Somerset Levels and Moors: Assessment of the impact of water level management on flood risk

Report to Somerset Drainage Boards Consortium

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Executive Summary

The aim of this document is to provide the reader with a robust understanding of the processes that affect surface-water flooding in the area of the Somerset Levels and Moors. Particular attention is paid to the storage of water in the ditch network and adjacent soil body and a key output of this report is an assessment of the role of ditch management in the severity of flood events. The Somerset Levels and Moors consist of low-lying organic peat soils sitting on top of marine silts and clays, and form in effect an impermeable bowl. Rain falling on the surrounding catchments will either infiltrate and recharge the groundwater system or find its way to the network of channels that pass through the Levels and Moors before ultimately entering the Bristol Channel. The area is naturally susceptible to flooding.

Extensive drainage was carried out in the 17th and 18th centuries with the aim of making the land more accessible and increasing its agricultural value. The drainage network is principally managed to minimise the impact of flooding, enable agricultural production and also provide conditions required for the conservation of the natural and historic environment. In summer, water levels in the ditch network are generally maintained at 0.3 m below field surface for the purposes of land management, predominantly cattle grazing. In winter, water levels in the ditch network are generally maintained at 0.6 m below field surface whereas in the subset of channels that are managed in accordance with the raised water-level area (RWLA) scheme water levels are maintained level with the field surface. The aim of RWLA management is primarily to sustain wetland habitats and create conditions for over-wintering and breeding birds. It is acknowledged that water level management for both agriculture and wildlife results in a reduction in the storage capacity of the drainage network. The study area is divided into 10 water level management plan (WLMP) areas which cover 19,265 ha, or 35%, of the Parrett IDB and Axe Brue IDB districts.

Episodes of flooding occur when the total of the inputs from one or more of the driving mechanisms (precipitation, runoff, groundwater discharge, over-bank flow and lateral exchange in) exceeds the total of the outputs (evaporation, groundwater recharge, surface outflow and lateral exchange out) in excess of the storage capacity of the system. This report assesses the total ditch storage capacity, which consists of two components: the available volume in the surface water bodies and the available volume in the soil profile. Surface water body storage is calculated by multiplying the channel dimensions by the available storage depth before the channel is full. Soil profile storage is more difficult to establish but is quantified in this study by multiplying the distance of influence of ditch water level (Distance of influence: mean 9 m, range 5 m to 30 m) by the amount of pore space available for storage (Specific yield: mean 0.2, range 0.15 to 0.25). The numbers in brackets indicate the most likely values for each parameter established by a review of the relevant literature.

A numerical model was set up to estimate the volume of water stored under different water level management conditions. The theoretical maximum ditch storage volume was calculated by comparing the difference in volume between winter pen levels (without RWLA) and ground level. The volumes occupied by RWLA management in winter and agricultural pen levels in summer were also calculated and compared with the theoretical maximum ditch storage. For some areas it has been possible to calculate peak flood volumes and extents during winter 2014, as well as the volumes and extents for a less severe flood that reaches the level of the lowest road. These flood volumes and extents have been used to assess the flood impacts of ditch storage volumes occupied by RWLA management in winter and agricultural pen levels in summer.

The model results indicate that:

1. Raised water level area schemes cover 2529 ha, or 4.6% of the Parrett and Axe Brue Drainage Boards area.

2. The volume of water required to maintain raised water level areas in winter is equivalent to just 0.6% of maximum flood volume during winter 2013/14, or an increase in flood level of between 0.03 and 1.2 cm.

3. The volume of water required for agricultural water levels in summer is equivalent to 3.6% of the maximum flood volume during winter 2013/14, or an increase in flood level of between 2.1 and 6.2 cm.

4. For less severe flooding, where the flood level reaches the lowest road in an area, the volume of water required to maintain raised water level areas in winter is equivalent to 2.5% of the flood volume, or an increase in flood level of between 0.08 and 2.3 cm. In summer, this increases to 10.1% of the flood volume, or an increase in flood level of between 2.7 and 6.6 cm.

5. For moors that depend on pumping stations for drainage, the volume of water used to maintain raised water level areas in winter would take between 0.05 hours and 5.47 hours (average 3.5 hours) to evacuate using the permanent pumping station capacity. This increases to between 7.1 and 25.1 hours (average 15.2 hours) to pump the volume of water required for agricultural water levels in summer.

6. The maximum storage capacity of ditches and soils is equivalent to just 9.5% of the total rainfall that fell directly within the study area during December, January and February 2013-

In conclusion this assessment finds that in relation to the volumes of water that were present during the winter 2013/2014 floods, the volume of water occupied by the RWLA and subsequent reduction in ditch storage capacity represents a very small fraction of the total. Expressed both as a proportion of the theoretical maximum ditch storage and as a reduction in flood level, the calculations presented here indicate that the areas managed with raised water levels have only a very minor impact on large flood events. Water levels for agriculture in summer occupy larger volumes, but these are still small compared to volumes of water stored on the moors during major flood events.

Contents

1. The purpose and scope of this document

This document addresses some of the issues of flood water and its management on the Somerset Levels and Moors. Particular attention is paid to the storage of water in the ditch network and adjacent soil body, and how the management of water in the ditch network might affect storage volume. This document addresses the question ‘does raising water level in ditches in conservation areas reduce flood storage on the Somerset Levels and Moors?’ A key output of this report is an assessment of the role of ditch management in the severity of flood events and whether certain management approaches might either mitigate or exacerbate flood risk. A spreadsheet-based model was developed to quantify the ditch storage under different water level management conditions, and this is an additional output of this study.

There is an extensive body of literature on the hydrology of the Somerset Levels and Moors and this has been reviewed and summarised in this document. Great effort has been taken to present the information in an easily understandable manner so that the key messages are accessible to those without a particular background or interest in wetland hydrology. For those who wish to investigate further, a clear link between conclusions drawn and underlying text will be provided and relevant extracts from key texts will be included. A full reference list is also provided.

2. Background and introduction

The Somerset Levels and Moors sit in the bottom of what is in effect an impermeable bowl. The organic peat soils that cover much of the area sit on top of marine silts and clays that hydrologically isolate the peat from the underlying strata. The area receives surface and groundwater water from the surrounding uplands. Rain falling on the Mendip Hills to the north, the West Wiltshire Downs to the east, the Blackdown Hills to the south and Quantock Hills to the west will either infiltrate and recharge the groundwater system or find its way to the network of channels that pass through the Levels and Moors before ultimately entering the Bristol Channel (Figure 1). Areas of groundwater upwelling (e.g. springs) typically found along the base of hillslope ridges, also contribute water to the surface water system.

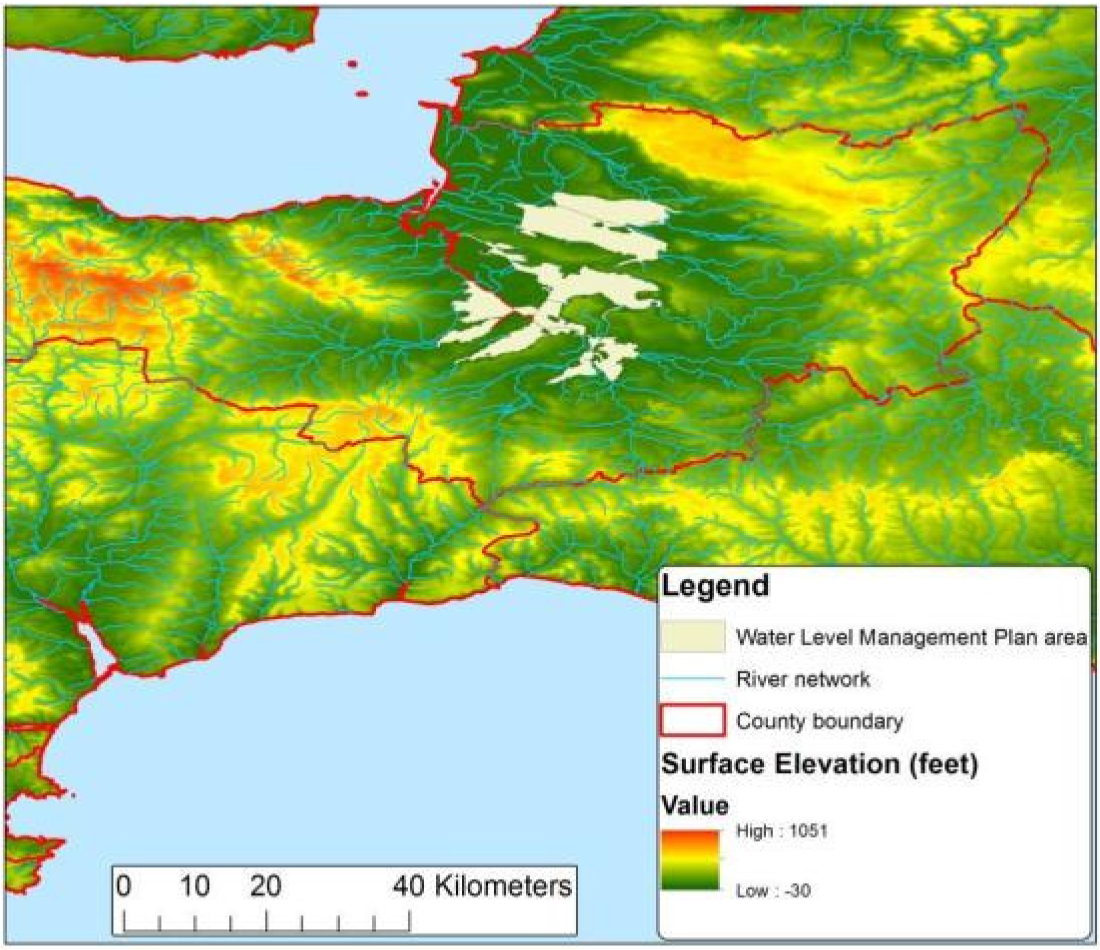


Figure 1. Overview map showing regional surface topography, rivers, county boundaries and the Water Level Management Plan (WLMP) area. The position of the WLMP area in a bowl surrounded by higher ground can be clearly seen.

The typical base flow index for rivers in this area is around 0.4 indicating that 60% of water in the river is derived from surface, or near surface flow processes whilst the remaining 40% is derived from groundwater. The movement of water to the sea by gravity is hindered due to the low-lying nature of the Levels and Moors, which in places are only 3 to 4 m above O.D. By comparison high tides can be up to 8 m above O.D. To overcome this there is a network of embanked rivers that act as high level carriers to convey water from high ground across the Levels and Moors to the sea. Pumping stations lift the water from the moors into the high level main river network.

2.1. The Drainage Network

During the 17th and 18th centuries, a dense network of ditches (also known locally as rhynes) was dug across the Levels and Moors, with the aim of making the land more accessible and increasing its agricultural value (Figure 2). The ditch network is still maintained, however the maintenance of water levels within the ditches varies across the area. In 1987, the Ministry of Fisheries and Food introduced the Environmentally Sensitive Area (ESA) scheme with the aim of safeguarding areas of the landscape. Under this scheme, land owners and managers can obtain subsidies to maintain high water levels that conserve peat soils and promote biodiversity. Tatem (1994) summarises the development of ESA water level management prescriptions:

'The ESA scheme was reviewed in 1991, the main change being the introduction of voluntary water level prescriptions to agreement types Tier 1 and Tier 2 and the addition of a Tier 3 and a water level supplement. The purpose of Tier 3 and the water level supplement is 'To further enhance the ecological interests of grassland by the creation of wet winter and spring conditions on the Moors.' This is to be achieved through land management measures combined with the following water level management prescriptions. From 1st May to 30 November water levels in the adjacent/peripheral ditches and rhynes must be maintained at not more than 300 mm below mean field level and from 1st December to 30th April at not less than mean field level so as to cause conditions of surface splashing.'

The network of watercourses is divided up into three categories; main river, viewed rhyne and ordinary watercourse. In this study, we focus on two areas: first where water level management plans (WLMP) have been produced and second a subset of raised water level areas (RWLA). The water level management of ditches within each is treated separately. The extent and locations are indicated in Table 1 and Figure 2. The categories are:

- WLMP (Ditches that fall within the Water Level Management Plan area). The WLMP area covers 19,265 ha in total and is the full extent of the area considered in this study. Sites of Special Scientific Interest (SSSI) and areas of Raised Water Level (RWLA) management sit within the WLMP area. There are 211 km of main rivers, 447 km of viewed rhyne and 1781 km of ditches in the WLMP area. In general, the management of water levels in these ditches typically follows a pattern of high summer levels, in order to provide 'wet fencing' for cattle, and low winter levels to provide flood storage capacity.

- RWLA (Ditches that fall within the Raised Water Level Areas). These cover an area of 2530 ha, equivalent to 13 % of the total WLMP area. The total lengths, and corresponding percentages of the total WLMP lengths, of water courses in this area are; 3.8 km (2%) of main rivers, 34.4 km (8%) of viewed rhyne, and 227 km (13%) of ditch. Water level management in these areas is well defined and follows the tiered system described previously and detailed in Table 2.

Table 1. Area and length of interest features. *(Data provided by Somerset Drainage Board).*

	Area (ha.)		Watercourse length in WLMP area (km)				Watercourse length in RWLA area (km)				
Name	**WLMP**	**RWLA**	**Main river**	**Viewed rhyne**	**Ordinary watercourse**	**Total**	**Main river**	**Viewed rhyne**	**Ordinary watercourse**	**Total**	**Percentage of total length of watercourse in WLMP that is RWLA (%)**
Allermoor	902	29	23.7	19.6	78.1	**121.4**	0.0	0.0	2.1	**2.1**	**1.7**
Brue Valley North	2926	196	38.9	70.6	287.2	**396.7**	0.0	4.6	15.2	**19.8**	**5.0**
Brue Valley South	4743	298	24.7	77.1	437.7	**539.5**	0.0	1.6	28.3	**29.9**	**5.5**
Curry Moor	773	19	21.0	22.0	64.7	**107.7**	0.0	0.0	0.7	**0.7**	**0.6**
Kings Sedgemoor	4499	588	50.3	104.2	420.9	**575.4**	0.0	7.7	51.4	**59.1**	**10.3**
North Moor	1613	125	7.1	45.9	181.8	**234.8**	0.0	2.2	15.2	**17.4**	**7.4**
Southlake	206	179	5.3	5.2	23.2	**33.7**	3.0	4.9	20.6	**28.5**	**84.6**
West Moor	541	148	9.2	13.7	45.2	**68.1**	0.0	1.4	10.8	**12.2**	**17.9**
West Sedgemoor	1576	577	6.0	47.5	159.6	**213.1**	0.0	2.5	48.8	**51.3**	**24.1**
Wet Moor	1487	371	24.4	41.1	82.2	**147.7**	0.8	9.5	33.4	**43.7**	**29.6**
Total all areas	**19265**	**2530**	**210.6**	**446.9**	**1780.6**	**2438.1**	**3.8**	**34.4**	**226.5**	**264.7**	

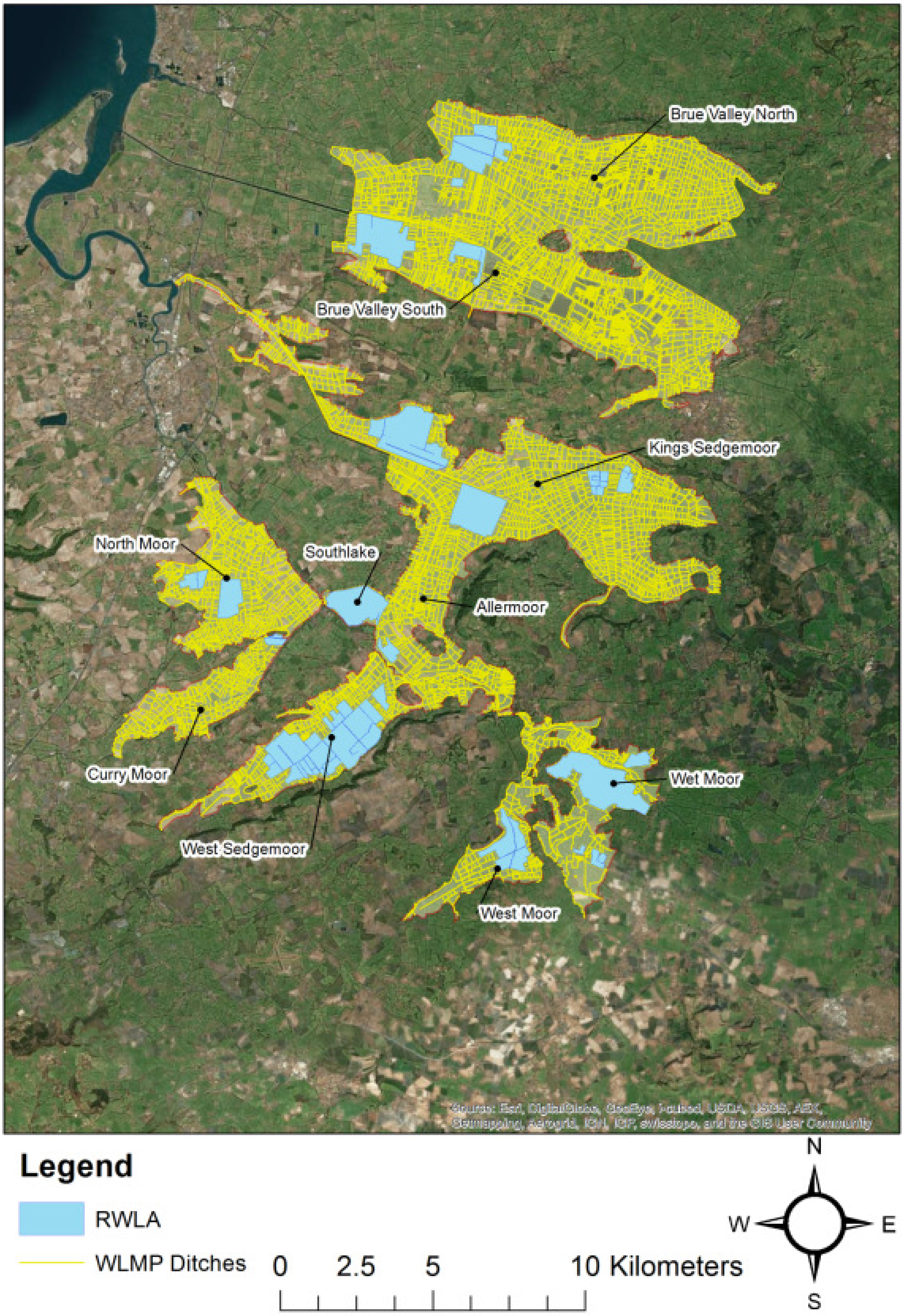
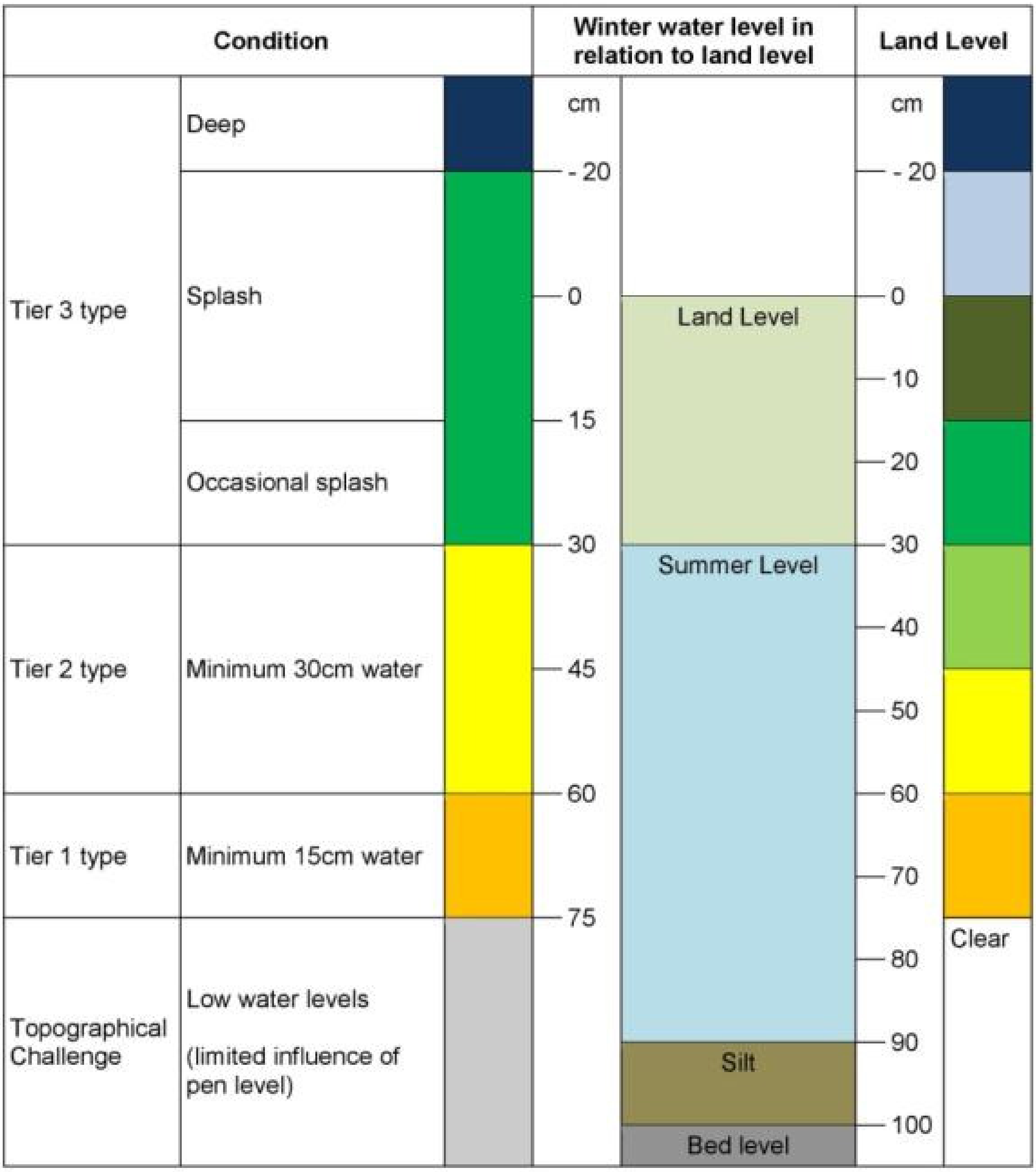


Figure 2. Aerial photo of the Somerset Levels and Moors showing the Water Level Management Plan (WLMP) areas. Also shown is the network of watercourses in the WLMP area and the watercourses managed as part of the Raised Water Level Areas (RWLA). (ii) © NextPerspectives

Table 2. Summary of criteria used to determine the water level regime required and extent of associated conditions required to achieve favourable condition for North Moor SSSI. *(Table provided by the Parrett Internal Drainage Board)*



3. Hydrological Conceptualisation

In order to understand the mechanisms that drive the quantity of water within the study area, a conceptual understanding of the hydrological processes is presented. This simplified representation is a robust starting point for any subsequent analysis. The main hydrological processes in the Somerset Levels and Moors are shown in figure 3, adapted from Acreman (2005). Note that this conceptualisation does not include the wider pumping network or the influence of sea level upon the ability to remove water from the study area.

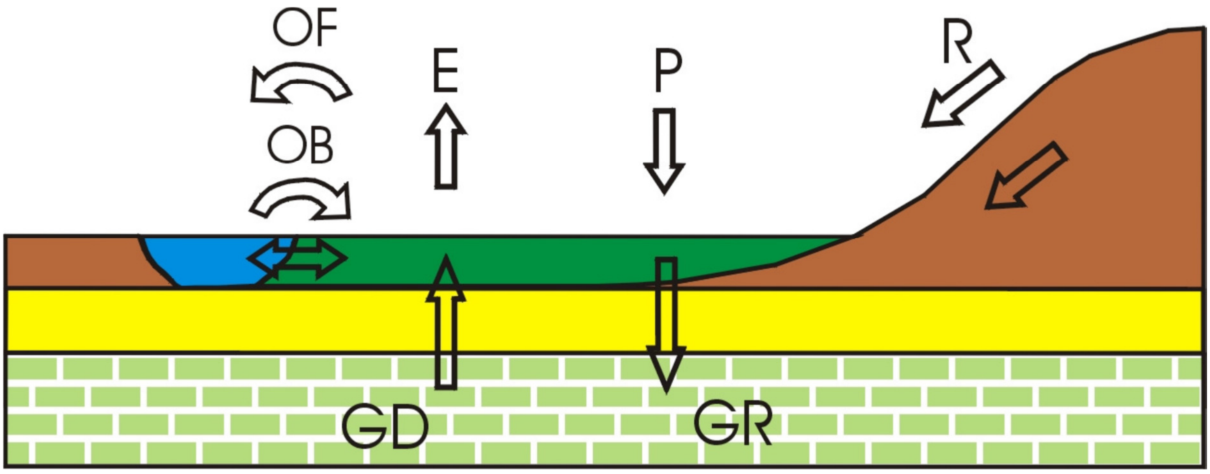


Figure 3. Valley bottom wetland Surface and groundwater-fed: Wetland (solid green shading) separated from underlying aquifer (green 'brick-style' shading) by lower permeability layer (yellow). Input from over-bank flow (OB) and groundwater discharge (GD), supplemented by runoff (R) and precipitation (P). Output by surface outflow (OF), evaporation (E) and groundwater recharge (GR). The surface water body (blue) facilitates lateral exchange of water to and from the wetland (indicated by the ↔ symbol) depending on the relative water levels within each. (Adapted from Acreman, 2005).

Episodes of flooding in this region will occur when the total of the inputs from one or more of the driving mechanisms (precipitation, runoff, groundwater discharge, over-bank flow and lateral exchange in) exceeds the total of the outputs (evaporation, groundwater recharge, surface outflow and lateral exchange out) in excess of the storage capacity of the system. The water balance equation for this system helps to illustrate the relationship between inputs, outputs and storage volume (Equation 1):

$$Equation\ 1: \quad P + R + GD + OB + Lat_{in} = E + GR + OF + Lat_{out} + \Delta Storage$$

Indicative values, where available, for each of the processes identified in the conceptualisation is presented in Table 3. Once the change in storage ($\Delta Storage$) exceeds the available storage capacity, then the excess water will contribute towards flooding. The available storage capacity is made up of water bodies (including rivers, drains, ditches, ponds, lakes etc), the soil body (whose capacity to store water is dealt with in detail in subsequent sections, and groundwater aquifers. The major aquifer in the region is the Carboniferous Limestone, however for much of the area this is confined under largely impermeable marine clays. It is therefore assumed that there is only minimal interaction between the surface and groundwater systems.

Table 3. Indicative hydrological information for the processes identified in the hydrological conceptualisation.

Hydrological process	**Average value**	**Comment**
Precipitation (P)	820 mm/yr *For reference, approximately 412 mm of rain fell on the study area in the period from 1st December 2013 to 28th February 2014.*	Catchment average rainfall. This doesn't show a strong seasonal trend.
Evaporation (E)	604 mm/yr *Summer monthly totals are typically in the order of 80 to 90 mm.* *Winter monthly totals are typically in the order of 15 to 20 mm.*	MORECS long term average potential evaporation. This shows a strong seasonal trend with higher values in summer.
Runoff (R)	Long term (1964 to 2013) average flow data for: *R. Sheppey @ Fenny Castle* Mean flow = 1.084 m^3/s Q_{10} = 2.231 m^3/s *R. Brue @ Lovington* Mean flow = 1.933 m^3/s Q_{10} = 4.917 m^3/s	Accurately quantifying the role of runoff in driving flooding in the study area requires a considerable amount of field data, and will most likely require development of a complex hydraulic model. These activities fall outside the scope of this piece of work.
Groundwater Discharge (GD) and Groundwater Recharge (GR)	Assumed negligible.	It is assumed that the considerable thickness of marine clay that underlies the peat soils inhibits most if not all exchange between groundwater and surface water.
Over-bank flow (OB) and surface outflow (OF)	Will be considerable as soon as the water level in the channel exceeds ground-surface level.	Difficult to measure directly, but can be estimated if the necessary water level data exist.
Lateral exchange	Depends upon the permeability of the soil body and ditch surface, and the difference in water level between the ditch and soil body (as described by Darcy's Law).	This is one of the main focuses of this report.

During the period from 1st December 2013 to 28th February 2014 inclusive, which will henceforth be referred to as winter 13/14, a considerable amount of rain fell in the study area. Analysis of the CEH GEAR (Gridded Estimates of Aerial Rainfall) dataset, suggests that the average rainfall over all WLMP units, was 412 mm during winter 13/14 which is equivalent to approximately 50% of the long term average for the area. Rainfall was not evenly distributed across the study area. Curry Moor received the highest rainfall (499 mm) and Brue Valley South received the lowest rainfall (382 mm) (Figure 4).

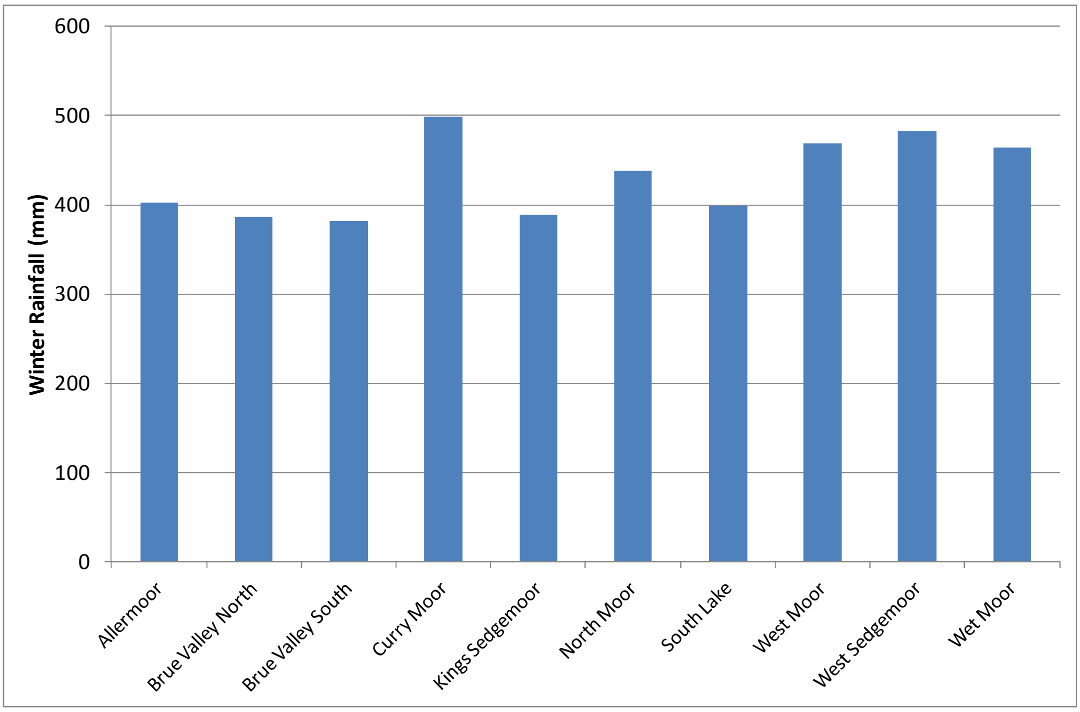


Figure 4. Winter 2013/2014 rainfall totals for each WLMP in the study area. Winter rainfall is the total of rain falling in December 2013, January 2014 and February 2014. These results are based on aerially averaged daily rainfall totals provided by the CEH GEAR (Gridded Estimates of Aerial Rainfall) dataset.

Having discounted the groundwater aquifer as a likely significant source of storage, the two components making up storage capacity are: the available volume in the surface water bodies and the available volume in the soil profile. These are introduced here and then dealt with in more detail subsequently.

Storage component 1: the available volume in the surface water bodies.

This will be quantified by measuring the length of surface water features, multiplying this by a standard width, and then multiplying this by the vertical distance from the open water surface to the adjacent land surface (i.e. when the water feature would be considered 'full').

Storage component 2: the available volume in the soil profile.

This will be determined by estimating the likely depth of unsaturated soil (i.e. from the soil surface to the water table) and multiplying this by a factor describing the active pore space (see next section), and then multiplying this by the likely width of soil that would receive water.

The storage and movement of water in peat soils has been, and still is, the subject of much research. Russian scientists began to adopt a two layered system, differentiating between above and below the water table, in the mid-Twentieth century in order to understand how peatlands function (Holden, 2005). This comprises an upper active 'acrotelm' peat layer with a high hydraulic conductivity and fluctuating water table and a more inert lower 'catotelm' layer, which corresponds to the permanently saturated main body of peat (e.g. Ivanov 1948). Ingram (1983) noted that the distinction between the acrotelm and catotelm is an important concept and fundamental to any understanding of the hydrology, ecology and pedology of peatlands (Holden, 2005).

A method similar to this was developed by Mould (2008) to compare hydrological storage capacity at Otmoor in Oxfordshire with Tadham Moor in the current study area. The method was as follows: A GIS was created for the catchment and populated with the necessary detail. Two scenarios were proposed. The first considered the area of Tier 3 water level management to accurately reflect the current situation, and the second simulated complete coverage of Tier 3 management across the catchment. The volume of ditch storage was presented in relation to typical flood event volumes, calculated using methods following those in the *Flood Estimation Handbook* (Robson and Reed, 1999).

The Mould study considered both within ditch storage and soil-body storage (Figure 5). For ditch storage, it was determined from CEH monitoring data that winter ditch water levels in the non-Tier 3 area were on average 0.57 m below the soil surface whilst within the Tier 3 areas the winter ditch water levels were at the soil surface. 0.57 m was therefore taken as the lost depth of storage in the raised water level areas. Ditch widths were assumed to be a standard 3 m. For soil storage, a specific yield of 0.2 was applied and it was assumed that ditch level only influenced the water level in the 10 m width of soil on either side of the ditch.

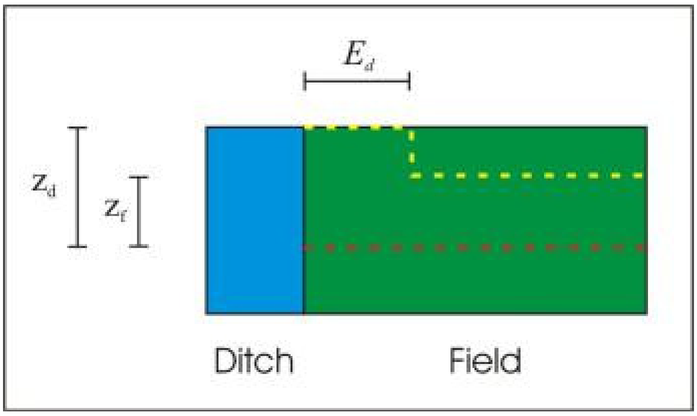


Figure 5. Components of ditch storage calculations; yellow dashed line shows Tier 3 water levels, red dashed line shows normal conditions. *From Mould, 2008.*

where

E_d	=	distance of lateral protrusion into field of ditch water level (m)
z_d	=	change in ditch water level storage of T3 (m)
z_f	=	change in field water level storage of T3 (m)

Total changes in storage were compared with the volume of the median annual maximum flood (V_{med}) which was derived using flow records from 1993 to 2000 and the peaks over threshold model of the Flood Estimation Handbook (Robson and Reed, 1999). This method gave a value for V_{med} of 4.3 Mm^3. The results of the calculations are shown in Table 4. This study concluded that under the current situation, the impact of the raised water level area was equivalent to 1.8% of V_{med}.

Table 4. Calculated water volumes in the North Drain catchment. From Acreman *et al.*, 2006.

Scenario	Soil storage (m^3)	Ditch storage (m^3)	North Drain (m^3)	Evaporation (m^3)	Total (m^3)	% V_{med}
Current T3	59,232	18,722	N/A	224,825	77,954	1.8
Complete T3	3,015,619	527,743	40,169	224,825	3,808,356	83.8

4. Storage component 1: the available volume in the surface water bodies

The method adopted here is to use GIS data to quantify the area of surface water features. As shown in table 1, these fall in to one of three categories: Main river, Viewed Rhyne and Ordinary watercourse. For each category, the total length of each has been calculated and where quantifiable differences in water level management exist (i.e. those areas subject to Tier 3 management and those not), the total length under each management regime is calculated. The widths of each of main river, viewed rhyne and ordinary watercourse has been established through field investigation in 2014, and this is applied to the corresponding lengths in order to calculate the area of each surface water feature type. The results of the watercourse width field survey are shown in table 5.

Table 5. Summary of watercourse widths established by field survey.

Site	Watercourse type	Average width (m)	Sample size
Tealham and Tadham Moor	Ordinary watercourse	2.9	52
	Viewed rhyne	3.1	44
	Main river	11	6
North Moor	Ordinary watercourse	2.8	36
	Viewed rhyne	3.5	18
	Main river	5.6	6

For the purposes of a generalised model, it was felt that 3.0 m widths for ordinary watercourses, 3.5 m widths for viewed rhynes, and 6 m widths for main rivers were reasonable estimates (Brewin, *pers. comm.)*.

The available depth of water storage varies between WLMP area and RWLA. The RWLAs follow the Tier 3 water level management prescriptions with a summer pen of not more than 0.3 m and a winter pen of 0 m. The WLMP non-Tier 3 management areas have winter pen levels on average 0.6 m below the soil surface, and summer pen levels of 0.3 m below the soil surface**.** It is acknowledged that these levels will vary between sites, but they represent a reliable average for the study area. The numbers are summarised below in table 6.

Table 6. Summary of surface water feature types and corresponding winter and summer water levels.

	Water level relative to soil surface	
	Summer	**Winter**
WLMP area	-0.3 m	-0.6 m
RWLA	-0.3 m	0 m

5. Storage component 2: the available volume in the soil profile

The organic soils that are exposed at the surface in much of this area are capable of holding large quantities of water. Holden (2005) notes that saturated peat tends to be 90–98% water by mass. Even above the water table (maximum height of the saturated zone), peat can still hold large volumes of water (approximately 90–95% water by mass).

There are two key elements to quantifying the amount of water that can be stored and these are:

1. The storage of water in the soil body. This is amount of pore space in the soil body that readily receives and releases water as water level conditions change and
2. The movement of water into, through and out of the soil body. This deals with the rate at which water moves.

Together these elements will adequately describe the total potential storage within the soil and the time taken for the full storage potential to be achieved. Each of these is dealt with below.

5.1. The storage of water in the soil body

In describing the volume of water that can be stored in a body of soil, it is important to first define some commonly used terms. These are described and illustrated below.

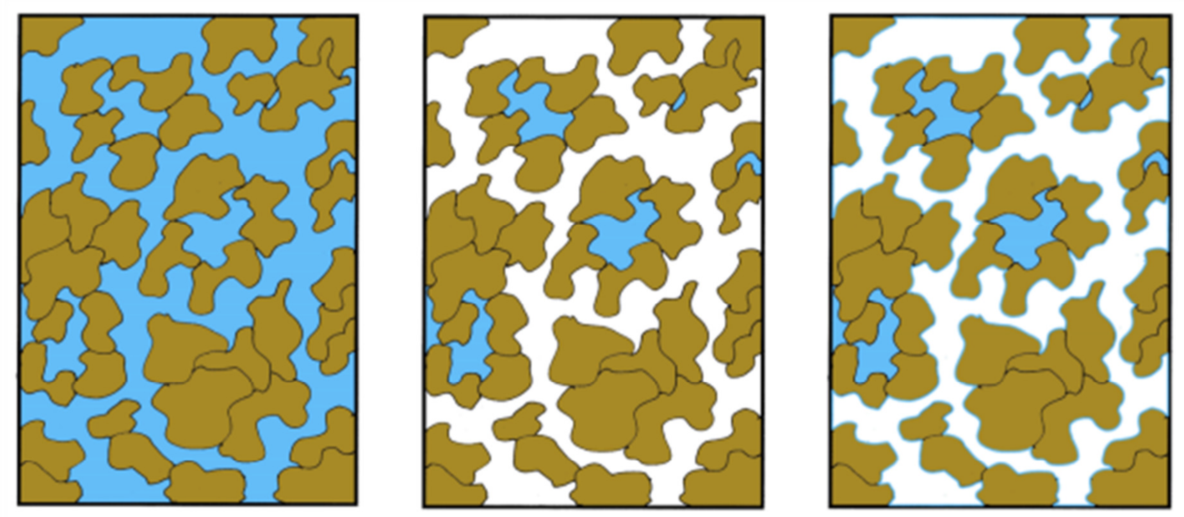


Figure 6 Illustration of total porosity (left), effective porosity (middle) and drainable porosity (right). Light brown shading indicates soil particles, light blue shading is water, and white is empty pore space.

Total porosity. This is a measure of the amount of open space in the soil and is typically given as a percentage calculated by dividing the volume of pores in the sample by the total volume of the sample (Hillel, 1998). The *Porosity* tells us nothing about how well connected those pores are and it is possible to have a substance with high porosity but which if submerged will only accommodate a small volume of water. They may also have a relatively low permeability (e.g. pumice).

Effective Porosity. This describes the amount of interconnected pore space and is defined as the porosity available for fluid flow (Fetter, 1994).

Drainable Porosity (generally used interchangeably with the term Specific Yield). This is the ratio of the volume of water that drains from a saturated rock or soil owing to the attraction of gravity to the total volume of the rock (Meinzer, 1923). This value is generally less than or equal to the *effective porosity*. It is described by Beavan *et al.* (2008); 'If a fully saturated waste material is allowed to drain under gravity, its water content will decrease as drainable pores empty. It will eventually reach a state (termed the field capacity) when no further drainage occurs. The amount of freely draining water per unit volume of waste defines the drainable porosity. The drainable porosity is given by the difference between the saturated volumetric water content and the volumetric field capacity. The drainable porosity is the same as the specific yield, which is well established in the hydrogeology literature as the amount of liquid that will drain from a unit volume of soil following a unit reduction in the water table level.

In order to determine the volume of water that would be stored in a body of soil, drainable porosity is the most relevant property to measure. With the question established as 'how much water can be stored in the soil body', the answer is 'the depth of soil above the water table multiplied by the drainable porosity'. This will give a value as depth of water per unit area that can then be applied to areas where depth of soil above the water table is known.

To illustrate; if a soil body has a water table at 1 m below the surface (i.e. 1 m thickness of unsaturated soil sitting above the water table), and a drainable porosity of 0.1, it will be able to accommodate a total of 0.1 m of water before the water table is at the surface. To put the same example in terms of area, a field of dimensions 10 m by 10 m with a water table 1 m below the surface, will have 100 m^3 of unsaturated soil sitting above the water table. If the drainable porosity is 0.1, it will be able to store 10 m^3 of water before being saturated and the water table reaches the surface.

5.2. The impacts of drainage on the water storage capacity of peat soils

The drainable porosity of peat depends on the extent of humification and compaction. Compared with the fresh, undecomposed peats found near the surface of acid mires where the specific yield is typically above 50%, fen peats derived from reed and sedge remains, and humified peats from deep in acid mires, have higher bulk densities (based on saturated volume) and their porosity, though still very high, consists of small pores which do not drain readily (Boelter, 1964), resulting in specific yields between 10% and 20% (Gilman, 1994). Drainage and land management practice are among the factors that influence drainable porosity in peat soils. Whilst short to medium term lowering of the water table will provide increased water storage, the long-term drying of peatlands is liable to result in subsidence and peat decomposition (Holden *et al.*, 2004). Shrinkage, although partly reversible, can severely alter the soil hydraulic properties including water retention, hydraulic conductivity and specific yield (Price and Schlotzhauer, 1999; Kellner and Halldin, 2002; Kennedy and Price, 2005). The subsidence is also associated with the collapse of readily drainable macropores (Silins and Rothwell, 1998)

After drainage, there is a decrease in macropore space and increase in micropore space which results in a lower permeability (Egglesmann, 1972). The duration and intensity of drainage have an important influence on permeability with an initial rapid decrease over the first 3 to 5 years, gradually becoming asymptotic to minimum value after approximately 10 to 20 years (Egglesmann, 1972). The effect on the water balance of peat subsidence will be to release water: lowering the soil surface by 10 cm liberates 100 mm of water, which is either evaporated or drained (van der Molen, 1975). This irreversible change in moisture storage should be included in accurate determinations of the water balance of such areas.

Kechavarzi *et al.* (2010) notes that bio-oxidation of soil organic matter leads to irreversible changes in soil physical characteristics including soil structure as evidenced through variations in the hydraulic properties of peat soils at different stages of degradation. In order to understand the influence of anthropogenic activities, such as water table management, on the mineralisation process of peat soils knowledge of the influence of shrinkage and long-term changes in peat physical properties on the hydraulic relationships is required (Weiss et al., 1998). However Kechavarzi *et al*. (2010) also notes that the influence of long-term changes in peat soils physical characteristics on hydraulic functions is poorly understood and, as a result, generally discounted in modelling peat soil hydrology (Letts et al., 2000; Kellner and Halldin, 2002).

5.3. Determination of drainable porosity

An approximation of specific yield can be achieved by measuring the water table response to rainfall events. Such measurements were taken at West Sedgemoor in late September and early October of 1990 using the Institute of Hydrology lysimeter. The results are shown in figure 7, and analysis of these results suggests a specific yield of 25 %, which is consistent with estimates by other means (Gilman, 1994). Also noted during this experiment was the virtually instantaneous rise in the water level following rainfall and subsequently the very rapid fall in the water level in the hours following the peak. The water level took several days to stabilise. Having ruled out surface or sub-surface runoff as the maximum water table was 0.1 m below the ground surface, and evaporation as the cause of the water table decline, it is believed that the cause of this sharp rise and fall is the entrapment of air by rapidly infiltrating water. This may have relevance when calculating how the storage capacity might change with time.

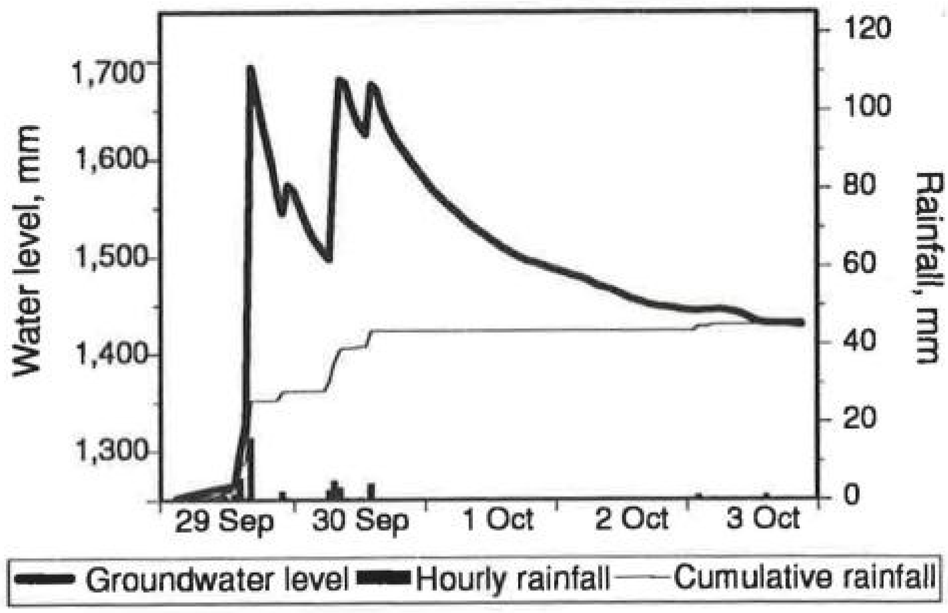


Figure 7. Hourly measurements of water table elevation at the West Sedgemoor lysimeter site. *From Gilman, 1994.*

Kechavarzi *et al.,* (2010) carried out extensive analysis of the physical characteristics of the peat at West Sedgemoor (WSM). The measured physical characteristics are presented in Table 7. At WSM, the peat is capped with an organic mineral soil layer with a thickness ranging from 0.06 to 0.15 m classified as peaty loam (Burton and Hodgson, 1987). The results from this layer are unlikely to be typical of the wider peat soils and although included in the table, are therefore not included in further analysis. The underlying peat horizon is humified and can reach a maximum depth of 1 m. Below this horizon, the peat is less decomposed, being classified as semi-fibrous peat (Kechavarzi *et al.,* 2010). The results here concur with the findings of Schwärzel et al (2002) that progressive decomposition of peat soils results in lower porosity and SOM and higher bulk density.

Dawson (2006) also carried out analysis of samples from West Sedgemoor and his results are also included in table 7. Note that although these are results from two separate tables and the only common identifiers between the sample sets are the study area and soil type. It is possible that the analysis values do not relate to exactly the same sample, even though they do appear to be from the same site. The specific yield of peat was determined at -1.0 m pressure potential as recommended by Boelter (1968). At -1.0 m pressure potential Dawson (2006) found the specific yield of all peats under investigation to average 0.2 $cm^3\ cm^{-3}$; with a mean of 0.18 $cm^3\ cm^{-3}$ for West Sedgemoor peats and 0.22 $cm^3\ cm^{-3}$ for Methwold Fen peats. These values are comparable with those reported by a number of authors (Boelter 1968, Letts *et al.* 2000, Murtedza *et al.* 2002 and Parkin *et al.* 2004) for the specific yield of a range of peat soils.

Table 7. Physical characteristics of soil profiles sampled. From Kechavarzi *et al.,* 2010).

Data Source		1	1	1	1	1	1	1	1	1	1	1	2
Study area	Soil type	Sampling depth (cm)	von Post ranking	% SOM content ($g\ g^{-1}$)	SOM content ($g\ cm^{-3}$)	Ash content ($g\ cm^{-3}$)	% Organic carbon content ($g\ g^{-1}$)	Dry bulk density ($g\ cm^{-3}$)	Particle density ($g\ cm^{-3}$)	Porosity ($cm^3\ cm^{-3}$)	Horizontal saturated hydraulic conductivity ($m\ d^{-1}$)	Vertical Saturated hydraulic conductivity ($m\ d^{-1}$)	Specific Yield ($cm^3\ cm^{-3}$)
WSM	Peaty loam	0–15	–	39	17.1	26.8	18.3	0.44	1.57	0.72	1.51	0.24	0.13
WSM	Humified peat	35–50	H8	60.1	10.2	5.9	37.7	0.17	1.33	0.87	1.55	0.14	0.16
WSM	Semi-fibrous peat	85–100	H6	69.3	6.2	2.5	41.7	0.09	1.24	0.92	2.3	1.1	0.24

Armstrong (1993) reported specific yield values of 0.05 for the Somerset Levels and Moors from an analysis of water level fluctuations. Values in the range 0.18 to 0.22 have been obtained for herbaceous peat using the same method in other locations (Bradley and Brown, 1995). Armstrong and Rose (1999) carried out water level modelling at Southlake Moor and used a value of 0.15 for the porosity (understood to be drainable porosity in this case) of the peat and a hydraulic conductivity of 1 m/d. Like Dawson (2006) and Kechavarzi (2010), Armstrong and Rose (1999) note a two layer system with a permeable peaty subsoil overlain in places by a less permeable peaty silty topsoil. The soil parameters used for this top layer were porosity of 0.12 and hydraulic conductivity of 0.08 m/d. A trial application of a MODFLOW groundwater model to Tadham Moor found a reasonable calibration was achieved using a specific yield of 0.2 and hydraulic conductivity of 2 m/d (Bradford, 2004). Bradford (2004) also noted that ‘In general, specific yield values as high as 0.2 to 0.3 are generally considered typical, although there is a lack of information relating to peat deposits’.

Various measurements of the specific yield of peat have been made in other studies and these are summarised below in table 8.

Table 8. Summary of other studies reporting peat porosity and/or specific yield.

Reference	**Country**	**Sample Description**	**Sample Depth**	**Porosity**	**Specific Yield**
Price *et al.*, 2003.	The Netherlands	Young living *Sphagnum*	0 – 15 cm	-	0.23 to 0.34
Price *et al.*, 2003.	The Netherlands	Slightly humified *Sphagnum*	10 – 30 cm		0.11 to 0.17
Price *et al.*, 2003.	The Netherlands	Moderately humified *Sphagnum*	0 to 40 cm		0.11 to 0.13
Price *et al.*, 2003.	The Netherlands	Strongly humified *Sphagnum*	0 to 35 cm		0.14 to 0.33[a] 0.05 to 0.10[b]
Carter and Price, 2014	Canada	Restored site	0 to 12.5 cm	0.97 ± 0.01	
Carter and Price, 2014	Canada	Natural site	0 to 12.5 cm	0.94 ± 0.02	
Carter and Price, 2014	Canada	Restored site	27.5 cm	0.91	
Carter and Price, 2014	Canada	Natural site	27.5 cm	0.82	
Carter and Price, 2014	Canada	Unrestored site	No trend with depth	0.83 ± 0.05	
Letts *et al.*, 2000.	Canada	Fibric peat	-	-	0.66
Letts *et al.*, 2000.	Canada	Hemic peat	-	-	0.26
Letts *et al.*, 2000.	Canada	Sapric peat	-	-	0.13

6. Water storage in the soil body: the values to use in this study

This review of literature values forms the basis of the estimate of specific yield to be used in this study. There is spatial heterogeneity in both soil properties and soil profile and it is unlikely that sufficiently detailed spatial information exists to be able to account for this. The proposed solution is therefore to calculate a mean value and also a likely range of values. Table 9 shows the summary of values relating to the study area.

Table 9. Summary of specific yield values relevant to the study area.

Reference	Study type	Study area	Depth (m)	Soil Type	Specific Yield
Gilman, 1994.	Lysimeter	West Sedgemoor	Approx. > 0.1		0.25
Dawson, 2006.	Lab sample	West Sedgemoor	0 to 0.15	Peaty loam	0.13
Dawson, 2006.	Lab sample	West Sedgemoor	0.35 to 0.50	Humified peat	0.16
Dawson, 2006.	Lab sample	West Sedgemoor	0.85 to 1.0	Semi-fibrous peat	0.24
Armstrong, 1993.	Water table analysis	SLMs	Single value	Single value	0.05
Armstrong and Rose, 1999.	Water table analysis	Southlake Moor	0 to 0.4	Clay topsoil	0.12
Armstrong and Rose, 1999.	Water table analysis	Southlake Moor	0.4 to > 2.0	Subsoil peat	0.15
Bradford	Groundwater modelling	Tadham Moor			0.2
			Top soil – mean		**0.125**
			Top soil – likely range		**0.12 to 0.13**
			Subsoil peat – mean		**0.2**
			Subsoil peat – likely range		**0.15 to 0.25**
Notes. The value of 0.05 from Armstrong (1993) is unusually small and is not included in the calculations of mean and likely range shown above.					

7. The movement of water into and out of the soil body

Understanding and ultimately quantifying the movement of water between a water body and adjacent soil body is central to this study. The flow of groundwater through the saturated zone is governed by the hydraulic gradient and the permeability of the soil, the measurement of the permeability of peat soils has been found to be very difficult (Gilman, 1994). Other soil properties such as the degree of humification as expressed on the Von Post scale, are sometimes used as a surrogate for direct measurement of soil permeability (Belding *et al.,* 1975)

A useful initial step is to observe the water table profile, from the open water in a ditch and across the soil body. The water table profile reflects not only the water table in the ditch, but also the balance between rainfall and evaporation. Whilst evaporation shows a strong seasonal trend, with higher values in summer, there is not a clear seasonal trend in the precipitation dataset. When rainfall exceeds evaporation, the water table typically has a convex shape and water drains from the soil into the adjacent ditches. The reverse occurs when evaporation exceeds rainfall and water moves from the ditches into the soil.

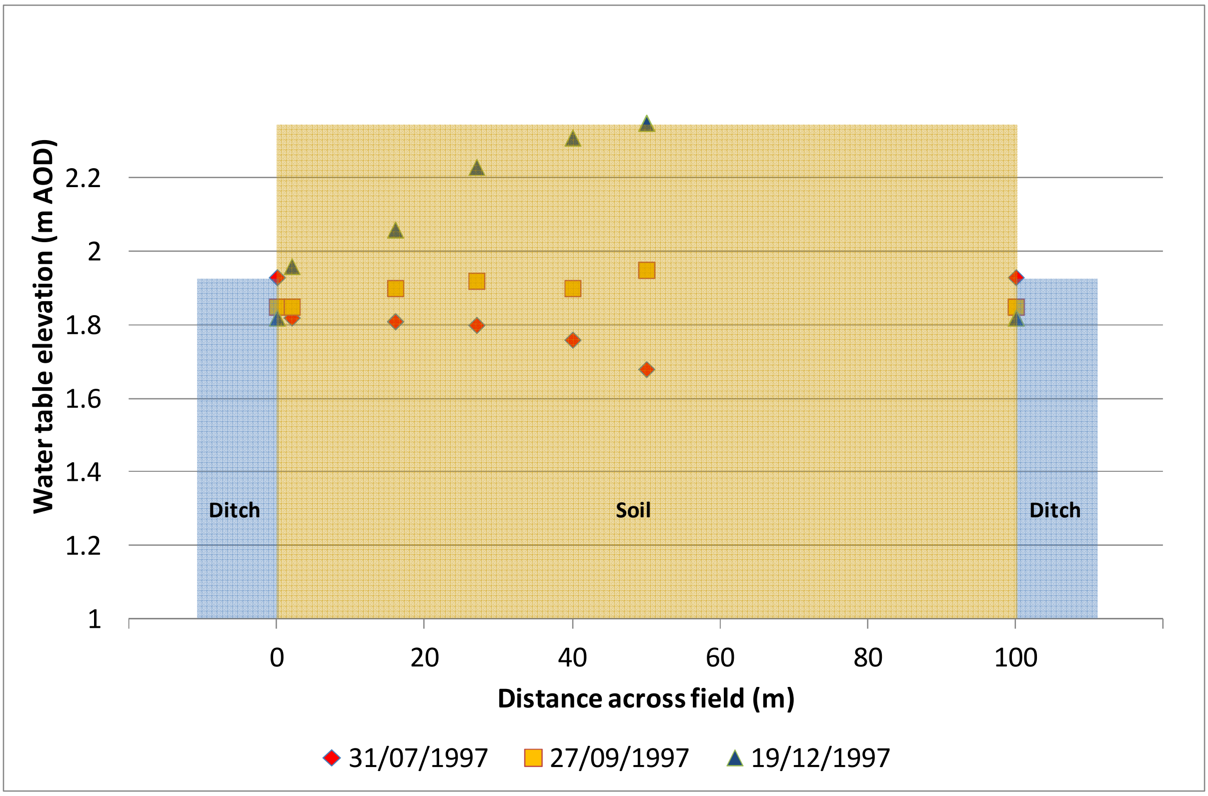


Figure 8. Cross section from ditch, through the soil body, to ditch showing the elevation of the water table at Tadham Moor. The figure shows a cross-section through a field, with ditches on either side at 0 m and 100 m across the field. The x axis is the horizontal distance across the field and the y axis is the elevation measured against a local datum. For reference the soil surface is at approximately 2.3 m. Measurements of the water table in the soil were made at the following distances across the field; 1 m, 16 m, 25 m, 40 m and 50 m. Three time periods are shown and the changing shape of the water table can be clearly seen.

Figure 8 shows water level data collected from Tadham Moor in July, September and December of 1997. The changing shape of the water table can be clearly seen. In July, the water level in the ditch is at 1.93 m whilst in the centre of the field the water table is at 1.67 m. Through September and on to December, decreasing evaporation drives a change in amount of rainfall that recharges the water table so whilst the level in the ditch decreases from 1.87 m in September to 1.82 m in December, the water level in the centre of the field increases from 1.96 m to 2.35 m. It is important to note the limited influence of the difference in ditch water level. Most notable in July and December, there is an abrupt change in water level between the ditch and the monitoring point at 1 m from the ditch in both cases of the order of 10 cm in 1 m (a gradient 10%). By comparison, the gradient across the field as a whole is 0.8% in winter and 0.3% in summer. The significance of this abrupt change at the ditch/field interface is that it suggests that there is only weak hydraulic connectivity between the two. If the hydraulic connectivity was higher, and the movement of water between the two was more rapid, then it would be unlikely that such a difference in water levels could be sustained.

The range of values of permeability of peats is very large and there is generally no consistent difference between the permeabilities in the horizontal and vertical directions. Boelter (1965) found values from 0.0065 m d^{-1} for moderately decomposed fen peat to 33 m d^{-1} for undecomposed mosses. Very large permeabilities, sometimes too large to measure, can be found in the upper horizons of mires where undecomposed material contains large voids. Hence at some sites, much of the lateral groundwater flow occurs in these upper horizons (Gilman, 1994). Dawson (2006), carried out numerical simulations of water table observations from West Sedgemoor. A good fit between observed and modelled data was achieved using a saturated hydraulic conductivity value of 1.77 m/d. Bradford (2004) constructed a numerical groundwater flow model of fields at Tadham moor and found that the best fit between observed and modelled data was achieved using a hydraulic conductivity value of 2 m d^{-1}. Similar modelling was reported by Acreman *et al*. (2004) and the results for one dipwell at Tadham Moor are shown in Figure 9.

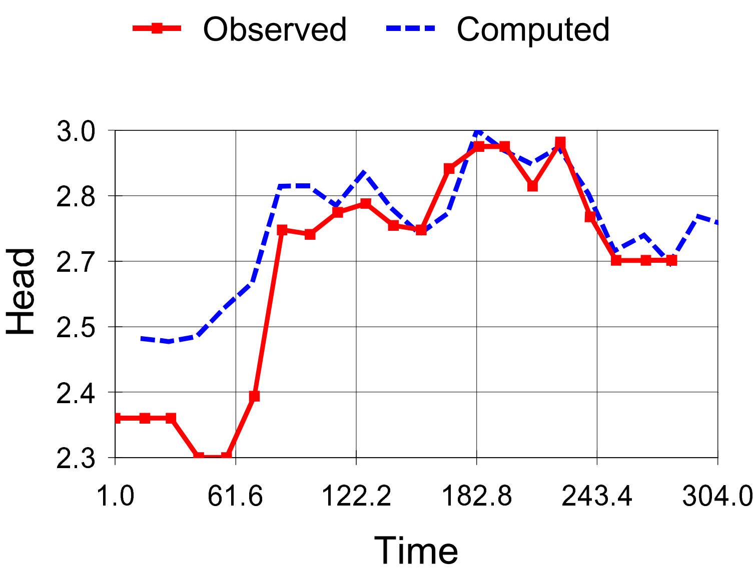


Figure 9. Output from application of MODFLOW to Tadham Moor. Graph shows dipwell 4 - observed and modelled results.

Despite the high variability of hydraulic conductivity of peat soils, Armstrong *et al.* (1993) propose a value of 0.96 m/day as representative of a typical value for peat soils in the UK. By contrast, a value of 0.024 m/day is proposed for alluvial clay soils. Kechavarzi *et al.,* (2010) analysed samples from West Sedgemoor and found horizontal saturated hydraulic conductivity to range from 1.51 m d^{-1} to 2.3 m d^{-1} depending upon soil type (Table 5). Vertical hydraulic conductivity ranged from 0.14 m d^{-1} to 1.1 m d^{-1}. Dawson (2006) measured the field derived saturated hydraulic conductivity of peats at West Sedgemoor and found the mean to be 0.8 m d^{-1}. Of 16 samples, the minimum was 0.28 m d^{-1} and maximum was 3.57 m d^{-1}.

Clymo (2004) found that the hydraulic conductivity of peat at Ellergower Moss varied non-linearly from 1 x 10^{-5} cm s^{-1} at a depth of 10 cm below the surface, to 0.1 x 10^{-5} cm s^{-1} at a depth of 600 cm below the surface. Letts et al., (2000) carried out a literature review for the Canadian Land Surface Scheme (CLASS) and found that saturated hydraulic conductivity varies from a median of 1.0×10^{-7} m s^{-1} in deeply humified sapric peat to 2.8×10^{-4} m s^{-1} in relatively undecomposed fibric peat.

The wide range of permeabilities has a direct influence on the extent of influence of surface drains. Boelter (1972) found that the flow of groundwater towards a drain was highly dependent on the nature of the peat and on the layer structure of the peat. Once the water table was drawn down into moderately well¬humified (hemic or mesic) peat, the low permeability meant that the zone of influence of the ditch did not extend beyond 5 m. In less humified (fibric) peat, the hydraulic gradient towards the drain extended 50 m. Similar conclusions were reached by Burke (1961), who investigated the effects of drains on blanket peat in Glenamoy, western Ireland. In this gelatinous low permeability peat, regardless of drain spacing, the fall in groundwater level brought about by the drains was confined to a strip about 6 feet wide.

Acreman *et al.,* (2002) carried out analysis of water table data from Tadham Moor and concluded that dipwells up to 8 m from the ditch are influenced by the presence of the ditch, but at locations further away ditch water levels have no impact on water table elevation. Hence in winter the water table is highest towards the middle of the field and lowest at the edges because of drainage to the ditch. In summer there is a gradual transition to higher water table at the field edge (i.e. close to the drain) and slightly lower water table in the middle of the field. At this time the ditches act as a source of water maintaining near edge water-levels. The water table response of fields is largely governed by rainfall and evaporation.

Gilman (1994) monitored and modelled water table fluctuations at West Sedgemoor and found that in May 1987, although rhyne levels were maintained high, there was a tendency for the water table in the centre of the field to lag behind the area closer to the rhyne in its decline. A strip about 30 m wide running along the rhyne dried out more rapidly than the rest, although very close to the rhyne water tables remain high (Figure 10). Sutherland &Nicolson (1986) quote a Somerset Levels farmer: "You've got to get the water table down roughly two foot so you can actually work it. If you get less, that means the middle of the field is a day late getting dried out, after rain or whatever, than the edge. So ... you'll find you're taking smashing silage cuts off most of the field but in the middle you begin to get bogged because you haven't waited for the extra day."

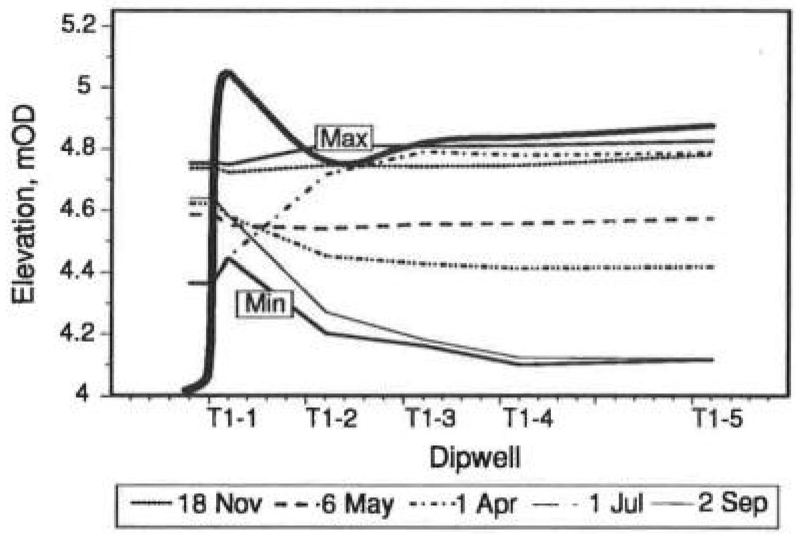


Figure 10. The rhynes of West Sedgemoor, with their lateral drains, form a reticular pattern which divides the Moor into rectangular fields. Results from transect T1, consisting of dipwells at 2, 12, 22, 32 and 52 m from a principal rhyne, the New Cut, show that the groundwater levels in the field are independent of the rhyne water level, except in a strip about 30 m wide. The data shown in the figure are for the summer of 1987. *From Gilman, 1994.*

Baird and Gaffney (2000) measured the rate of bromide solute movement through peat at Catcott Heath. They found that solute breakthrough was more rapid than expected from existing hydraulic conductivity data. The mean of hydraulic conductivity of 9 auger hole tests was 3.2 m d^{-1} and the range was 0.5 m d^{-1} to 5.5 m d^{-1}. There was clear evidence of the heterogeneity of conditions, reflected in the K values. In addition, double and treble peaks in concentration suggested that there are in places multiple porosity systems within the peat. They conclude that the existing understanding of buffer zones in the Somerset Moors may be too small and that further investigation is required. The relevance of this to the present study is that it may be misleading to apply a single value of 'active field width' across all sites.

Bromley *et al*. (2004) carried out an investigation at Thorne Moor into the effect of scale on hydraulic conductivity taking both lab measurements of soil cores, and field measurements at a point scale, and using ditches of lengths 10 m and 400 m. This gave a comparison of sample volumes ranging from 0.002 m^3 to around. 360 m^3. They found that measurements of hydraulic conductivity varied from 2.4 x 10^{-6} m/s in the lab to 4 x 10^{-4} m/s for the 400 m ditch length.

Gilman (1994) incorporated variation of permeability with vertical position, and specific yield with water table elevation into a digital model for West Sedgemoor and found it was necessary to have both parameters varying exponentially with depth below the surface. The attenuation of the effects of ditch levels with distance was particularly rapid, and in order to simulate this a zone of much reduced permeability was introduced immediately adjacent to the rhyne. Three possible reasons were given for this apparent reduction in permeability: the shallow depth of the ditch compared with the full depth of the peat, sealing of the bed and banks of the rhyne or compaction of the peat near to the rhyne by heavy equipment used in the management of the ditches.

8. The movement of water into and out of the soil body: the values to use in this study

This review of literature values forms the basis for the estimate of the likely distance of influence of ditch water levels into the field and the hydraulic conductivity to be used in this study. There is considerable variability depending on sample method and spatial heterogeneity in soil properties. As with specific yield, it is very unlikely that sufficiently detailed spatial information exists to be able to account for this. The proposed solution is therefore to calculate a mean value and also a likely range of values. Tables 10 shows the summary of values relating to the study area.

Table 10. Summary of distance of influence and hydraulic conductivity relevant to the study area.

Reference	Study area	Distance of influence of ditch (m_	Comment
Acreman *et al.*, (2002)	Tadham Moor	8 m	
Boelter, (1972)	?	5 m	Well-humified peat
Boelter, (1972)	?	50 m	Less humified peat
Burke, (1961)	Glenamoy, western Ireland	1.8 m	Blanket peat
Gilman, (2004)	West Sedgemoor	30 m is stated as the distance affected however in figure 9 it appears that the majority of influence is in the first 10 m.	
It is concluded that the most likely value for the study site is between 8 m and 10 m, with a potential minimum of 5 m and maximum of 30 m.			

Reference	Study type	Study area	Depth (m)	Soil Type	Saturated Hydraulic Conductivity
Dawson (2006)	Water table modelling	West Sedgemoor			1.77 m/d
Bradford (2004)	Water table modelling	Tadham Moor			2 m/d
Armstrong (1989)		UK wide			0.96 m/d
Kechavarzi (2010)	Lab sample analysis	West Sedgemoor	0 – 0.15 m	Peaty loam	1.51 m/d
Kechavarzi (2010)	Lab sample analysis	West Sedgemoor	0.35 to 0.5 m	Humified peat	1.55 m/d
Kechavarzi (2010)	Lab sample analysis	West Sedgemoor	0.85 to 1.0 m	Semi-fibrous peat	2.3 m/d
Dawson (2006)	Field derived measurement	West Sedgemoor			Mean 0.8 m/d Min 0.28 m/d Max 3.57 m/d
Baird and Gaffney (2000)	Solute tracing	Catcott Heath			Mean 3.2 m/d Min 0.5 m/d Max 5.5 m/d
			Mean		**1.9 m/d**
			Min		**0.28 m/d**
			Max		**5.5 m/d**
Note the UK wide value given by Armstrong (1989) has not been included as the more relevant values from sites within the SLMs are likely to be more representative.					

9. Calculation of ditch storage capacity

As previously outline, ditch storage capacity consists of two elements which combine to give the total ditch storage. The first, in-channel storage, is calculated by multiplying the available water depth (the distance from the current water level to the bank full level of the ditch) by the channel width, and then by the length of ditch. The second element, in-soil storage, is calculated by multiplying the amount of soil likely to receive water by the available pore space in the soil. This can be done with varying levels of complexity. The shape of the water table, and hence the amount of soil that can receive water, is approximated to a straight line from the water table in the ditch to the soil surface at the point given by the distance of influence. It is felt that a straight line approximation of the water table profile will provide an acceptable estimate of the soil water volume. The area formed by the resulting triangle is multiplied by the specific yield in, giving the amount of water that can be readily accommodated by the soil per unit length. A graphical explanation of both storage elements is provided in figure 11 below.

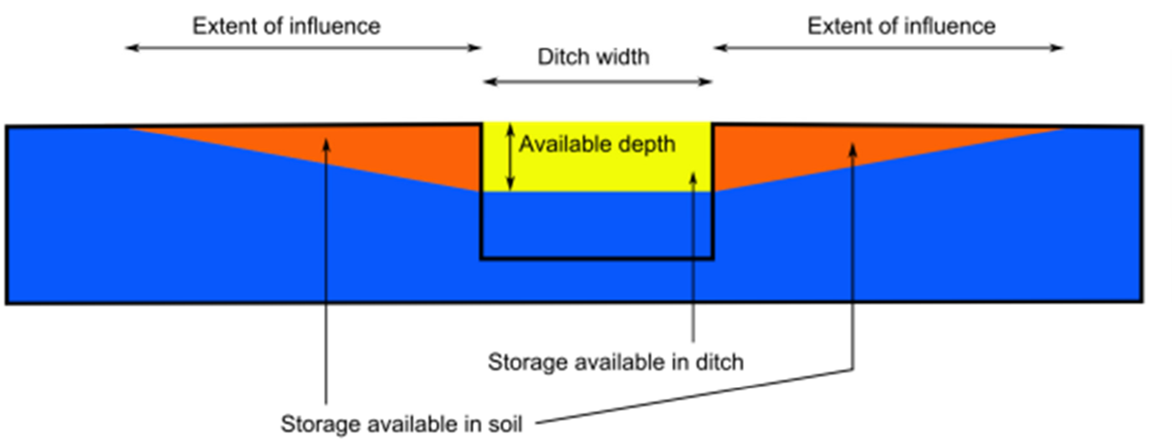


Figure 11. Illustration of the two storage elements included in the calculation of total ditch storage. The figure is based upon the likely winter water level condition of a ditch managed according to the WLMP. The winter drawdown in the ditch has an influence on the adjacent soil water table. Yellow shading indicates the available storage capacity in the ditch and brown shading indicates the available storage capacity in the soil. The blue shading indicates the water level in the ditch and saturated soil.

The main set of calculations uses the mean parameter values derived from the literature review. These are:

Distance of influence: 9 m

Specific yield: 0.2

Having quantified the two storage elements per unit length of ditch, this is multiplied by the length of ditch under the corresponding water level management condition:

1. Winter ditch storage under current conditions. This assumes that water levels in the WLMP watercourses are maintained at 0.6 m below ground surface, except those in the RWLA which are maintained at ground surface.
2. Winter theoretical maximum ditch storage. This assumes all WLMP and RWLA watercourses are maintained at 0.6 m below ground surface. No ditches are managed with water levels maintained at ground surface.
3. Summer ditch storage. This assumes that all WLMP and RWLA watercourses are maintained at 0.3 m below ground surface.

The results are shown as total ditch storage volumes for each WLMP area, and also broken down as in-channel storage and in-soil storage. Table 11 and figure 12 show the results of these calculations.

To set the total ditch storage volumes in context, estimates have also been made of the winter direct rainfall, total flood volume in winter 2013/2014, and the flood volume that would affect the road of lowest elevation in each WLMP area. Calculation of these volumes was carried out as follows:

Winter Direct Rainfall (Table 12 and figure 13). Aerial average daily rainfall (mm) was extracted from the CEH 1km^2 GEAR dataset for each WLMP for the period covering 1st December 2013 to 28th February 2014 inclusive. The total depth of rainfall was calculated and multiplied by the area of WLMP. The resulting figure is the total volume of rainfall falling directly on each WLMP area during winter 2013/2014. These calculations were carried out for all WLMP areas in the study.

Total flood volume in winter 2013/2014 (Table 14). GIS analysis of topographic data are used to construct a relationship between flood volume, flood extent and water level. Water level records exist for various telemetered gauges across the study area and flood extent has been estimated from remote sensing data captured on the 8th of February 2014. By combining these pieces of information it is possible to estimate the total flood volume. Data were not available for all WLMP areas and therefore results are only presented for a subset of WLMP areas.

Total flood volume to lowest road (Table 14). Similar to the method outlined above, a GIS-derived relationship between flood volume and water level was used in combination with data on the elevation of roads in each WLMP area. The elevation of the lowest road was established and the corresponding flood volume estimated using the volume to water level relationship. As above, results are only presented for the subset of WLMP areas where data exist.

The volume to water level relationship was further used to estimate the change in level resulting from different storage volumes. The final set of calculations used data on the pumping capacity and used this to estimate the time taken to pump a volume of water equivalent to that occupied by seasonal water level management. As above, results are only presented for the subset of WLMP areas where data exist.

An investigation of the impacts of uncertainty in the parameter values on calculation of total ditch storage volume is included later in this report (Figure 14).

Table 11. Summary results of ditch storage calculations. In these calculations, the distance of influence was set to 9 m and the specific yield set to 0.2. Three situations are show: Winter ditch storage available under current conditions (this includes the current RWLA), the winter theoretical maximum ditch storage (if there were no RWLA) and summer ditch storage. Channel, soil and total ditch storage volumes are given for each WLMP unit. As previously defined, winter is the period from 1st December 2013 to 28th February 2014.

	Winter ditch storage available under current conditions (m^3)			**Winter theoretical maximum ditch storage (m^3)**			**Summer ditch storage (m^3)**		
WLMP Area	**Channel storage**	**Soil storage**	**Total ditch storage**	**Channel storage**	**Soil storage**	**Total ditch storage**	**Channel storage**	**Soil storage**	**Total ditch storage**
Allermoor	263280	128844	392124	267060	131112	398172	133530	65556	199086
Brue Valley North	768240	407052	1175292	805260	428436	1233696	402630	214218	616848
Brue Valley South	984390	550368	1534758	1038690	582660	1621350	519345	291330	810675
Curry Moor	237000	115560	352560	238260	116316	354576	119130	58158	177288
Kings Sedgemoor	1048830	557604	1606434	1157520	621432	1778952	578760	310716	889476
North Moor	417210	234792	652002	449190	253584	702774	224595	126792	351387
Southlake	13590	5616	19206	71760	36396	108156	35880	18198	54078
West Moor	120870	60372	181242	143250	73548	216798	71625	36774	108399
West Sedgemoor	315540	174744	490284	408630	230148	638778	204315	115074	319389
Wet Moor	239160	112320	351480	322110	159516	481626	161055	79758	240813
Total all areas	4408110	2347272	6755382	4901730	2633148	7534878	2450865	1316574	3767439

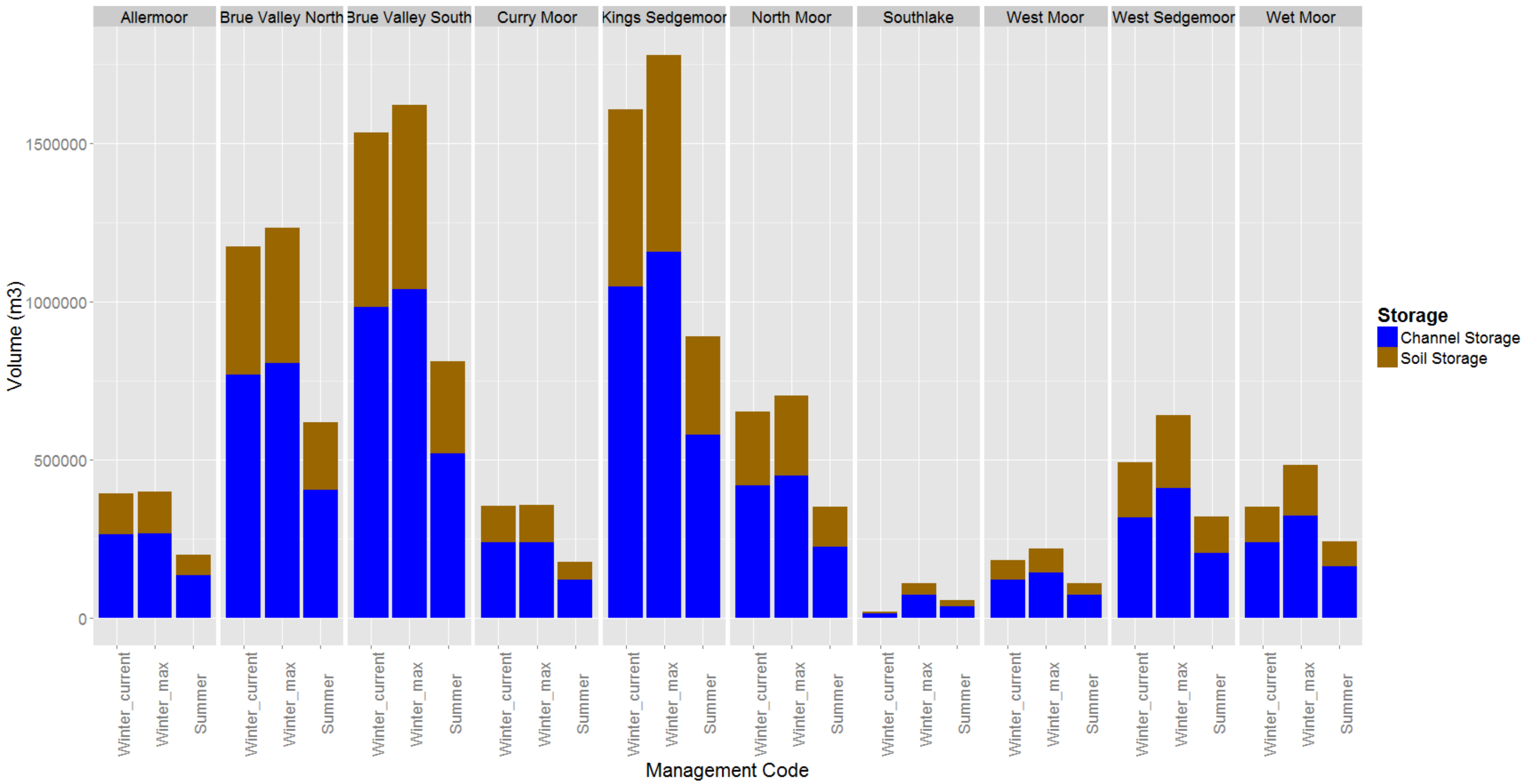


Figure 12. Ditch storage volumes for each WLMP unit under each of three water level management conditions: Winter ditch storage available under current conditions (Winter_current), the winter theoretical maximum ditch storage (Winter_max) and summer ditch storage (Summer). Each bar represents the total ditch storage available under the corresponding conditions and is divided between channel storage (blue) and soil storage (brown) volumes. The distance of influence is 9 m and the specific yield is 0.2.

Table 12. Total ditch storage expressed in relation to total winter 13/14 direct rainfall volume.

Name	Winter direct rainfall (m3)	Theoretical max ditch storage (m3)	Theoretical max ditch storage as % of winter rainfall	Winter ditch storage with RWLA (m3)	Winter ditch storage as % of winter rainfall	Summer ditch storage (m3)	Summer ditch storage as % of winter rainfall
Allermoor	3627040	398172	11.0	392124	10.8	199086	5.5
Brue Valley North	11311010	1233696	10.9	1175292	10.4	616848	5.5
Brue Valley South	18126599	1621350	8.9	1534758	8.5	810675	4.5
Curry Moor	3855016	354576	9.2	352560	9.1	177288	4.6
Kings Sedgemoor	17476299	1778952	10.2	1606434	9.2	889476	5.1
North Moor	7077577	702774	9.9	652002	9.2	351387	5.0
Southlake	820820	108156	13.2	19206	2.3	54078	6.6
West Moor	2533972	216798	8.6	181242	7.2	108399	4.3
West Sedgemoor	7601846	638778	8.4	490284	6.4	319389	4.2
Wet Moor	6895849	481626	7.0	351480	5.1	240813	3.5
Average all areas			9.7		7.8		4.9

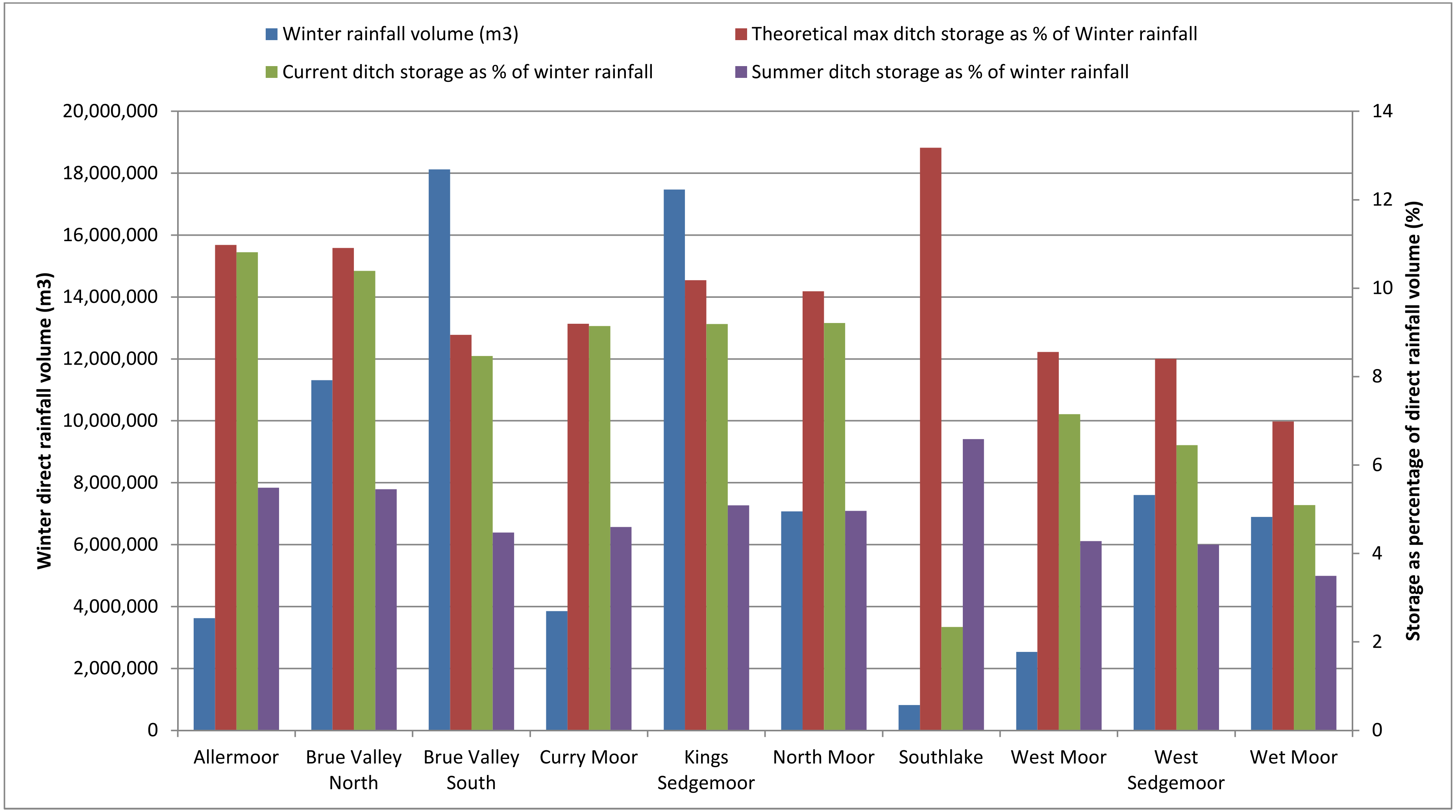


Figure 13. Winter 13/14 total direct rainfall volume for each WLMP area. The total ditch storage for each of the three water level management conditions is expressed as a percentage of the total winter rainfall volume.

10. Results and analysis

Land managed as RWLA in winter covers 2529 ha or 13.1% of all WLMP areas and incorporates 264 km, or 10.9%, of all watercourses. The maximum theoretical ditch storage across all WLMP areas is 7,534,878 m^3 and varies between units from a minimum volume of 108,156 m^3 at Southlake, to a maximum volume of 1,778,952 m^3 at Kings Sedgemoor. The total ditch storage under current conditions totals 6,755,382 m^3 across all areas and similarly varies between units from a minimum volume of 19,206 m^3 at Southlake to a maximum volume of 1,606,434 m^3 at Kings Sedgemoor. Summer ditch storage is 50% of maximum theoretical ditch storage and follows the same pattern of variability between WLMP units.

By comparing the calculation of total current ditch storage with the calculation of theoretical maximum ditch storage volume, it is possible to estimate the magnitude of influence that the raised water level areas have on the total ditch storage available. The total ditch storage volume occupied by maintenance of high water levels in winter (the difference between maximum theoretical storage and storage under current conditions) is 779,496 m^3 and equates to 10% of the theoretical maximum across all sites. There is however great variability between sites from a minimum of 0.6 % of the total ditch storage at Curry Moor, to 82.2 % of the total ditch storage at Southlake. As would be expected, the pattern follows that shown in table 1 where the length of watercourses in the WLMP is compared with that in the RWLA. It should be noted that the management at Southlake is different to that at the other WLMP areas, and the majority of sites have a reduction in ditch storage of between 5 % and 27%. Summer ditch storage is 50% of the maximum theoretical ditch storage at each site. The split between channel storage and soil storage is consistent across sites with channel storage contributing approximately two thirds and soil storage contributing one third of the total ditch storage volume.

For reference the current winter ditch storage, winter theoretical maximum ditch storage volume and summer ditch storage volumes are also presented in the context of the total volume of rainfall to fall on each WLMP unit during winter 13/14 (Table 12 and figure13). The volumes only reflect rainfall falling directly on each unit and not any surface inflow or any other component of the water balance, and are therefore likely to overestimate ditch storage as a proportion of total flood volume. These numbers are not suitable for a thorough assessment of the water balance however they do provide a useful backdrop against which to assess ditch storage volume. Averaged across all areas, the theoretical maximum ditch storage is 9.7%, winter ditch storage is 7.8% and summer ditch storage is 4.9% of the total rainfall volume. In all except one of the WLMP areas, the ditch storage volume lost through maintenance of RWLA is 2% or less. This indicates that in most units, the loss in ditch storage resulting from RWLAs is small in comparison to the incoming volume of water. In all except one area, the reduction in ditch storage through maintenance of summer water levels is greater than the reduction due to maintenance of RWLAs.

Where data are available, the ditch storage volumes are also presented in relation to estimates of maximum flood volume calculated from a combination of LiDAR-based level to volume relationships, telemetered water-level data and remotely sensed imagery (Table 14). In the six units where results exist, the average RWLA volume occupied as a percentage of the maximum flood volume in 2014 across all sites is 0.6% and the average increase in flood level across all sites is 0.7 cm. Between

WLMP units, the range of proportion of volume occupied is 0.01% to 1.38% and the range of flood level increase is 0.03 cm to 1.16 cm. By comparison, the volume occupied by maintenance of summer penning levels is between 1.02% and 14.6% (average 3.6%) of the maximum flood volume and this equates to an increase in flood level of between 2.1 cm and 6.2 cm (average 2.9 cm). The same calculations were made for a less severe flood event, one in which the flood level would reach the lowest road in each WLMP area, and the results are: RWLA volume equates to between 0.1% and 6.1% (average 2.5%) of the flood volume, equating to an increase in flood level of between 0.05 cm and 2.3 cm. For the summer agricultural pen volume this increases to between 3.9% and 20% (average 10.1%) of the flood volume, or an increase in flood level of between 2.7 cm and 6.6 cm.

Pump capacity data were then used to convert the volumes into the number of hours of pumping required to remove an equivalent volume. Across the six areas where results exist, it would take on average 3.5 hours to remove the 425,388 m^3 of water occupied by RWLA management based on permanent pumping station capacity (between WLMP units this would range from 0.05 hours and 5.47 hours. To pump the volume occupied by the agricultural pen level in summer, this increases to an average of 15.2 hours (range 7.1 hours to 25.1 hours).

Sensitivity analysis was carried out to investigate the impact of uncertainty in specific yield and distance of influence. The total current ditch storage volume (with RWLA) and theoretical maximum ditch storage (without RWLA) were calculated for combinations of specific yield ranging from 0.15 to 0.25 and distance of influence ranging from 5 m to 30 m. The results are shown in figure 14. There is variability in total ditch storage between sites similar to that seen in figure 12. Within each site, the most dramatic difference on total ditch storage comes from uncertainty in distance of influence. The maximum value of 30 m suggested by Gilman (2004), has the potential to double available the total ditch storage. As noted previously however, a value of between 8 m and 10 m appears to be more likely on the basis of the current evidence. Specific yield has a smaller impact on the calculated volume, with the range of possible values (0.15 to 0.25) translating to a ~15% change in total ditch storage.

Table 13. Uncertainty analysis. The impact of combined maximum and minimum values of distance of influence and specific yield on loss in ditch storage due to RWLAs as a percentage of winter 13/14 rainfall

Loss in ditch storage as a percentage of winter 13/14 rainfall			
	Mean	Min	Max
Distance of influence =	9 m	5 m	30 m
Specific Yield =	0.2	0.15	0.25
Mean	1.90	1.51	4.04
Min	0.05	0.04	0.11
Max	10.84	8.65	22.71

These uncertainties have a considerable impact on the calculation of absolute ditch storage and continued efforts to refine these parameters will aid future calculations. However, as the uncertainties are currently applied equally to both the raised water level areas and non-raised water level areas, it is possible that they become less significant when assessing the ditch storage volume of one in relation to the other. To establish the outer limits of the impact of uncertainty, the model was tested using the combined maximum and minimum values of distance of influence and specific yield (Table 13). The results in table 13 indicate that although the impact of uncertainty on total ditch storage is considerable, expressed relative to the total volume of rainfall (winter 13/14) the mean range of percentage loss in ditch storage due to maintenance of RWLSs is 1.51% to 4.04%.

Table 14. Assessment of ditch storage volume in summer and winter in relation to the flood volume and extent observed 2014 and for a flood to the level of lowest section of road. Results are presented for WLMP areas where flood volume data exist. For each area the RWLA volume is calculated as the difference between the RWLA and IDB winter water levels, and summer ditch storage is calculated as the difference between IDB summer and winter water levels.

WLMP area	Maximum flood level (mAOD)	Maximum flood volume (m^3) 2014	Maximum flood extent (ha) 2014	Lowest road level (mAOD)	Flood volume to lowest road level (m^3)	Flood extent at lowest road level (ha)	Permanent pump capacity (m^3/s)	Volume pumped per hour (m^3/s) permanent capacity	Seasonal water level management	Volume occupied - channel and soil (m^3)	Volume occupied as a proportion of max flood volume 2014 (%)	Increase in flood level at max flood extent due to volume occupied 2014 (cm)	Volume occupied as a proportion of flood volume to the lowest road level (%)	Increase in flood level at lowest road level due to volume occupied (cm)	Pump hours to evacuate volume occupied by permanent station capacity
Brue Valley North	2.62	4226000	994	2.5	3091000	931	6.8	24480	RWLA volume	58404	1.38	0.59	1.89	0.63	2.39
									Summer pen volume	616848	14.6	6.21	19.96	6.63	25.19
Curry Moor	8.0	17408000	748	5.75	2646000	437	5.33	19188	RWLA volume	2016	0.01	0.03	0.08	0.05	0.11
									Summer pen volume	177288	1.02	2.37	6.70	4.06	9.24
North Moor and Saltmoor	6.19	27014000	1446	4.1	3288000	862	5.35	19260	RWLA volume	50772	0.19	0.35	1.54	0.59	2.64
									Summer pen volume	351387	1.30	2.43	10.69	4.08	18.24
West Moor	9.04	10152000	525	7.5	2799000	396	4.26	15336	RWLA volume	35556	0.35	0.68	1.27	0.90	2.32
									Summer pen volume	108399	1.07	2.06	3.87	2.74	7.07
West Sedgemoor	6.44	15871000	1283	5.33	3784000	970	5.84	21024	RWLA volume	148494	0.94	1.16	3.92	1.53	7.06
									Summer pen volume	319389	2.01	2.49	8.44	3.29	15.19
Wet Moor	8.88	15938000	1134	7.3	2149000	559	5.61	20196	RWLA volume	130146	0.82	1.15	6.06	2.33	6.44
									Summer pen volume	240813	1.51	2.12	11.21	4.31	11.92

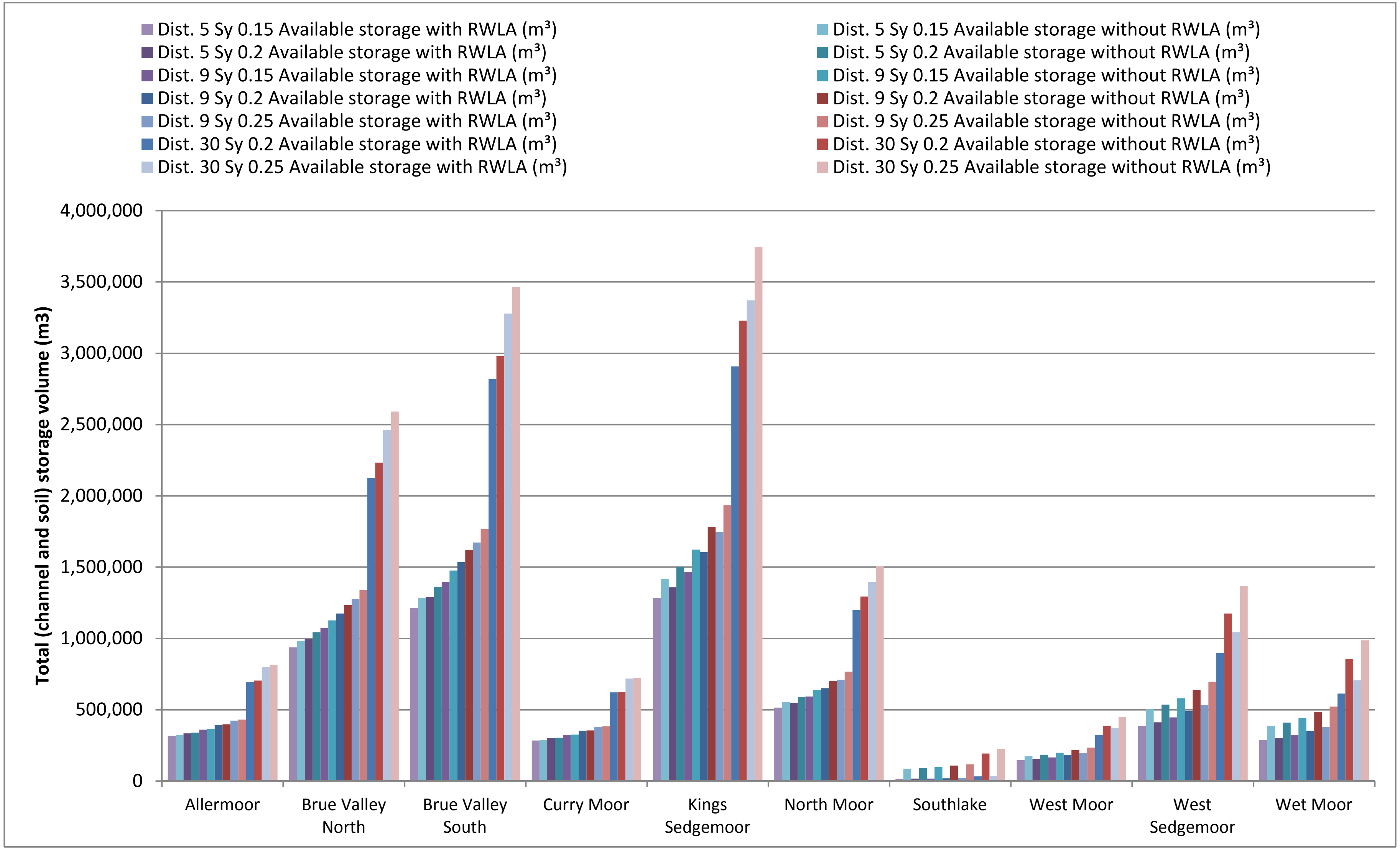


Figure 14. Results from sensitivity analysis of distance of influence and specific yield. The total ditch storage volumes are presented, calculated with values of distance of influence of 5 m, 9 m and 30 m, and specific yield values of 0.15, 0.2 and 0.25.

11. Summary and Conclusion

The review presented here sets out to assess the impact of three different water level management scenarios on flooding in the Somerset Levels and Moors. Raised water level ditches exist in ten water level management plan units in Somerset, covering 2529 ha or 13.1% of all WLMP areas and incorporating 264 km, or 10.9%, of all watercourses. The extent of RWLA in each area varied considerably from 0.6 % and 84.6% of the total ditch length. Water levels in the raised water level areas are maintained at bank full level between December and April to mimic the 'natural' hydrological condition. Water levels in ditches outside of the raised water level areas are maintained at 0.6 m below bank full level during the same period. This represents a reduction in the flood storage capacity of the ditch network between December and April. Between May and November, all ditches are maintained at 0.3 m below ground surface.

The total ditch storage volume consists of channel storage and soil storage. Quantification of the channel storage volume has been carried out by multiplying the channel dimensions by the available depth of water. Soil storage is more difficult to quantify and the simplified approach used here considers a distance of influence extending from the ditch into the field, and soil specific yield which describes the volume of water that can be accommodated by a volume of soil. An extensive review of the literature indicates that the mean likely distance of influence is 9 m, and specific yield has a mean value of 0.2. Storage calculations were carried out using these parameter values. The maximum theoretical ditch storage of watercourses and soil profiles varies between WLMP areas from a minimum volume of 108,156 m^3 at Southlake, to a maximum volume of 1,778,952 m^3 at Kings Sedgemoor. The maximum theoretical ditch storage across all areas is 7,534,878 m^3.

The volume of ditch and soil profile storage that is lost through maintenance of the raised water level areas varies from 2016 m^3 to 172,518 m^3 depending on the unit. As a percentage of the total ditch storage available, the raised water level areas account for 10% of the theoretical maximum ditch storage across all areas, although this varied considerably between WLMP areas from 0.6 and 82.2%. Expressed as a percentage of the total rainfall volume falling on each unit in winter 13/14 the volume of ditch storage lost as a result of the raised water level areas is 2% or less for 9 out of the 10 sites. The maximum theoretical ditch storage of watercourses and soil profiles across all areas is also relatively small, at less than 10%, when compared to the total winter rainfall that fell within WLMP areas during December, January and February 2013-14. The reduction in ditch storage through maintenance of summer water levels compared to the winter theoretical maximum ditch storage is uniformly 50% across sites, equating to absolute volumes varying between 54,078 m^3 at Southlake and 889,476 m^3 at Kings Sedgemoor.

Analysis in relation to the estimated flood volume during the winter 2013/14 floods indicates that the volume of ditch storage occupied by the raised water level areas was equivalent to between 0.01% and 1.38% (average 0.6%) of the maximum flood volume in 2013/14, or an increase in flood level of between 0.03 and 1.2 cm. The volume occupied by the agricultural pen volume in summer ranged from 1% to 14.6% (average 3.6%) of the maximum flood volume in 2013/14, or an increase in flood level of between 2.1 and 6.2 cm.

For less severe flooding, where the flood level reaches the lowest road in an area, the RWLA volume equates to between 0.1 and 6.1% (average 2.5%) of the flood volume, or an increase in flood level of between 0.08 and 2.3 cm. For the agricultural pen volume in summer, this increases to between 3.9 and 20% (average 10.1%) of the flood volume, or an increase in flood level of between 2.7 and 6.6 cm.

For the six pump drained catchments that experienced severe flooding in winter 2014, calculations suggest it would take between 0.05 hours and 5.47 hours (average 3.5 hours) to evacuate the volume occupied by RWLA using the permanent pumping station capacity. This increases to between 7.1 and 25.1 hours (average 15.2 hours) for the volume occupied by the agricultural pen level in summer.

In conclusion this assessment finds that in relation to the volumes of water that were present during the winter 2013/2014 floods, the volume of water occupied by RWLA and subsequent reduction in ditch storage capacity represents a very small fraction of the total. Expressed both as a proportion of the theoretical maximum ditch storage and as a reduction in flood level, the calculations presented here indicate that the areas managed with raised water levels have only a very minor impact on large flood events. Water levels for agriculture in summer occupy larger volumes, but these are still small compared to volumes of water stored on the moors during major flood events.

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