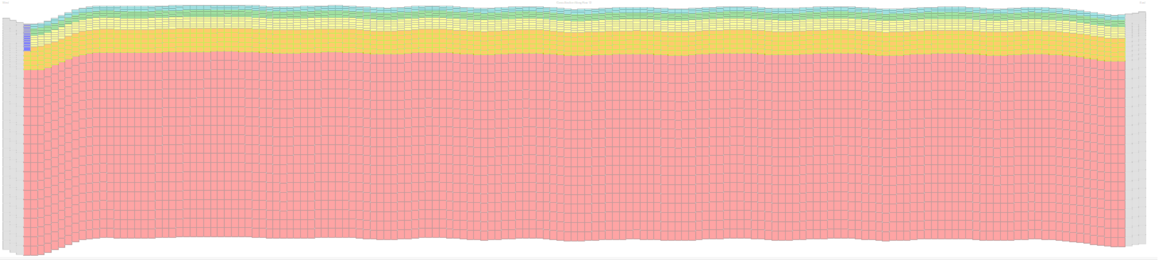

Figure 8.1-5.  Cross section through the Great Newra model, showing the model layers and coloured depth-intervals within which hydraulic conductivity is set at the same value.

The tops and bottom elevations of the model nodes in each of the model layers are all defined relative to the topography, and vary spatially such that at any location each model layer always represents the same depth intervals relative to the ground surface (e.g. Figure8.1-5).

### 8.1.5 *Boundary conditions*

External boundary conditions

The external boundary conditions of the groundwater models are defined as no-flow boundaries, based on the principle of zero flow across flow divide and flow convergence lines, and assuming symmetry within the repeating patterns of field drainage, as described in Section 8.1.3.

Rainfall

Daily rainfall is introduced into the top layer of the models based on the rainfall recorded at the rain gauge at Collister Pill (Section 2.1.1). An average rainfall rate of 1,075 mm/a (calculated for the year 2020) was applied for the initial steady state stress period, followed by recorded daily rainfall rates for the remainder of the simulation.

Evapotranspiration (EVT)

EVT occurs via grass growing in the fields. The modelled rate of AEVT occurs at the PEVT rate (Section 2.1.2) until soil water levels fall below a specified fraction ($P_{crop}$) of the full effective rooting depth ($Z_r$). Below this level the AEVT rate starts reducing, reaching zero once soil water levels fall below $Z_r$.

The effective grass rooting depth ($Z_r$) was set to 1.5 m, based on the measured decline in soil water levels at Great Newra, and verified through expert advice (*pers. comm.*, Peter Danks, 2021). The $P_{crop}$ value was set to 0.62, based on typical values used in UK water resource assessments, and based on FAO guidelines (Allen, *et. al.*, 1998).

An average PEVT rate of 677 mm/a was applied for the initial steady state stress period, followed by the daily rates from the MORECS record for the remainder of the simulation. The effective rooting depth and $P_{crop}$ value remain fixed throughout the simulation.

Surface water runoff

When soils are fully saturated, and are not underlain by unsaturated strata, any rain which falls on the saturated soils cannot be absorbed and instead starts to form puddles on the ground surface, which eventually overflow, becoming surface runoff. In the case of the Gwent Levels, this runoff invariably flows to the network of field-side ditches.

This process has been represented in the groundwater models through the specification of streamflow routing (SFR) nodes across the upper surface of the models. The surface is based on the LIDAR topography, but raised within localised depressions where puddles would form, with a shallow gradient across the surface of each of the puddles towards their overflow points.

For the Great Newra groundwater model modifications were made to the SFR surface to represent the presence of a shallow pipe which allows runoff to flow from the main furrow through the headland (see Section 8.1.4) to the ditch, without the need for the development of a large puddle behind the headland.

Water flows from the soil to the SFR nodes whenever the simulated soil water levels exceed the SFR surface. Flow is then routed between the SFR nodes based on gradients across the modified ground/puddle surface, and can subsequently leak back into the ground (or the ditch) where simulated water levels are below the SFR surface.

In order for the simulated runoff to enter the ditch, the SFR surface needs to be above the typical maximum measured water levels in the ditch. In the case of Great Newra, the LIDAR data gives elevations along the ditch which are above all but one of the daily measured water levels in the ditch. However, for Cross Farm Nash the LIDAR data at the ditch is below most of the typical water levels. Therefore, the SFR elevations for Cross Farm Nash are based on a surface which was allowed to fill up to form a synthetic puddle over the ditch to a level of 5.7 maOD. This allows the simulated runoff water to flow into the ditch, helping to reproduce the responses to rainfall observed in the water level recorded in the ditch.

In both models, the calculated routing network predicts that some of the runoff should exit at multiple boundaries of the model, not just the boundary where the field-side ditch is located. However, when considering each field as a whole (of which only segments are represented in these models) all the simulated runoff would be expected to enter the ditch. Therefore, in the models the flows from the runoff exit points at the non-ditch boundaries have been re-directed directly to the simulated ditch boundaries, in order to help simulate the responses to rainfall-runoff events, as observed in the water level records in the ditches.

Ditch inflow rates and level controls

As discussed in Section 2.5, water levels in the field-side ditches are controlled by NRW with a number of objectives, and evidence for ditch water level management at the monitoring sites is discussed in Sections 6.2-6.6 inclusive.

Table 8.1-1. Simulated ditch inflow and level control changes.

| Date | Great Newra | | Cross Farm Nash | |
|---|---|---|---|---|
| | Inflow ($m^3/d$) | Level (mAOD) | Inflow ($m^3/d$) | Level (mAOD) |
| 31/12/2019 | 0.1 | 4.4 | 0.1 | 4.9 |
| 24/03/2020 | “ | 4.8 | “ | “ |
| 09/05/2020 | 0.5 | “ | 0.4 | “ |
| 27/08/2020 | “ | 4.7 | “ | 5.1 |
| 03/10/2020 | “ | 4.5 | “ | 5.2 |
| 25/10/2020 | “ | “ | “ | 4.8 |
| 01/01/2021 | “ | “ | “ | 4.7 |
| 11/03/2021 | “ | 4.6 | “ | “ |
| 17/03/2021 | “ | “ | “ | 5.1 |
| 09/04/2021 | “ | 4.66 | “ | “ |

Records are not collected for the level control changes, and it is not easy for estimates to be made of the resulting ditch flow changes over time. However, in order for the groundwater models to be able to reproduce a reasonable approximation of the ditch water level, a rough representation of the level control and ditch flow rate changes have been included as part of the model inputs, a presented in Table8.1-1.

### 8.1.6 *Hydraulic properties*

Soil water storage capacity

The specific yield (Sy, or drainable porosity) values used in the regions of the models which represent soil were initially based on the difference between typical water contents at field capacity (FC = 36%) and wilting point (WP = 22%) for typical clay soils (Allen, *et. al.*, 1998), giving an Sy value of 14%. However, model calibration revealed that a lower Sy value was required in the upper part of the soil profile in order to be able to reproduce the relatively rapid reductions in soil water levels observed at the onset of dry periods, especially evident at Great Newra (see Section 8.2). Therefore, the Sy value was changed to a typical value for sandy soils of 8% (FC = 12% minus WP = 4%) in the upper 0.5 m of the soil profile.

Specific (elastic) storage values have been set to 1 x $10^{-5}$ per metre throughout the model domains.

Soil hydraulic conductivity

The hydraulic conductivity (K) of the soil would be expected to decrease with depth, reaching quite low values quite quickly into the underlying clay deposits. It has been assumed that the distribution of hydraulic conductivity values down through the various soil horizons is the same at both sites. The K values have been determined through calibration of the Great Newra model, and then also applied to the Cross Farm Nash model. The K values vary with depth, as presented in

Table8.1-2.

Table 8.1-2. Soil hydraulic conductivity values used in the models.

| Depth (mblg) | | Hydraulic conductivity (m/d) |
|---|---|---|
| From | To | |
| 0 | 0.2 | 100 |
| 0.2 | 0.5 | 10 |
| 0.5 | 1 | 0.1 |
| 1 | 2 | 0.01 |
| 2 | 10 | 0.001 |

Representation of the field-side ditches

In the regions of the models which represent field-side ditches, the Sy has been set to 100% and the K to an arbitrarily high value of 10,000 m/d, reflecting the high conveyance capacity of the ditch network.

The base elevations of the ditches have been defined at a fixed distance below the LIDAR data, such that the maximum ditch base elevation is below the minimum recorded ditch water level. For Great Newra, the simulated ditch reaches 1.2 m depth below the LIDAR level along the ditch, and for Cross Farm Nash the simulated ditch extends 0.6 m depth below the LIDAR level.

In both cases a small arm of the high Sy and high K associated with the ditch has been extended out to the location of the stilling well to ensure that the simulated water levels at the stilling well locations reflect those in the field-side ditch.

Representation of the under-drain

The under-drain in the Cross Farm Nash model has been represented as a line of high K nodes (10,000 m/d) at a depth of 0.8 to 0.9 m below ground level, becoming shallower (0.6 mbGL) as the ground topography dips down towards the field-side ditch, and allowing hydraulic connection between the under-drain and the ditch. This is deeper than the original estimated under-drain depth of 0.6 mbGL, but it was found that the under-drain needed to be deeper in order to be able to reproduce the observed low water levels at CF2DW1 and CF2DW2 (see Section 8.2).

The simulated under-drain directly underlies the dipwells CF2DW1 and CF2DW2, and is overlain by a region of modestly high K (100 m/d) representing a stone and gravel backfill up to 0.2 mbGL, above which is assumed to be topsoil.

## 8.2 Model calibration

The groundwater models have been calibrated (parameters are adjusted to allow model output to fit observed data) against soil water levels monitored in dipwells and ditch water levels monitored in stilling wells. There are five dipwells and two stilling wells at Great Newra, and four dipwells and two stilling wells at Cross Farm; Nash.

For this project the approach was to first calibrate the model representing the traditionally-drained field at Great Newra, and then to apply the same hydraulic property distributions to the Cross Farm; Nash model, to which the under-drain was then added.

### 8.2.1 *Great Newra (traditionally-drained site)*

The Great Newra model was calibrated first, and the main changes that were made to improve the reproduction of the observed water levels were as follows:

1. Increased the effective grass rooting depth from 0.75 m to 1.5 m (see Section 8.1.5).
2. Significantly increased hydraulic conductivity at all soil horizons, particularly near the surface (from 0.01 to 100 m/d in the upper 0.2 m) (see Section 8.1.6).
3. Reduction of specific yield from 14% to 8% in the upper 0.5m of the soil profile (see Section 8.1.6).
4. Introduction of ditch water level inflow modifications through time.

The results for the Great Newra model (run number 25) are presented in Figures 8.2-1 and 8.2-2. GNSW1 represents water levels in the field-side ditch, and all the other plots show soil water levels from dipwells.

The simulated water level in ditch (GNSW1) is strongly influenced by the assumptions made about the flow and level management in the Gwent Levels IDD (see Section 0), but nevertheless shows a good reproduction of the observed response to rainfall events.

Except at GNDW1, the model reproduces very well the overall pattern of low soil water levels during the summer, high levels in the winter, and the responses to individual rainfall events and dry spells. A little too much drawdown is simulated during June 2020, and not enough during some of the winter dry spells, but many of the other features of the hydrographs are relatively well represented.

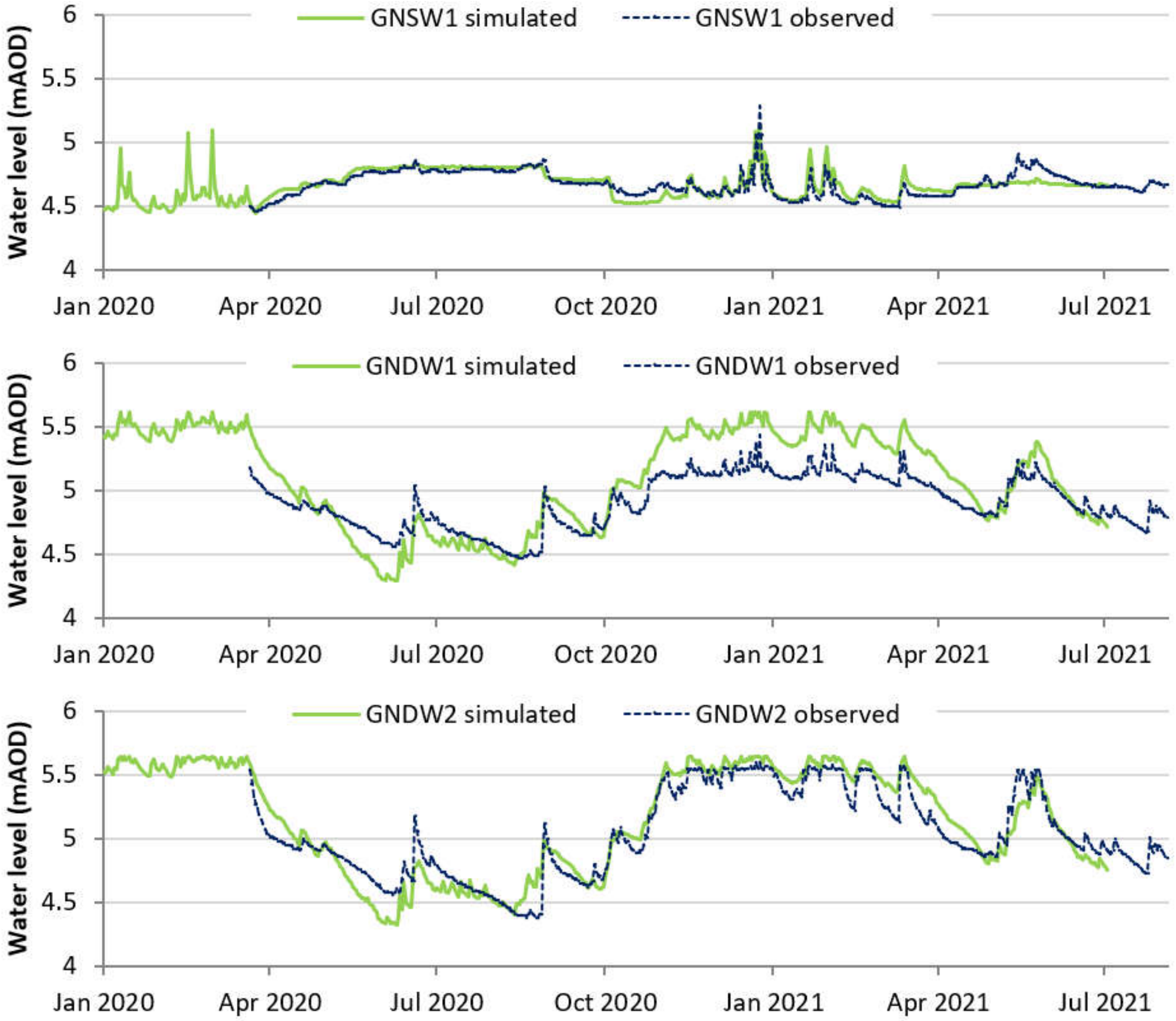

Figure 8.2-1. Calibration against measured water levels at Great Newra (traditionally-drained site), part 1.

At GNDW1 the simulated soil water levels are consistently above the observed soil water level during the winter months. This dipwell is located in the localised depression close to the headland separating the furrow from the field-side ditch, and its associated pipe (see Section 8.1.4). It is probable that the pipe, or the soil used to build the headland (presumably originally removed from the ditch) represent a higher hydraulic conductivity (and/or lower storage) than is currently represented in the model. It is likely that the assumptions made about the reduction of hydraulic conductivity with depth through the soil horizons should be adjusted in this area, where the natural soil profile has been modified by the construction of the headland.

The introduction of a zone of higher hydraulic conductivity in this area would increase the hydraulic connection to the field-side ditch, helping to lower the simulated soil water level at GNDW1. However, exploring the potential impact of these more detailed changes on the model calibration is beyond the scope of the current project.

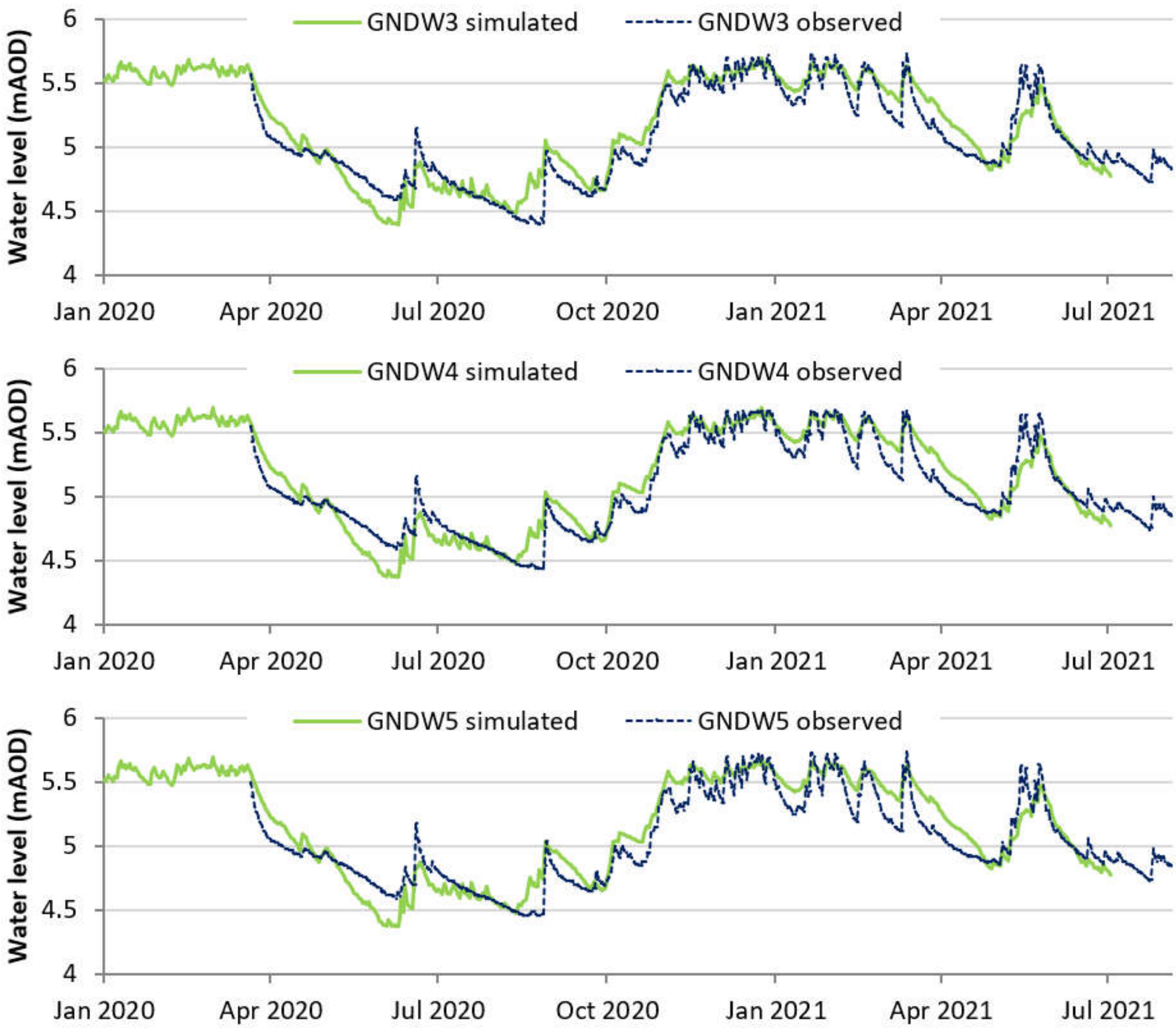

Figure 8.2-2. Calibration against measured water levels at Great Newra (traditionally-drained site), part 2.

### 8.2.2 *Cross Farm Nash (under-drained site)*

The parameterisation of the Cross Farm Nash model was based on the results of the calibration work undertaken on the Great Newra model, and so the main focus of the calibration for this model was simply to adjust the representation of the field-side ditch flow and level management, and then to add the representation of the under-drain. The inclusion of enhanced hydraulic conductivity to represent mole drains was not found to improve the model calibration, and so has not been included.

The results for the Cross Farm Nash model (run number 13) are presented in Figure 8.1-3. CF2SW1 represents water levels in the field-side ditch, and all the other plots show soil water levels from dipwells.

The representation of the under-drain directly affects the simulation of the soil water levels in the two dipwells located along its length, at CF2DW1 and CF2DW2. The under-drain was initially included in the model at a shallower depth (0.6 mbgl), but it was not possible to reproduce the observed low soil water levels at these two dipwells without lowering the under-drain to 0.9 mbgl (see Section 0). Even then, some of the simulated soil water levels at CF2DW1 and CF2DW2 are still above the observed water levels.

Nevertheless, the Cross Farm Nash model also reproduces very well the observed pattern of low soil water levels during the summer, high levels in the winter, and the responses to individual rainfall events and dry spells.

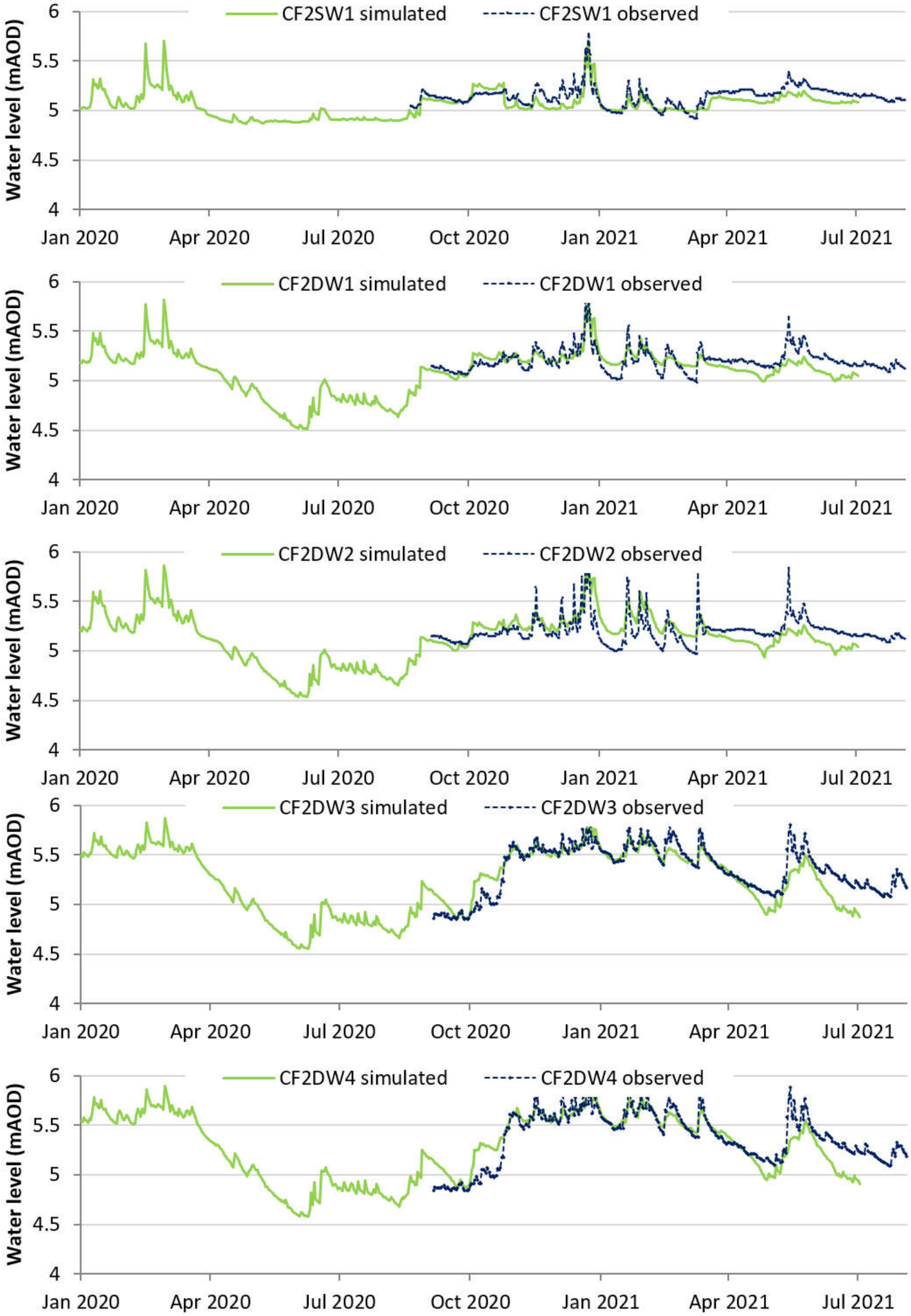

Figure 8.2-3. Calibration against measured water levels at Cross Farm Nash (under-drained site), part 1.

The model also reproduces the low soil water levels at CF2DW1 and CF2DW2, which are significantly further below ground level than the other dipwells at either site. This is important for being able to use the models to draw conclusions about any differences between the ways that the two differently drained sites respond to rainfall events, and in how they interact with the ecologically important field-side ditches.

The following sections report on analysis of the calibrated models.

## 8.3 Simulated water balances

### 8.3.1 *Great Newra (traditionally-drained site)*

The simulated water balance from the Great Newra model is presented in Figure 8.3-1. The water balance is shown in terms of the net inflows and outflows to and from the soil zone through time. The main input to the soil is from rainfall, and the main outputs are to evapotranspiration (EVT), runoff and direct flow from the soil to the field-side ditch.

Any excess inflow (i.e. when rainfall exceeds EVT, plus runoff, plus ditch outflow) results in an increase in the amount of water held in storage. This is shown on the water balance plot as a *negative* flow *from* the soil zone *out to* storage. Subsequently, when EVT exceeds rainfall during the summer, water is released from storage, and soil water levels fall. This is shown as a *positive* inflow to the soil, *in from* storage.

Because the simulation starts at a time of high soil water levels in the winter, and ends at a time of low soil water levels in the summer, there is a net release from storage over the duration of the full simulation period.

The flow rates presented here have been divided by the area of the soil zone represented in the model (the total area of the model minus the area of the ditch)[16]. This allows a direct comparison to be made between the simulation results for the two different sites.

The results show that the flows to the ditch (both direct and via runoff) predominantly occur during the colder months from November to March, with hardly any flow to the ditch occurring during the warmer months from April to October.

### 8.3.2 *Cross Farm Nash (under-drained site)*

The simulated water balance from the Cross Farm Nash model is presented in Figure 8.3-2. It is very similar to the simulated water balance from the Great Newra model, except that for the Cross Farm Nash model, whilst the dominant outflow is still to EVT, the components of outflow to runoff and direct flow to the ditch are reduced, with flow instead going to the under-drain.

Again, the results show that the flow to the ditch (direct from the soil, via runoff, plus under-drain flows) predominantly occur during the colder months from November to March, with hardly any flow to the ditch occurring during the warmer months from April to October.

### 8.3.3 *Comparison of the simulated water balances for the two sites*

A comparison of the total simulated inflows and outflows over the full simulation period is presented in Table 8.3-1. The final column shows the differences between the simulated flows for the two sites, and reiterates the point stated above that the increased flow to the under-drain at Cross Farm Nash is mainly balanced by a reduction in the flows to runoff and the direct flow from the soil to the ditch. The under-drainage initiates a change in hydrological dynamics of the system that is to be expected, and which is appropriately modelled.

The results also show a small reduction in the net storage release in the Cross Farm Nash model relative to the Great Newra model. This is due to the lower winter soil water levels in the vicinity of the under-drain (as can be seen at CF2DW1 and CF2DW in Figure 8.3-3), meaning that proportionally a little less water is held in storage at Cross Farm Nash than at Great Newra, and the releases from storage between the colder months and warmer months are therefore proportionally lower.

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[16] This explains why the flow rates for each water balance component are expressed in equivalent depth of rainfall (mm).

A small reduction can also be seen in the total simulated EVT rate from the Cross Farm Nash model relative to the Great Newra model. This difference is due to the soil water levels falling further below the depth at with the grass roots can easily obtain water, and the rate of evapotranspiration is reduced (Section 8.1.5). This relative EVT reduction occurs in May 2020, when the simulated soil water levels are at their lowest.

Because the runoff and under-drain both deliver water to the field-side ditch, the total flow to the ditch is the sum of the runoff, direct soil to ditch flow, plus the under-drain flow. The model results indicate that slightly more flow enters the field-side ditch at the under-drained Cross Farm Nash site than at the traditionally-drained Great Newra site. The 9.3 mm increase per unit area over the full 548-day simulation period shown in Table 8.3-1 represents just a 1.4% increase over the 680.7 mm value for Great Newra.

Consideration of the differences between the simulated water balances through time can help to show which times of year the differences are likely to occur. Figure 8.3-3 shows a water balance difference plot for the Cross Farm Nash model relative to the Great Newra model. This plot is produced by calculating differences in the same way as presented in Table 8.3-1, but for every time step of the model.

Table 8.3-1. Comparison of simulated water balances (mm) for the two sites (full simulation period).

| **Simulated flows (mm)** | **Great Newra** | **Cross Farm Nash** | **Difference** |
|---|---|---|---|
| Rainfall to soil | 1461.0 | 1461.0 | 0.0 |
| Storage to soil | 82.2 | 69.6 | -12.6 (-15.3%) |
| Total inflow | 1543.2 | 1530.6 | |
| Soil to EVT | 862.6 | 841.8 | -20.8 (-2.4%) |
| Soil to runoff | 346.6 | 58.2 | -288.4 (-83.2%) |
| Soil to ditch | 334.1 | 110.9 | -223.2 (-66.8%) |
| Soil to under-drain | 0.0 | 521.0 | +521.0 |
| Total flow to ditch | 680.7 | 690.0 | +9.3 (+1.4%) |
| Total outflow | 1543.3 | 1531.8 | |
| Error | 0.0 | -1.2 | |
| % error | 0.00% | -0.08% | |

Positive flows on the water balance difference plot indicate that either inflows have increased, or (as in this case) outflows have decreased. In this case the outflows to runoff and the direct soil flows to the ditch have decreased, along with a small reduction to the outflow to EVT. All of these are shown as positive differences from the point of view of the soil water balance. These positive differences are mainly balanced by the increased outflow to the under-drain, shown as a negative difference on the water balance difference plot.

There is also a small net reduction in the overall release from storage over the simulation period. This net reduction is the result of the sum of many different positive and negative storage flow differences throughout the full period of the simulation.

Comparison of the pattern of flow rates on Figure 8.3-3 shows that the under-drain flow (pink) is smoothed relative to the combination of runoff (green) and direct-ditch flows (brown) that it replaces. This indicates that the under-drains may help to attenuate a proportion of the highest winter flow rates through the ditches, via re-direction of what would normally be runoff to the slightly slower route through the under-drains.

The water balance difference plot shows that the models predict most of the differences in the behaviour of the two different systems occur during the colder months. However, there are still some small differences which occur during the warmer months, including the reduction to the EVT rate noted above. The impact on ditch inflow rates is of greater interest for the warmer months, as this is when the management of the ditch water levels becomes more critical. Table 8.3-2 shows a comparison of the simulated water balances for the two sites over the period from April to September 2020, during which the differences between the simulated flow rates are much smaller. It is interesting to note that both models predict a slight reversal of flow during this period, with water flowing back from the ditch into the soil (shown as negative flow rates in Table 8.3-2).

Table 8.3-2. Comparison of simulated warmer month water balances (mm equivalent) for the two sites (Apr-Sep 2020).

| **Simulated flows (mm)** | **Great Newra** | **Cross Farm Nash** | **Difference** |
|---|---|---|---|
| Rainfall to soil | 336.0 | 336.0 | 0.0 |
| Storage to soil | 55.6 | 32.6 | -23.0 (-41.4%) |
| Total inflow | 391.6 | 368.6 | |
| Soil to EVT | 398.6 | 381.5 | -17.1 (-4.3%) |
| Soil to runoff | 0.0 | 0.0 | 0.0 |
| Soil to ditch | -7.0 | -8.0 | -0.9 (-12.9%) |
| Soil to under-drain | 0.0 | -4.9 | -4.9 |
| Total flow to ditch | -7.0 | -12.9 | -5.9 (-84.3%) |
| Total outflow | 391.6 | 368.6 | |
| Error | 0.0 | 0.0 | |
| % error | 0.00% | 0.00% | |

It appears that the generally lower soil water levels at Cross Farm Nash help to induce a slightly larger flow from the ditch to the soil during the summer. However, the under-drain also enhances the connection between the ditch and the soil, providing the majority of the 5.9 mm per unit area of the reverse flow from the ditch to the soil over this period.

It should be noted that the onset of the increased reverse flow in the Cross Farm Nash model occurs on 27th August 2020, which coincides with a large rainfall event, but which also coincides with differences between the simulated IDD ditch water level management regimes at the two sites, with the assumed ditch water level having been reduced slightly at Great Newra, but increased at Cross Farm Nash (see Table 8.1-1). As noted in Section 8.1-5, there are no records of the actual IDD ditch water level management changes through the year, so the changes included in the model have just been inferred from the available ditch water level records.

For the purposes of comparing the water balances from the models of the two sites, it is worth noting that increased reverse flow from the ditch to the soil in the Cross Farm Nash model is largely a result of the differences between the assumed ditch water level management changes simulated for each site, and is not due simply to the presence of the under-drain.

## 8.4 Conclusions

The groundwater models of the two sites are well calibrated to the observed soil water levels, and reproduce the main features of the observed responses to rainfall events and dry spells. The models also reproduce the main observed difference between the soil water levels measured at the two sites, simulating lower winter soil water levels observed along the line of the under-drain at Cross Farm Nash. There is thus confidence that the models effectively simulate the hydrological processes occurring at the sites, and importantly the differences between them.

There are some minor deficiencies in the representation of some of the finer details of the transient soil water level hydrographs, and an under-estimation of the simulated soil water level at one of the five dipwells at the traditionally-drained Great Newra site. However, these are relatively small, transient and/or localised discrepancies which, if remedied, would likely have little impact on the overall simulated water balances of the two models, and hence little impact on the comparisons and conclusions.

The main conclusion from comparing the simulated water balances from the two models is that the presence of the under-drain looks to have very little impact on the total simulated flow rates to the field-side ditches, especially during the critical warmer month periods. The models predict a small overall positive impact on ditch water flows due to the presence of the under-drain of 1.4% averaged over the full 548-day simulation period. Since warmer months are disproportionately represented in the simulations, a longer-term increase of c. 4% can be assumed.

Over the critical summer period, both the models predict a small reversal of flow. The under-drained Cross Farm Nash model predicts a larger summer flow from ditch to soil than the traditionally-drained Great Newra model, but these differences are mainly due to assumed differences between the IDB ditch water level management operations at the two sites. There are large uncertainties associated with the ditch water level management practices, and the associated changes to flows within the ditches. These uncertainties can have an impact on interpreting the fine detail of the soil-ditch interactions during the summer months.

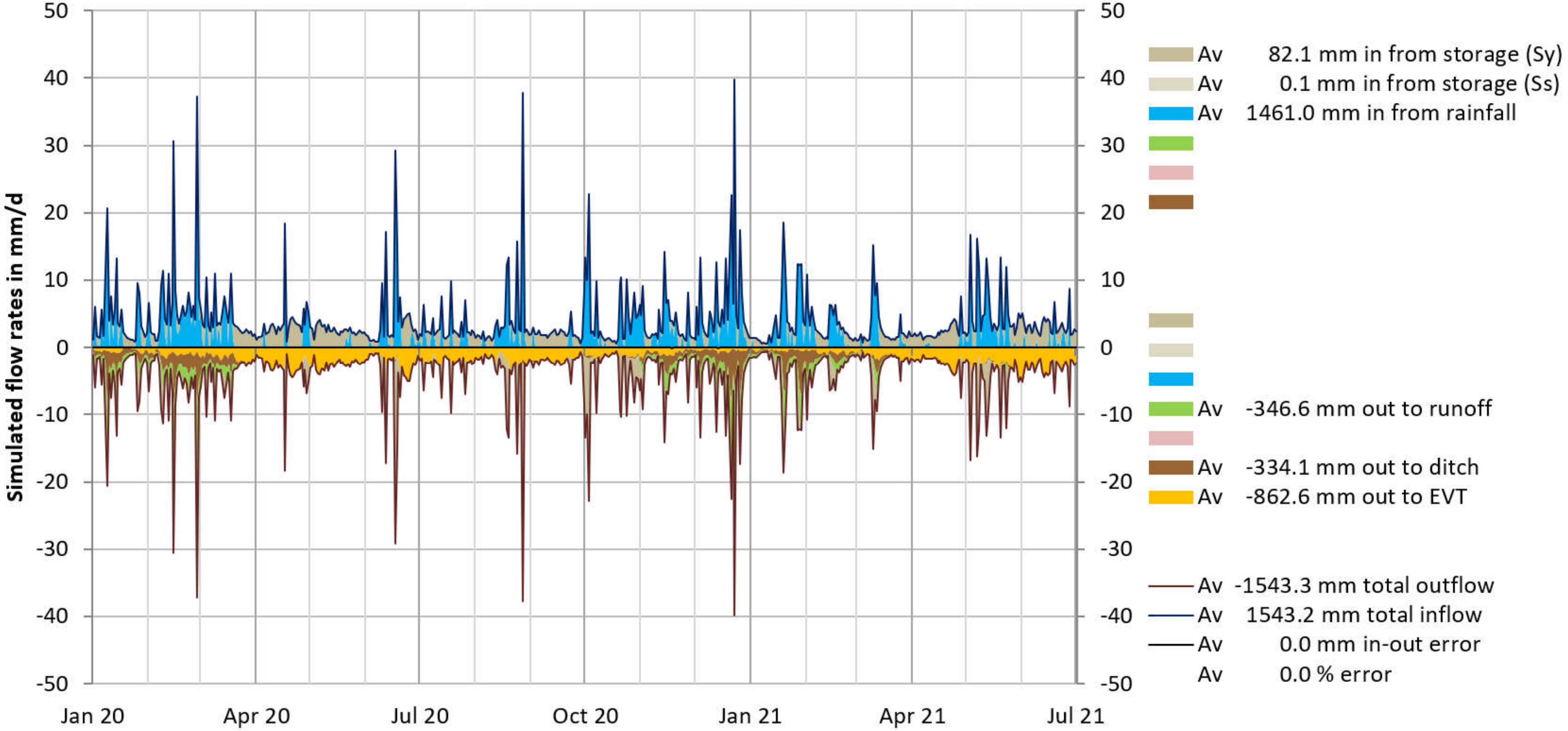

Figure 8.3-1. Simulated water balance from the Great Newra model (traditionally-drained site).

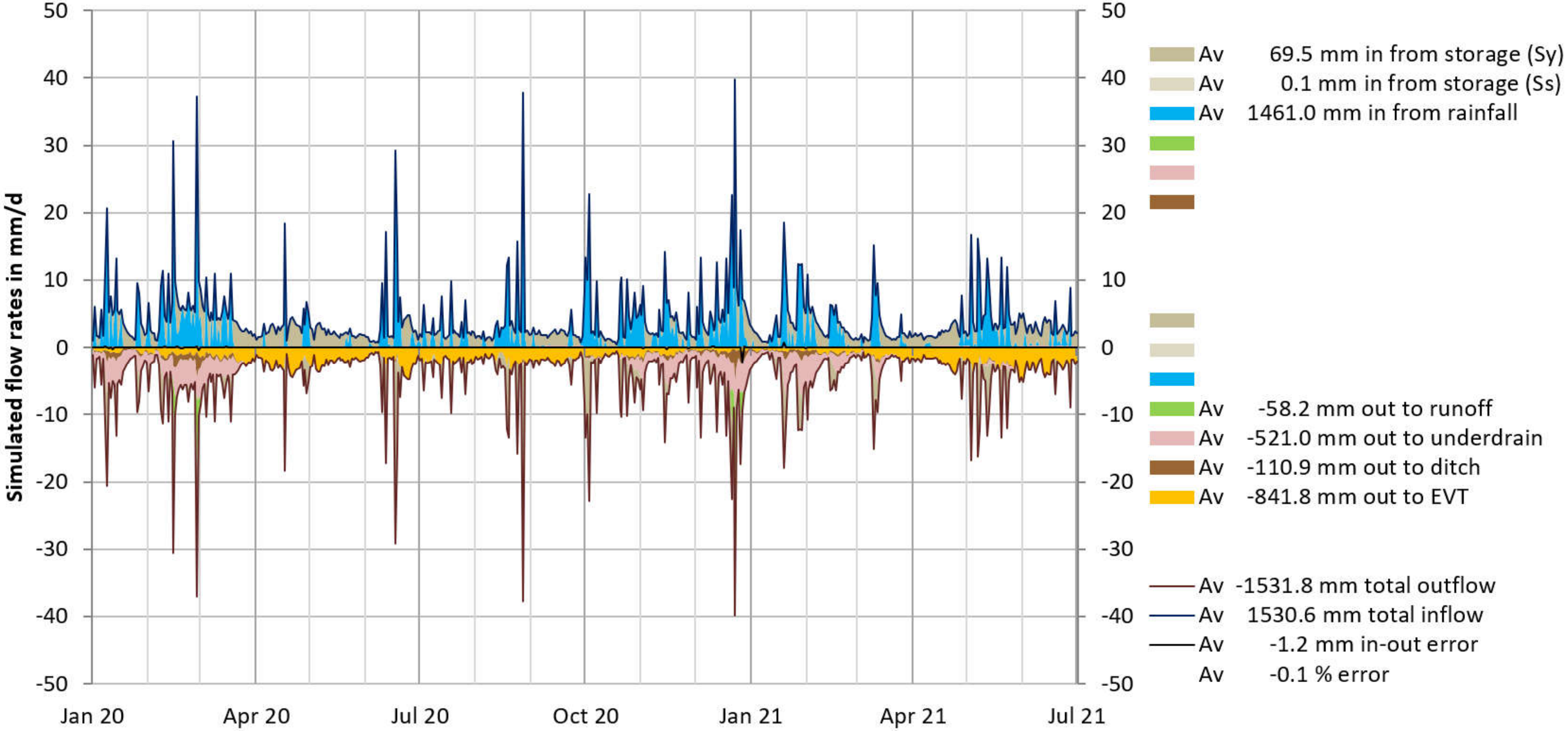

Figure 8.3-2. Simulated water balance from the Cross Farm Nash model (under-drained site).

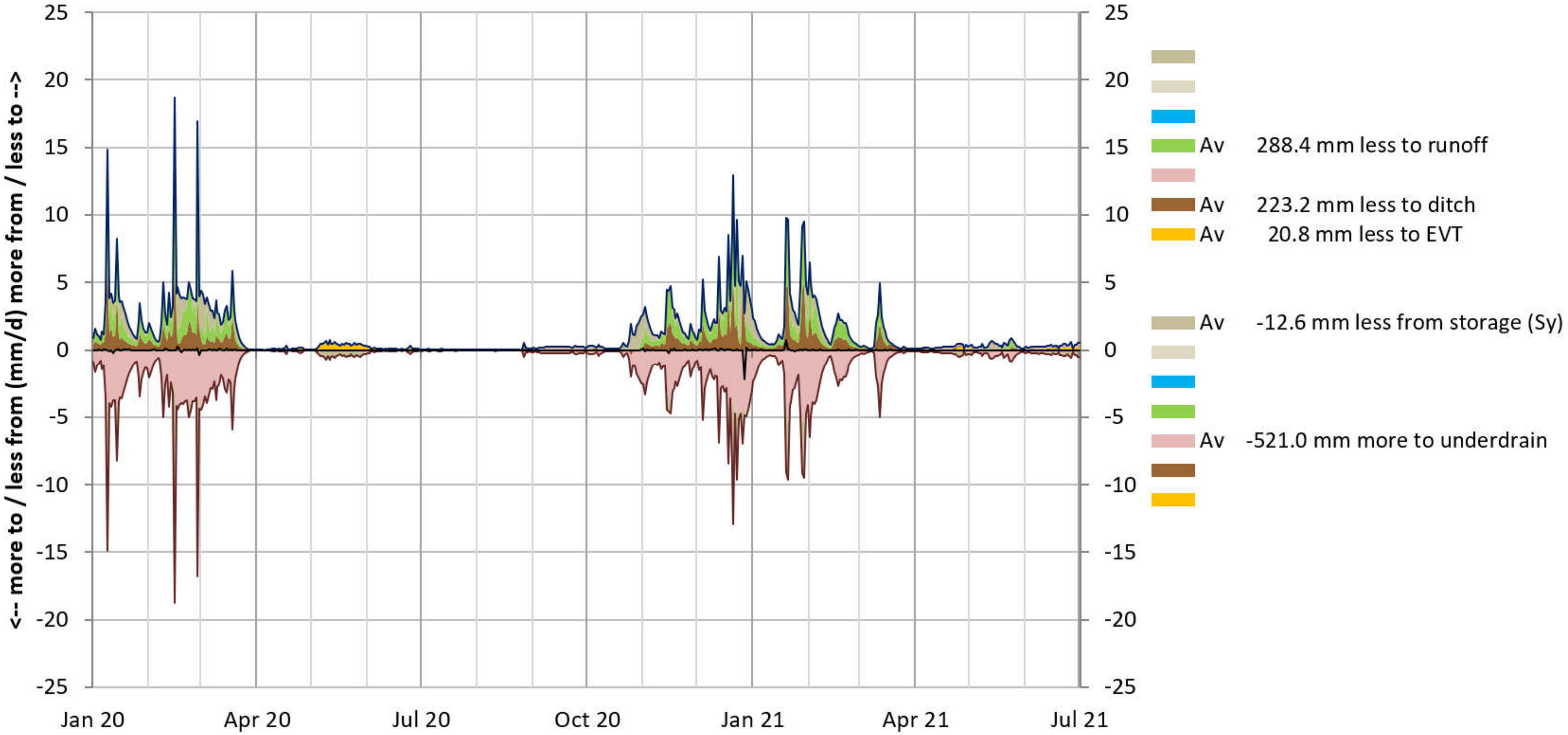

Figure 8.3-3. Water balance difference plot for the Cross Farm Nash model relative to the Great Newra model.

# 9 Assessment of the direct effects of under-drainage versus traditional drainage

## 9.1 Ecohydrological effects on ditch plant and invertebrate SSSI interest features

It has been established that the primary physical variable through which hydrological supporting conditions for the ditch-hosted interest features are defined is ditch water depth; maintenance of a stable summer water level is critical as this is when plants are most actively growing, flowering and setting seed. By inference from the literature, preferred warmer month ditch water depths of 0.30-1.25 m (average = 0.40 m) for field drains and 0.60-2.00 m (average = 1.25 m) for larger reens have been suggested.

Sensitivity of ditch water depth to the drainage arrangements on adjacent fields derives from the influence of the drainage arrangements on the amount of water which discharges to the ditches, from the fields, in response to rainfall.

It has been established during the current project that, during the warmer months:

- Within the Gwent Levels, EVT exceeds rainfall over the medium term, and there is a negative local water balance, i.e. a net loss of water from the system (Sections 2.1.3 and 8.3).
- Irrespective of field drainage type, this causes the water table to fall significantly, to below the elevation of the drainage features which would potentially host flows of water to field-side ditches (Sections 6.2-6.6 inclusive, and Section 7).
- Hence, for both field drainage types, there is no significant discharge from the fields to the field-side ditches, with the large majority of rainfall being lost to EVT (Section 8.3). Ditch water levels are not supported by flows from the fields during these periods.
- Frequent reversal of hydraulic gradients, so that ditch water levels are higher than adjacent soil water levels, occurs, but because of the poorly permeable nature of the substrate it is assumed that little ‘irrigating’ flow occurs in response.

Since there is no discharge from the fields to the ditch, there is no sensitivity linkage between ditch water depth and field drainage type. It therefore follows that there is very unlikely to be any systematic difference in ditch water depth regime between traditionally-drained and under-drained fields.

There is less concern about the sensitivity of ditch-hosted interest features to ditch water depth during the colder months; it is important that ditches retain water as over-wintering habitat for invertebrates, aquatic plants (and their overwintering propagules) but this is highly likely with the higher rainfall and water control over the winter months. However, it is worth noting that:

- Within the Gwent Levels, rainfall exceeds EVT over the medium term, and there is a positive local water balance, i.e. a net gain of water for the system.
- Irrespective of field drainage type, this causes the water table to rise to close to the ground surface, and to fluctuate within a shallow zone in response to rainfall and (primarily) drainage to the field-side ditches. The very dominant mechanism for drainage in traditionally-drained fields is surface runoff, whilst the more important mechanism in under-drained fields is through the under-drains.
- Whilst the water flows to the field-side ditches in different ways under the two types of drainage, the overall drainage yield (i.e. percentage of rainfall) from the fields is very similar.

So, again, there is very unlikely to be any systematic difference in ditch water depth regime between traditionally-drained and under-drained fields, but in this case it is because the drainage types, whilst exhibiting different drainage mechanisms, are functionally very similar in terms of the percentage of rainfall which falls onto the fields arrives in the field-side ditches.

In summary, there is very unlikely to be any systematic difference between ditch water depth regime and field drainage type, during either the warmer or colder month periods. Therefore, the ecohydrological supporting conditions for ditch plant communities, as defined through the ditch water level regime, is very unlikely to be sensitive to field drainage type.

## 9.2 Other potential ecohydrological effects

A range of relict wet grassland plant communities tend to be associated with the varying topography of ‘in-field’ hollows and furrows that are associated with traditional drainage, communities dominated by grasses such as Creeping Bent *Agrostis stolonifera* and Marsh Foxtail *Alopecurus geniculatus*. If these traditional features are replaced by underdrainage, it is possible that the resulting more even field surface would be less favourable to such a range of plant communities, and this is viewed as a negative impact in ecological terms.

## 9.3 Farming and land management

The water table monitoring and modelling during this project has also provided some insight into soil water dynamics in the context of farming:

- During the warmer months the soil water table behaviour in both traditionally-drained and under-drained fields is very similar, with the water table falling significantly below the ground surface.
- During the colder months there was some evidence in the monitoring data that the soil water table (away from underdrains) was slightly lower than that for traditionally-drained fields, but the difference was small, and because of the small number of monitoring sites it must be considered uncertain. Put simply, the benefits of under-drainage in relation to extending the period of active farming of fields have not been clearly demonstrated during the project.

## 9.4 Geographical variation

The small-scale hydrological functioning of the Levels is controlled ultimately during the warmer months by the excess of EVT over rainfall. This negative water balance applies over the whole of the Gwent Levels, and therefore it is considered highly unlikely that ditch water depth regimes will be sensitive to field drainage type anywhere within the Levels. As such, with regard to direct ecohydrological impacts, there is no evidence for geographical controls on where under-drainage should or should not be allowed.

## 9.5 Surface/shallow archaeology

Rippon (1996) details the staged reclamation and cultural evolution of the Gwent Levels, which is associated with the presence of a significant number of artefacts at or close to the surface; these include human artefacts, but also natural artefacts such as pollen and macrofossils in peats. Preservation of these artefacts is promoted within the Levels by the generally high soil water table, which results in anoxic conditions and retardation of decomposition.

Regarding the possible impacts of installation of under-drainage on the preservation of artefacts, in comparison with traditionally-drained fields:

- As noted above, during the warmer months, the hydrological functioning of the fields under the two drainage types is practically the same.
- During the colder months, the difference between the drainage types is only that narrow linear corridors of lower soil water levels (c. 0.6-0.7 mbGL) are maintained along the under-drains. Elsewhere within under-drained fields, and universally across traditionally-drained fields, the soil water table is maintained close to the ground surface.

Since the soil is annually aerated to a significant depth for a long period during the warmer months, it is thought unlikely that small differences in the distribution of soil water table depth during the colder months in under-drained fields, in comparison with traditionally-drained fields, will have any impact on the preservation of archaeological remains. Indeed, probably the most significant risk in this context is disturbance of the artefacts during installation of under-drains.

It is also worth noting that a direct, but not ecohydrological, effect of the adoption of under-drainage is loss of the ridge-and-furrow micro-topography of traditionally-drained fields. This would appear to be more a function of the intensification which goes along with under-drainage than a direct effect of any hydrological changes. At the three under-drained monitoring sites, whilst a residual micro-topography can often be identified within the LIDAR data, visually the fields have been flattened. The difficulties in machine-working within the micro-topography of traditionally-drained fields have been noted (e.g. *pers. comm.*, Mr Andrew Waters).

# 10 Assessment of the direct effects of under-drainage versus traditional drainage; drought- and flood-risk

## 10.1 Introduction

The field-scale hydrological functioning of the Gwent Levels has been characterised in Sections 6, 7 and 8. The system will respond to rainfall events of different magnitude in a defined way. This section aims to consider the storage available within the context of design storm events. For this the storage available (in different components of the wetland system) is derived. Rainfall modelling is undertaken to enable a comparison of that available storage against design rainfall events.

## 10.2 Method

Rainfall modelling is undertaken using the FEH13 Rainfall Model (Stewart *et al.*, 2013), as described below. Some parameters are taken from the ReFH2.3 rainfall-runoff model (WHS, 2021). This provides a range of representative rainfall depths for various return-period rainfall events.

Calculations are undertaken to determine available storage volumes within the system. Three storage components are considered:

1. Within the ditch network;
2. Within the soil profile; and
3. Above-ground storage.

The storage is assessed in the context of the rainfall that may be expected at the site. Available estimates of climate change impacts on rainfall events have been used to assess future changes.

## 10.3 Rainfall Modelling

### 10.3.1 *Introduction*

The rainfall modelling is obtained via the FEH Webservice (CEH, 2021). Information is provided for the nearest similar size catchment.

True flood modelling, where the catchment area is well-defined, can predict a hydrograph and peak river flow conditions. For the current study this is not possible as the study area consists of a collection of adjoining, artificially-drained catchments. Analysis using rainfall data alone is more useful, given the impact on soil storage is more relevant to the current study than discharge from the drainage system, the latter being a heavily managed artificial system.

### 10.3.2 *Method*

A representative catchment was therefore chosen for the current study. The nearest catchment of a size similar in magnitude was chosen to be that of the St. Bride's Brook, which discharges into the Magor Pill within the Magor and Undy SSSI, towards the eastern end of the Caldicot Level (Figure 10.3-1). It has an area of 16.3 km², compared to the 58.6 km² area of the SSSI site itself.

The FEH13 rainfall model (Stewart *et al.*, 2013) used in this analysis is the industry-standard model recommended for widespread application of hydrological studies. The rainfall model has been interrogated at the catchment level, as opposed to the 1 km grid point level. The model is a three parameter DDF model with *Depth, Duration and Frequency* interacting in a three-parameter space to provide representative rainfall values for the catchment.

The *Duration* parameter provides a benchmark storm duration which is used to extract the rainfall *depth* for a given return period (*frequency*). The *Duration* parameter is derived as the default value extracted from the ReFH v2.3 software using the method described by WHS (2021). A value of 9.5 hours is used. Figure 10.3-2 shows the rainfall model with various return periods.

No distinction between summer and winter rainfall profiles is made under this approach. In reality, there would be differences, as winter rainfall is dominated by frontal systems with lower intensity but longer events; high magnitude summer rainfall events are dominated by convective events which are shorter in duration but of higher intensity. In winter there would also be a risk of consecutive events, with more closely-spaced events. In this instance, storage used by an earlier event would not be available for a following event, which would thus produce greatly enhanced runoff.

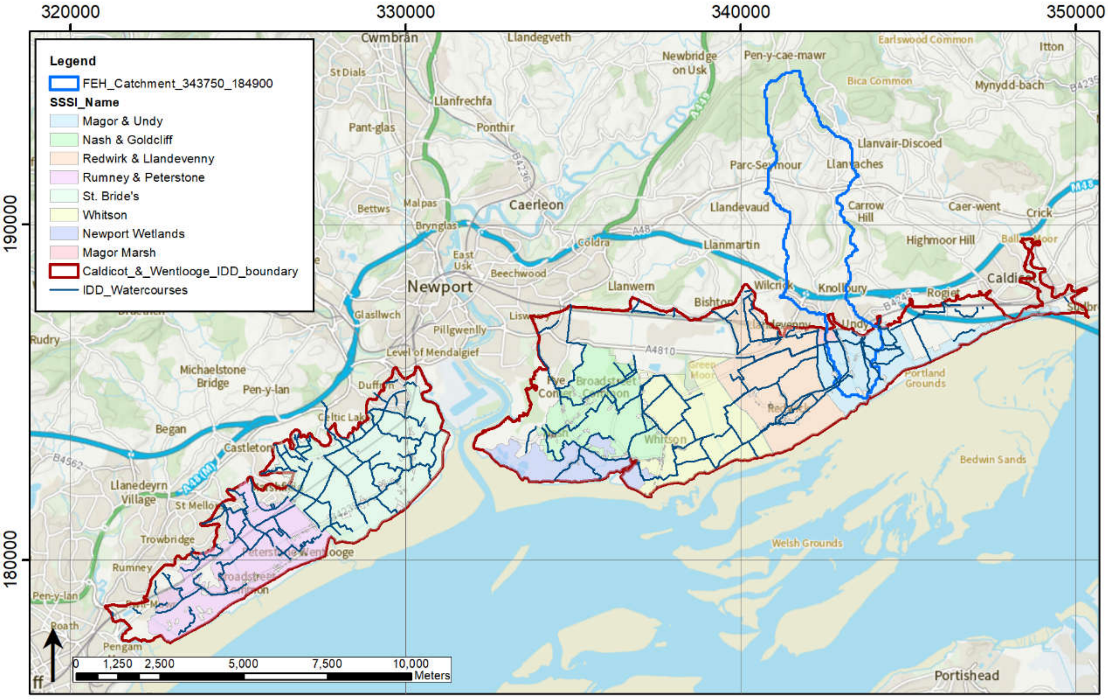

Figure 10.3-1. Map of study site vs rainfall catchment.

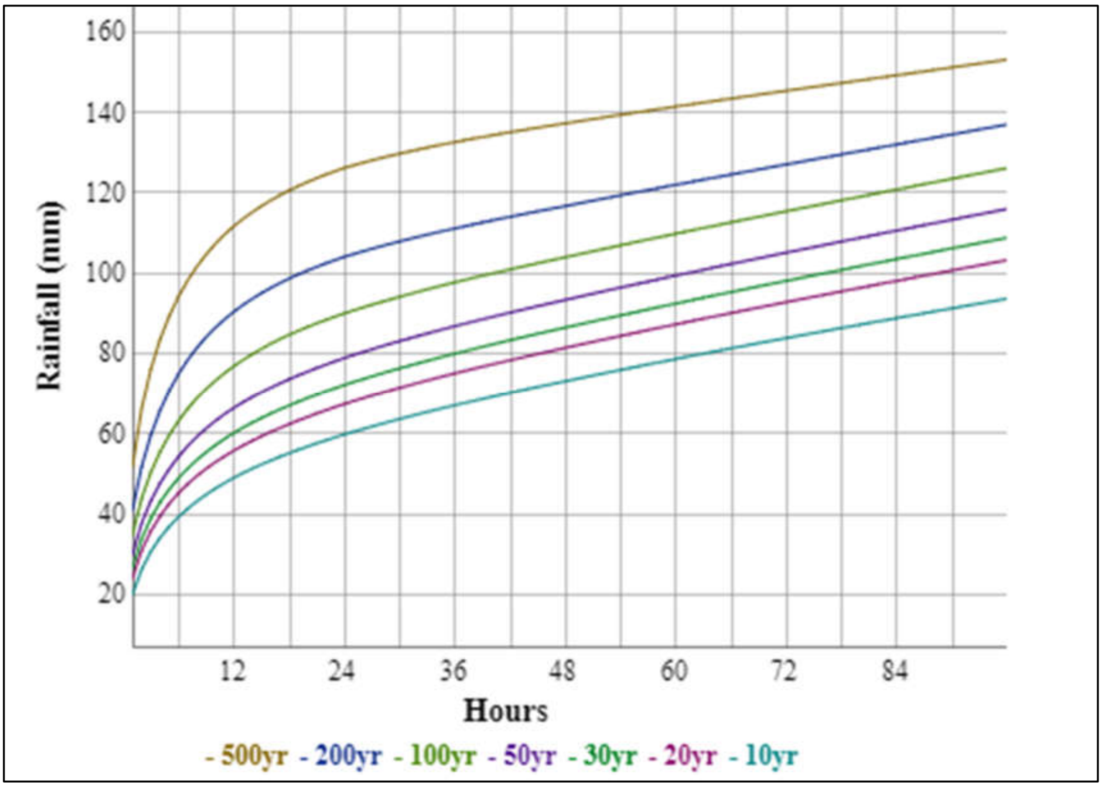

Figure 10.3-2. The rainfall values from the depth-duration-frequency model for the 16.3 km² representative catchment. The duration (in hours) on the x axis and rainfall depth (y axis) are given for various return periods (frequency of event).

### 10.3.3 *Results*

Table 10.3-1 below provides summary results for storm events of various return periods. These are for the catchment area of 16.3 km², as discussed above, and should be scaled for the subject site to give volumes of water resulting in the wetland system.

The results used for the storage calculations below take forward the 1-year return period design event only for clarity in presentation of results.

Also shown in Table 10.3-1 is the volume of water each event corresponds to per km², for comparison against subsequent storage calculations. Each square km is 1,000,000 m².

Table 10.3-1. The rainfall values for the representative catchment derived from the rainfall modelling.

| **Return Period** | **Rainfall Depth (mm)** | **Volume, m³/km²** |
|---|---|---|
| 1 year | 28.24 | 28,240 |
| 2 year | 33.46 | 33,460 |
| 5 year | 40.58 | 40,580 |
| 10 year | 46.28 | 46,280 |
| 20 year | 52.56 | 52,560 |
| 30 year | 56.66 | 56,660 |
| 50 year | 62.58 | 62,580 |
| 75 year | 68.08 | 68,080 |
| 100 year | 72.52 | 72,520 |
| 150 year | 79.79 | 79,790 |
| 200 year | 85.56 | 85,560 |
| 500 year | 106.25 | 106,250 |
| 1,000 year | 122.79 | 122,790 |

### 10.3.4 *Comparison with observed values*

It is important to note that the rainfall values modelled herein are not necessarily comparable with the observed record presented in Section 6.1.

The modelled values are from a nominally representative nearby catchment and are thus catchment-wide average totals. The observed dataset presents data collected at a single point, and which is therefore subject to much more significant rainfall totals that may be generated at such a small scale given the dynamics of storm events producing locally-intense rainfall. Such totals would not be sustained over a whole catchment.

Second, the observed dataset is aggregated daily totals measured over 24-hour periods with a common delineation at 0900 (not midnight), as per established hydrological practice. Thus, a daily total may measure more than one storm event: remember the design storm duration is 9.5 hours in the current example, significantly less than 24 hours.

### 10.3.5 *Climate Change Factors*

Hydrological analyses are commonly subject to climate change allowance factors. These give an uplift to peak rainfall intensities, peak flows and resultant flood levels to account for the impacts of climate change. Change factors for use in the England are provided on the Government website (UK Government, 2021). No rainfall scale factors are used in Wales (Welsh Government, 2021).

The (England) guidance only provides allowances for peak rainfall intensities. These are used to ensure drainage systems can convey the flow to storage within a system. This is not relevant to the current study which is analysing the impacts of the total rainfall depth of a storm event. For this reason, climate change has not been applied to the current analysis.

It is appreciated that the context of climate change impacts may need to be considered by the client. For this reason, the allowances for England are provided in Table 10.3-2 (UK Government, 2021). Note that the Central and Upper End bands are used for different development types (e.g., whether water-compatible or not).

Table 10.3-2. Climate change allowances for peak rainfall intensity. These are not used in the analyses, see text for detail.

| **Applies across all of England** | **Total potential change anticipated for the '2020s' (2015 to 2039)** | **Total potential change anticipated for the '2050s' (2040 to 2069)** | **Total potential change anticipated for the '2080s' (2070 to 2115)** |
|---|---|---|---|
| Upper end | 10% | 20% | 40% |
| Central | 5% | 10% | 20% |

## 10.4 Storage Calculations

### 10.4.1 *Ditch Network*

The storage available within the ditch network is derived using a representative ditch surface area. The representative ditch length has been derived using GIS, along with measurements from the site work of the typical width. These are provided in Table 10.4-1. The calculations are representative of the plots studied in the monitoring programme as described in Section 5. A typical ditch is 2.5 m wide, and inspection of mapping indicates that there are typically 10.95 km of ditch per km².

It is assumed that the ditch level increases linearly with rainfall depth, i.e. that 10 mm of rainfall initiates 10 mm of level increase. This distinguishes it from the storage within the soil profile as the specific yield parameter is effectively 100%, and all of the unit depth can be used to store water in the ditches.

It is assumed that the ditch level can rise and thus accept any depth of rainfall event, although this will rise and cause higher discharges downstream within the ditch and reen network. This is not true for the soil profile, which has a fixed available storage.

Given this, it is derived that there is 766.53 m³ storage within the reen network per km² for the one-year return period rainfall event. For the 2-year event (33.46mm) this rises to

Table 10.4-1. Ditch storage calculations. The 1-year rainfall design event is used.

| **Rainfall Event** | **Length of ditches (km)** | **Width (m)** | **Surface area (m²)** | **Rainfall depth (m)** | **Storage (m³)** |
|---|---|---|---|---|---|
| 1-year | 10.95 | 2.50 | 27,375 | 0.028 | 766.53 |
| 2-year | | | | 0.034 | 930.75 |

### 10.4.2 *Soil Profile*

The depth to water table is taken from the programme of monitoring. Given the understanding developed from that monitoring, typical values for depth to in-field water table are provided in Table 10.4-2 for both summer and winter for both traditional and under-drained systems.

Specific yield as a critical parameter here, as it represents the proportion of the soil profile not comprising soil material and thus available for storing water. When not saturated, this is air within the soil profile. This parameter is estimated from the modelling presented in Section 8.

As the ditch network covers 27,376 m² per km², which represents *2.74%* of the catchment area. Therefore, 97.26% of the land area is in-field areas. It follows that for each square kilometre of land (1,000,000 m²), the available storage in the soil profile is scaled by 97.26%.

Note that the one-year rainfall is 28.24 mm rainfall depth. When considering the effect that the specific yield has in scaling the available storage, the fifth column of the table (grey text) presents the resultant effective storage depth enabling a comparison with rainfall depth.

Table 10.4-2. Soil profile storage calculations: deriving storage per km².

| **Season** | **Plot type** | **Depth to water table (m)** | **Sy (%)** | **Available depth (m)** | **In-field Area m/km²** | **Available storage (m³/ km²)** |
|---|---|---|---|---|---|---|
| Summer | Traditional | 1.10 | 14% | 0.154 | 972,623 | 149,793.9 |
| | Under-drained | 1.10 | | 0.154 | | 149,793.9 |
| Winter | Traditional | 0.15 | | 0.021 | | 20,425.1 |
| | Under-drained | 0.20 | | 0.028 | | 27,233.4 |

### 10.4.3 *Above-Ground Storage*

Above-ground storage is only used when the soil profile up to the surface is fully saturated. Any rainfall falling subsequent to this condition being reached will not infiltrate, and water will pool above the surface. It may then runoff into the ditch network via saturation-excess overland flow if the water level in the ditch network is lower (usually as drainage out of the system is facilitated by the hydraulic control structures). If the level in the ditch network is equal to that across the in-field areas, this transfer will not occur as there will be no hydraulic gradient to initiate flow. In either situation, the rainfall falling on the ditch network directly will increase the level of the ditch.

In this situation, flooding will occur and thus no calculations are required. As discussed above, sequential rainfall events will produce this situation as any available storage within the wetland system will be taken up. Runoff will be generated rapidly by the subsequent rainfall events.

When the system is saturated, water levels will increase by the same depth as the rainfall falling, and thus flooding will occur.

## 10.5 Comparing Rainfall Depths with Storage

The one-year rainfall event is modelled as being 28.24 mm depth. That corresponds to 28,240 m³ per km². The total storage available within the Levels, under various scenarios, is given in Table 10.5.1. It is clear that most of the available storage for significant rainfall events lies within the soil profile rather than in the ditch network, which remains relatively stable throughout the seasons.

The seasonal difference in soil water levels is very significant to the ability of the Levels to store water from significant rainfall events. The storage created in summer by the water levels dropping is broadly equivalent to the 1,000-year storm event. In winter, very little storage is available, less than the one-year storm event. This seasonal discrepancy should be considered in any updates to the Water Level Management Plan.

However, the prevailing conditions are important. If rainfall occurs ahead of the storm event, this storage will be curtailed. Flood risk should not be disregarded in summer months. It must be remembered that these rainfall events are unlikely to occur in isolation, but within the context of a series of Atlantic depressions crossing the UK, in winter months at least. Therefore, the storage available will often be at or close to zero, and the above calculations provide a best-case scenario despite their conservative approach to the detail of parameterisation.

As discussed elsewhere in the current report, there are only minor differences in water levels between traditional and under-drained areas. And the differences are only noticeable to the relatively modest depth of the installed drains.

Table 10.5-1. Total available water storage ($m^3/km^2$) for different seasons and drainage types within the Gwent Levels.

| **Rainfall Event** | **Ditch Network** | **Season** | **Plot type** | **Soil Profile** | **Total** |
|---|---|---|---|---|---|
| 1-year | 766.53 | Summer | Traditional | 149,793.9 | 150,560.4 |
| | | | Under-drained | 149,793.9 | 150,560.4 |
| | | Winter | Traditional | 20,425.1 | 21,191.6 |
| | | | Under-drained | 27,233.4 | 27,999.9 |
| 2-year | 930.75 | Summer | Traditional | 149,793.9 | 150,724.65 |
| | | | Under-drained | 149,793.9 | 150,724.65 |
| | | Winter | Traditional | 20,425.1 | 21,355.85 |
| | | | Under-drained | 27,233.4 | 28,164.15 |

## 10.6 Drought

Although the monitoring period for the data collection programme has been relatively short at 12 months, a detailed understanding of the hydrological functioning of the system has been developed (Section 7).

There is a strong seasonal variation in water levels in the soil profile, with much less so in the ditch networks given the management of the system using weirs and sluices. The control of the system in part uses the vast experiences of the land managers. Significant changes occur seasonally, with changes made also in response to significant rainfall events.

As a result of this management, the system is considered to have a strong resilience to drought events. Any inflows to the top of the system, thought primarily to be from groundwater discharges via the northern feeders, are held in the system in summer months to retain reen levels. As described above, there is (very) significant storage in the soil profile to absorb rainfall, and thus very little runs off into the ditch network.

The impact of climate change is considered to result in changes to the distribution of rain through the seasons, with more rainfall in winter and less in summer (UKCRP, 2021). Also, a higher proportion of summer rainfall is likely to fall in intense convective storms. The Levels may be quite resilient to these changes given the storage available, especially given the summer levels that the sluices are set to in order to retain water on site for ecological management. As the impacts of climate change are realised on the Levels, the Water Level Management Plan should be updated to ensure maximum retention of water.

Given the importance of management of the site, it is possible that subtle changes to the operation of tilting sluices would make more of a difference than the impact of a reasonable length drought event.

As concluded in Section 12.3.1, there is no discharge from the fields to the ditch in warmer months. Therefore, there is no sensitivity linkage between ditch water depth and field drainage type. Consequently, there is very unlikely to be any systematic difference in ditch water depth regime between traditionally-drained and under-drained fields. The type of drainage is not likely to have any effect on the impact of drought events on the Levels.

## 11 Assessment of the possible indirect effects of under-drainage versus traditional drainage

As noted in Section 1.4.3, the possible impacts considered here would flow from potential secondary changes, driven by socio-economic factors, which might occur as a result of more widespread adoption of under-drainage. Identification of these secondary changes is, of course, somewhat speculative, and therefore assessment of their impacts is provided as a 'what if' scenario for the relevant environmental managers; it is important to note that the secondary changes identified here, which relate to agricultural intensification, are almost certainly not exhaustive.

### 11.1 Ditch water depth management in the context of under-drainage

Concern has been raised that should under-drainage be installed more widely, there would be increasing pressure from farmers to lower ditch water levels to ensure its functionality.

During the warmer months, as noted above, the local negative water balance within the Levels ensure that the soil water table falls below the base of, and is therefore hydraulically disconnected from, the under-drains for the majority of time. Since the under-drains do not function during this period, there is no justification to request lowering of ditch water levels.

During the colder months, it is noted in Section 7.3 that the effectiveness of under-drains is probably only sensitive to the water level which is maintained in the adjacent ditch when the latter is at or above the base of the shallow, highly permeable soil zone. This would reduce or reverse the hydraulic gradient from the under-drains into the wider field, which means that rapid drainage of this zone would not occur. It is important to note the criterion for acceptable ditch water levels in terms of under-drain functionality should be a comparison between the ditch water level and the elevation of the base of the highly permeable zone (ground level minus c. 0.45 m), rather than whether the outfall of the under-drain is underwater.

Widespread monitoring of ditch water levels has not been carried out during the current project, but it is worth noting that ditch water levels were more than 0.6 m below general field level at the three under-drained monitoring sites during the colder months, except for very short episodes following significant rainfall. It is thought unlikely that ditch water levels would be less than 0.45 m below general field level extensively across the Levels, and therefore it is unlikely that there would be significant pressure to lower ditch water levels during the colder months, should under-drainage be implemented more widely.

### 11.2 Grazing livestock

Whilst it has been shown that traditionally-drained and under-drained fields are almost indistinguishable in terms of water table regimes, it is possible that the slightly lower water table during the colder months in under-drained fields would result in a higher carrying capacity for grazing animals (cattle, ponies or sheep). The resulting increased stocking density could negatively affect field-side ditches by over-grazing of emergent vegetation as well as by increased non-point nutrient enrichment associated with livestock grazing. While over-grazing and poaching in winter is likely to be less harmful ecologically than during the summer months, nevertheless it could have an adverse effect in early Spring when wet grassland herbs commence growth.

### 11.3 Re-seeding

Replacing traditional surface drainage features with underdrainage will, with time, result in a more even field surface. Agricultural improvement of the sward by reseeding with a more agriculturally intensive grass mix (such as those dominated by Perennial Rye-grass *Lolium perenne*) could then be both a more favourable and likely successful option for land owners. Such an improvement (while needing SSSI consent) could be the catalyst for further agricultural intensification of the farmscape, with increased negative impacts on the important SSSI ditch features, including nutrient runoff.

### 11.4 Loss of ditches

Longer-term loss of ditches is a recognized problem within the Gwent Levels (Rippon, 1996), and maintenance of the extent of the standing water feature (reen and field ditch habitat feature) of the Gwent Levels as that mapped at the time of SSSI notification, to guard against loss of ditch to infilling, development or successional changes from neglect, is a PI for the Gwent Levels SSSIs (Section 3.4.1).

It is possible that any moves towards intensification in the context of widespread adoption of under-drainage would put pressure on this PI.

# 12 Summary and conclusions

Conception of this project was driven by the RSPB and NRW having concerns about the possible hydrological and ecohydrological effects of draining fields using under-drains, and associated infrastructure, within the Gwent Levels, rather than the traditional field drainage practices.

## 12.1 Larger-scale ecohydrological conceptual model of the Gwent Levels

A larger-scale ecohydrological model of the Gwent Levels, centred around the ditch plant and invertebrate SSSI interest feature communities has been developed (see Sections 2-4 inclusive). The key characteristics are:

- Ditch water depth was identified as the key variable through which the hydrological supporting conditions of the SSSI interest features could be defined.
- During the colder months rainfall exceeds evapotranspiration within the area of the Levels, and therefore there is a positive water balance. There is runoff from fields into the ditch system, primarily during and after rainfall events. The primary objective of hydrological management is flood-risk reduction, and therefore the control level for ditch water levels is lowered to increase the hydraulic conductance of the ditch network.
- During the warmer months evapotranspiration generally exceeds rainfall within the area of the Levels, and there is generally a negative water balance. There is little runoff from fields into the ditch system. The primary objective of hydrological management is maintenance of ditch water depths to support the SSSI interest features. This is fulfilled by management of the system of sluices and other infrastructure to distribute surface water flows which enter the Levels across their northern boundary (within the *northern feeders*).
- The evidence suggests that there is unlikely to be significant diffuse, vertical groundwater flow between surface layers and the underlying bedrock, either upwards or downwards.

## 12.2 Smaller- or field-scale ecohydrological conceptual model of the Gwent Levels

In order to develop a more detailed understanding of hydrological functioning at the field scale, under both traditionally-drained and under-drained scenarios, hydrological monitoring was installed at five sites. Ideally, runoff from fields would have been monitored directly, but it was decided that developing a method to carry this out reliably within the timescale of the project was not possible. Rather:

1. Dipwells (2 m deep) were installed to monitor soil water levels, and stilling wells were installed to monitor ditch water levels in the field-side ditches (Section 5). Water level measurements were taken and logged hourly using data-loggers. The maximum monitoring period was 16 months, but two sites were monitored for 12 months because of SARS-CoV-2-related delays in installation.
2. Combined surface water-groundwater models were constructed for the traditionally-drained and under-drained cases (Section 8), and the soil water and ditch water level data were used to confirm that they represented the real systems adequately. Time-series field runoff into adjacent ditches were then extracted from the models.

The field-scale ecohydrological conceptual models for traditionally-drained and under-drained cases are described in Section 7. Groundwater models representing a traditionally-drained field (based on the Great Newra monitoring site) and an under-drained field (based on the Cross Farm; Nash monitoring site) were developed (Section 8). The models were based on the conceptual models developed through analysis of the monitoring data, and were successfully able to simulate the monitored soil and ditch water level conditions. Analysis of the results of the models has yielded more detailed information about the likely hydrological functioning of the two field drainage types.

### 12.2.1 *General; ditch water levels*

- Evidence of ditch water level management could be seen at all sites, but the water level responses to raising (spring) or lowering (autumn) of sluices vary spatially. They are controlled by factors such as distance from a sluice or sluices, and availability of both autogenic water (from rainfall within the Levels) and allogenic water (via the northern feeders) within the ditch network.

- The relationship between recorded ditch water levels at the monitoring sites and the recorded levels of local sluices was inconsistent; the understanding of the hydrological functioning of the ditch network at a local level is often incomplete.
- During the warmer months, there are lengthy periods of relatively constant ditch water levels; this is the result of; 1) very little water discharging from the adjacent fields (see below), and 2) constant inflows of water (IDD management), with levels being controlled at the overflow level of local sluice(s) downstream.
- During the colder months, ditch water levels are much more responsive to rainfall events because of water discharging from the adjacent fields.

### 12.2.2 *General; soil water levels*

- Soil water levels exhibit very distinct colder and warmer month period behaviours, being:
    - High, and responsive to rainfall, during the colder month period. This is because the water table is close to the ground surface, so infiltrating rainfall reaches the soil water table almost immediately. There is very little water storage capacity in the soil, and therefore discharge off the fields, into the ditches, occurs in response to rainfall events.
    - Low, and mostly unresponsive to rainfall, during the warmer months. This is because the water table is at greater depth, and infiltrating rainfall can be stored above (in the unsaturated zone) before being lost to transpiration or direct evaporation. Soil water levels respond to large rainfall events when they overwhelm the storage capacity of the unsaturated zone. There is very little discharge off the fields, into the ditches, during the warmer months, irrespective of drainage type.
- Soil water levels often fall below the water level in the adjacent field-side ditch, but because of the poorly permeable deeper substrates (primarily silty clay), very little flow occurs in response to the reversed hydraulic gradient. This means that the sometimes-stated purpose of maintaining high ditch water levels, to provide water to support the water table in adjacent fields, is unlikely to be significantly fulfilled.

Traditionally-drained fields

- During the colder months:
    - The water table resides close to (generally within 0.3 m) the ground surface at all locations. It fluctuates at a relatively high frequency within a more permeable shallow (0 – c. 0.3-0.4 mbGL) zone, rising in response to rainfall, and then falling rapidly as the water flows laterally towards the lower elevation furrows.
    - Soil water level is often ‘controlled’ at or close to the ground surface by removal of water by flow across the ground surface, and furrows are often inundated.
    - The furrows host surface flow to the field-side ditches, in which low water levels are maintained. Water levels in field-side ditches rise transiently in response to rainfall-derived runoff.
- During the warmer months the water table is generally significantly below the ground surface, within poorly permeable substrate, and there is little or no lateral groundwater flow.

Under-drained fields

- Under-drains act as axes of very high permeability within a field; this is reflected by the fact that soil water levels along monitored under-drains tend to be at very similar elevations all along under-drains.
- The soil water level along (within) the under-drain is either:
    - At the same as the ditch water level, if this is above the invert level of the under-drain, or;

  - At the invert level of the under-drain, if this is higher than the ditch water level and the under-drain is discharging freely into the drain.

- During the colder months:
  - There is a significant difference between the soil water levels along the line of the under-drains, and the much higher levels across the wider field away from the under-drains. This steep, local hydraulic gradient is maintained by the low permeability of the lower substrate.
  - The soil water table away from the under-drains fluctuates at a relatively high frequency within a highly permeable shallow (0 – c. 0.45 mbGL) zone, rising in response to rainfall, and then falling rapidly as the water flows towards the under-drains.

- During the warmer months soil water levels often fall below the invert level of the under-drains, becoming hydraulically decoupled from them. During these periods soil water levels along the lines of the under-drains behave similar to those across the wider field.

- The effectiveness of under-drains is probably only sensitive to the water level which is maintained in the adjacent ditch when the latter is at or above the base of the highly permeable zone discussed above, since this would reduce or reverse the hydraulic gradient from the under-drains into the wider field, which means that rapid drainage of this zone would not occur. It is important to note the criterion for acceptable ditch water levels in terms of under-drain functionality should be a comparison ditch water level and the elevation of the base of the highly permeable zone (ground level minus c. 0.45 m), rather than whether the outfall of the under-drain is underwater.

## 12.3 Direct effects of under-drainage versus traditional drainage

### 12.3.1 *Ecohydrological effects on ditch plant and invertebrate SSSI interest features*

The primary physical variable through which hydrological supporting conditions for the ditch-hosted interest features are defined is ditch water depth; maintenance of a stable warmer month water level is critical as this is when plants are most actively growing, flowering and setting seed (Section 3.3.2).

Sensitivity of ditch water depth to the drainage arrangements on adjacent fields derives from the influence of the drainage arrangements on the amount of water which discharges to the ditches, from the fields, in response to rainfall. The Gwent Levels exhibit different warmer and colder month hydrological responses.

Warmer months (April to September inclusive)

- EVT exceeds rainfall over the medium term; there is a negative local water balance.
- Irrespective of field drainage type, this causes the water table to fall significantly, to below the elevation of the drainage features which would potentially host flows of water to field-side ditches.
- Hence, for both field drainage types, there is no significant discharge from the fields to the field-side ditches, with the large majority of rainfall being lost to EVT.

Since there is no discharge from the fields to the ditch, there is no sensitivity linkage between ditch water depth and field drainage type. Therefore, there is very unlikely to be any systematic difference in ditch water depth regime between traditionally-drained and under-drained fields.

The negative water balance during the warmer months applies over the whole of the Gwent Levels, and therefore it is considered highly unlikely that ditch water depth regimes will be sensitive to field drainage type anywhere within the Levels.

Colder months

- There is less concern about the sensitivity of ditch-hosted interest features to ditch water depth during these periods.
- Rainfall exceeds EVT over the medium term, and there is a positive local water balance.

- Irrespective of field drainage type, this causes the water table to rise to close to the ground surface, and to fluctuate within a shallow zone in response to rainfall and (primarily) drainage to the field-side ditches. The very dominant mechanism for drainage in traditionally-drained fields is surface runoff, whilst the more important mechanism in under-drained fields is through the under-drains.
- Whilst the water flows to the field-side ditches in different ways under the two types of drainage, the overall drainage yield (i.e. percentage of rainfall) from the fields is very similar.

There is very unlikely to be any systematic difference in ditch water depth regime between traditionally-drained and under-drained fields, but in this case it is because the drainage types, whilst exhibiting different drainage mechanisms, are functionally very similar in terms of the percentage of rainfall which falls onto the fields arrives in the field-side ditches.

In summary of the above, there is very unlikely to be any systematic difference between ditch water depth regime and field drainage type, during either the warmer or colder month periods. Therefore, the ecohydrological supporting conditions for ditch plant communities, as defined through the ditch water level regime, is very unlikely to be sensitive to field drainage type.

### 12.3.2 *Other direct impacts*

- Under-drainage is likely to reduce the extent of relict wet grassland communities of 'in-field' hollows and furrows that are dominated by grasses such as Creeping Bent *Agrostis stolonifera* and Marsh Foxtail *Alopecurus geniculatus* and associated with traditional drainage.
- Under-drainage also reduces, and potentially eliminates, standing water within (i.e. inundation of) furrows. Natural England and Countryside Council for Wales (2009) details supporting habitats for qualifying interest features of the Severn Estuary SPA, which extends along the entire southern boundary of the Gwent Levels. It lists freshwater coastal grazing marsh as a supporting habitat for; 1) the internationally important population of regularly occurring migratory bird species, and 2) the internationally important assemblage of waterfowl.

  It is possible that seasonally inundated furrows (e.g. Figure 1.6-1) are an element of favourable condition for the freshwater coastal grazing marshes in relation to the SPA bird populations. For example, Treweek *et al* (1997) notes that ephemeral water bodies provide suitable conditions for colonisation by invertebrate communities of high biomass, which can be an important food source for bird populations.

  Whilst the Gwent Levels do not fall within the designated area of the Severn Estuary SPA, they can be considered to be functionally-linked if they fulfil an important role in maintaining or restoring the population of qualifying species at favourable conservation status. Functionally-linked land must be considered as a part of the SPA for site management and impact assessment (Chapman and Tyldesley, 2016).
- Since the soil is annual aerated to a significant depth for a long period during the warmer months, it is thought unlikely that small differences in the distribution of soil water table depth during the colder months in under-drained fields, in comparison with traditionally-drained fields, will have any impact on the preservation of archaeological remains.
- In summer months there is a very significant amount of storage available within the soil profile across the levels. This makes it very resilient to potential flooding resulting from summer rainfall events. Sufficient storage may be present for up to the 1,000-year storm event.
- From a farming perspective, the benefits of underdrainage in relation to extending the period of vehicle access to fields during the colder months have not been clearly demonstrated through the water table monitoring during the project.
- In winter months this flood protection is not present as soil water levels are much closer to the surface.
- Neither flood-risk or drought-risk are significantly sensitive to field drainage type.

## 12.4 Possible indirect effects of under-drainage versus traditional drainage

- Concern has been raised that should under-drainage be installed more widely, there could be increasing pressure from farmers to lower ditch water levels to ensure its functionality.

  Soil water levels tend to be below the invert level of under-drains during the warmer months, and therefore they do not function. There is therefore no justification to request lowering of ditch water levels during these periods.

  During the colder months, the criterion for acceptable ditch water levels in terms of under-drain functionality should be a comparison between the ditch water level and the elevation of the base of the highly permeable zone (ground level minus c. 0.45 m), rather than whether the outfall of the under-drain is underwater. It is thought unlikely that ditch water levels would be less than 0.45 m below general field level extensively across the Levels, and therefore it is unlikely that there would be significant pressure to lower ditch water levels during the colder months, should under-drainage be implemented more widely.

- Any increase in stocking density as a result of the implementation of under-drainage could negatively affect field-side ditches by over-grazing of emergent vegetation as well as by increased non-point nutrient enrichment associated with livestock grazing.

- Replacing traditional surface drainage features with underdrainage will, with time, result in a more even field surface. Agricultural improvement of the sward by reseeding with a more agriculturally intensive grass mix could then be both a more favourable and likely successful option for land owners. It could be the catalyst for further agricultural intensification of the farmscape, with increased negative impacts on the important SSSI ditch features, including nutrient runoff.

- Any moves towards agricultural intensification in the context of widespread adoption of under-drainage could result in pressure to enlarge fields by filling-in of drainage ditches.

## 12.5 Project limitations and assessment of related uncertainties

The current project was relatively small in terms of its geographical coverage, its duration, and in terms of the time available to find and understand any significantly different designs (i.e.sub-types) of field drainage systems within the overarching traditionally-drained and under-drained categories. It is therefore important to assess whether the results are sufficiently representative of the Gwent Levels system as a whole, and over the longer-term, for them to be used to inform regulatory decision-making.

In order to assess the significance of the limitations, it is useful to consider:

1. The physical factors to which the results of the study are thought to be sensitive, e.g. the nature of the substrate, differences in drainage design.
2. The spatial and temporal ranges of variation of these physical factors across the Levels.
3. The degree to which the chosen monitoring sites are representative of the range of variation, and therefore how widely applicable are the results of the project.

The physical factors to which the results of the study are thought to be sensitive are considered below.

### 12.5.1 *The nature of the shallow substrate*

The results of the project could be sensitive to the nature of the shallow substrate, and specifically its permeability as a function primarily of its particle size distribution (i.e. clay, silt, etc). For example, if the substrate was more permeable the water table would be further below the surface during the colder months which would, in turn, change the temporal distribution of runoff to the ditches. It would also allow greater flow from the field-side ditches into the soil when hydraulic gradients are reversed during the warmer months.

Regarding the likely variation of the nature of the shallow substrate across the Levels, it is of note that practically the entire area is mapped as the same unit (Tidal Flat Deposits – Silt and Clay) by the BGS. Figure 2.3-4 (from Allen, 2001), whilst being schematic, also implies that there is very little lithological variation in the topmost 2-3 m of substrate within the Levels. From this information it is concluded that the nature of the shallow substrate within the Gwent Levels is relatively homogeneous.

The nature of the substrate at each of the five monitoring sites, in the form of a lithological log for one of the auger holes, is included in Sections 5.3-5.7 inclusive. Considering these logs, their degree of similarity is marked; at three of the sites silty clay was recorded to c. 1.5 mbGL, with clay below this down to 2.0 m. The log was very similar at a fourth site (Fair Orchard Farm), with silty clay recorded from 0.0-2.0 m. The log was very similar for the fifth site (Sluice House Farm), but a 0.3 m thickness of peat was recorded at 1.2-1.5 mbGL. On the whole, then, the natures of the shallow substrates at the five monitoring sites are consistent with the conclusion that the shallow substrate within the Gwent Levels is relatively homogeneous, and it is therefore concluded that the sites were adequately representative of the Gwent Levels as a whole in this regard.

### 12.5.2 *Variation within the traditionally-drained and under-drained categories*

The nature of traditional ridge-and-furrow drainage, as shown by the micro-topographic relief of fields, appears to vary somewhat across the Levels with, for example, variations in:

- The presence of absence of first-order furrows.
- The spacing of first- and second-order furrows
- The orthogonal arrangement of first- and second-order furrows.

These variations can be seen, for example, in the image on the front cover of this report.

These variations probably reflect an evolution of practice, both in terms of the effectiveness of drainage, and the labour and technological capabilities for earthworks. It is notable that the large majority of traditionally-drained fields have first-order drains spaced at 5-8 m, feeding into second-order drains spaced at c. 20 m. A smaller number of fields appear to have second-order drains only, spaced at c. 40 m.

The two traditionally-drained monitoring sites conform to the majority type, so are considered broadly representative of the Levels. It is also likely that the functional hydrological differences between the types are relatively small, and therefore that the sites were representative of the Gwent Levels as a whole.

It has not been possible to investigate in any detail whether the nature of under-drainage varies significantly across the Levels; under-drainage is implemented in a similar way at both of the under-drained monitoring sites. It is considered very unlikely that any significantly different implementations of under-drainage, e.g. with much deeper under-drains, or significantly different under-drain spacing, have significant representation within the Levels.

In general terms, the results of the study are sensitive to variations within the two main drainage categories as follows:

- Warmer months. It has been shown that the water table resides at depth within the soil profile during the warmer months for most of the time. This means that it is hydraulically disconnected from any drainage provision within the fields, and that little or no discharge occurs as a result of the water table intersecting the drainage features. Therefore, it can be concluded that the results of the project are not sensitive to any variations within the drainage categories which are not represented within the monitoring sites.
- Colder months. It has been shown that there is little difference in the proportion of rainfall which reaches the ditches between the two major drainage categories, but that the importance of routes by which the water can reach the ditches is different between the categories. It is considered extremely unlikely that these conclusions would be any different in the context of variations within the drainage categories which are not represented within the monitoring sites.

### 12.5.3 *Conclusion*

From the above, it is concluded that the results of the current project are sufficiently representative of the Gwent Levels system as a whole, and over the longer-term, for them to be used to inform regulatory decision-making.

# 13 Recommendations

As noted above, it is thought that the results of the current project are sufficiently representative of the Gwent Levels system as a whole, and over the longer-term, for them to be used to inform regulatory decision-making. Therefore, there are no recommendations for further work which are directly related to objectives of the current project.

Recommendations for further work relating to the wider hydrological management of the Gwent Levels are given below.

## 13.1 SSSI-related regulation

The primary conclusion of this project is that installation of under-drainage within the Gwent Levels would have no direct effect on the hydrological supporting conditions of the ditch SSSI interest features when compared with the case of traditionally-drained fields. However, there is a risk that widespread implementation of under-drainage would lead to a number of further changes, which could broadly be viewed under agricultural intensification. Section 11 details a number of possible negative ecohydrological effects associated with such intensification, including nutrient enrichment and loss of ditches.

It is therefore recommended that if under-drainage is permitted under SSSI-related regulation, it is tailored to identify and avoid the possible indirect negative ecohydrological impacts of more general agricultural intensification.

## 13.2 Formalisation, critical review and recording of NRW hydrological management of the Gwent Levels

It is noted in Section 2.5 that *management of the hydrology of the Levels is highly complex with, for example, the manipulation of networks of sluices to effect significant east-west movement of water during the warmer months, from zones of water surplus to zones of water deficit. Reactive management, for example to mitigate hazards during periods of acute water shortage or water surplus, also relies on a detailed understanding of the functioning of the system. During the current project it became apparent that the detailed management of the system is largely non-formalised, with relatively little being on record about how the system functions and related management decision criteria.*

The situation described above appears to leave NRW exposed to changes in, or temporary unavailability of, key staff, with the former being inevitable in the longer-term in relation to retirements. It is also possible that improvements to the hydrological management of the Levels are possible, through utilization of complementary knowledge and resources. It is therefore suggested that NRW gives urgent consideration to a programme to formalize, critically review and record the hydrological management practices within the Levels, with the ultimate aim of ensuring that effective management can continue in the longer-term. The following should be considered for inclusion in this project:

- Interviews and/or working time with key staff (e.g. John Southall) such that the management criteria, decision-structures and information sources can be understood. Higher-level management maps should be produced, which show the general directions of water from the northern feeders during the warmer months through the Levels, and how the directions might change in response to water shortage.
- Re-survey the network of sluices, including warmer month and colder month, levels.
- Locate and characterise flows in the northern feeders, such that an understanding of the sustainability of their flows through the warmer months can be developed.
- Consider the feasibility of using groundwater abstraction from the underlying bedrock as a source of water for systematically water-stressed zones within the Levels.
- Periodic review and development of the Water Level Management Plan (Pickup, 2011). This document should be contributed to by a wide variety of stakeholders to ensure buy-in and adoption of its operating plan for the Levels.

## 13.3 Further monitoring to confirm the hydrological effects of under-drainage during the colder months

As noted in Section 9.3, during the colder months there was some evidence in the monitoring data that the soil water table (away from underdrains) was slightly lower than that for traditionally-drained fields, but the difference was small, and because of the small number of monitoring sites it must be considered uncertain.

In order to develop a more refined and certain understanding of the effects of underdrainage on water table elevation during the colder months, and its effect on the length of the period when active farming of fields is possible, further instrumentation and monitoring would be required, including:

- Monitoring of a larger number of sites, both traditionally-drained and under-drained, and
- Monitoring for at least three colder month periods, such that any influence of varying weather is reduced.

## 13.4 Assessment of the impacts of climate change

Consideration of the possible effects of climate change was not a part of the current project. Significant changes in the climate of the UK are forecast (see UKCP[17]), including increases in temperature and changes in the temporal distribution and intensity of rainfall. The findings of the current project and, more widely, the hydrological management of the Levels, will almost certainly be sensitive to the forecast changes:

- The temporal distribution and rates of flows within the northern feeders, on which the hydrological management of the Levels during the warmer months and therefore the safeguarding of the SSSI interest features is wholly dependent, could be sensitive to climate change.
- The balance between rainfall and evapotranspiration through the year is likely to change, most probably with an increase in the length of the warmer month period of negative local water balance.

It is recommended that a scoping study on the implications of climate change for the hydrological management of the Gwent Levels is carried out as soon as possible.

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[17] https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

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