Irish Geography
Vol. 52, No. 1 May 2019
DOI: 10.2014/igj.v52i1.1376

Geographical Society of Ireland
An Cumann Tireolaíochta na hÉireann

Impacts of climate change and hydrological management on a coastal lake and wetland system

Elizabeth Ann Gardner[1], Helene Burningham[1] and Julian Richard Thompson[1].

[1] University College London Department of Geography, Pearson Building, Gower Street, London, WC1E 6BT, United Kingdom.

First received: 18 September 2018 *Accepted for publication: 3 April 2019*

Abstract: Lowland, shallow, coastal aquatic systems often comprise a complex array of habitats and species as a consequence of their geomorphic evolution in combination with marine and terrestrial forcing. They are vulnerable to changes in climate and human activities that influence hydrology, water quality, sediment dynamics and species assemblages. Conservation-oriented management practices are being implemented at many sites to maintain favourable conservation status, but have the potential to also deliver unforeseen impacts on the hydrological character of these systems and their wider catchments. Sheskinmore Lough, a shallow coastal freshwater lake and wetland system in County Donegal, Ireland, is managed to maintain water levels. In this study, hydrological modelling is undertaken to establish the potential future impacts of climate change and hydrological management on the ecohydrology of the lake and wetland system. Results show that hydrological management has the largest impact on system ecohydrology in comparison to climate change. When combined with climate change, however, these effects are even greater. Given that climate change is predicted to increase the magnitude of these impacts, environmental managers need to consider the array of vulnerable species, their specific ecohydrological requirements, and the overall biodiversity of the site, when developing future conservation management strategies.

Keywords: *climate change, conservation, ecohydrology, freshwater, hydrological management, coastal lake*

* h.burningham@ucl.ac.uk (Corresponding Author)

Introduction

Climate change during the 21st century will have important consequences for the conservation of aquatic and wetland habitats (Kundzewicz *et al.,* 2007; Bates *et al.,* 2008; Thompson *et al.,* 2017). The UK Climate Impacts Programme (UKCIP) projections for the future climate in Ireland predict hotter drier summers, warmer wetter winters and more frequent and intense precipitation events (Hulme *et al.,* 2002; Murphy *et al.,* 2009) in broad agreement with those of the EPA (Sweeney *et al*., 2003). The Environmental Protection Agency (EPA) assessment of future Irish climate reveals that by 2080, a general warming of between 1.25°C and 1.5°C is likely (McGrath *et al.,* 2005). For precipitation, the most significant changes are predicted to occur in June, when precipitation is likely to decline, and in December, when precipitation is likely to increase. Increases in the frequency of larger precipitation events (i.e., >20mmday^{-1}) are also projected, in addition to increases in the frequency of intense storm events.

The growing appreciation in recent decades of the ecosystem services offered by aquatic and wetland systems has led to acknowledgment that their loss and degradation is a major cause for concern (Maltby *et al.,* 2011; Mitsch and Gosselink, 2015). In response, many initiatives, often based around revised water level management, have been developed at the local, national and international level to support the conservation of existing systems and restore or recreate those that have been lost or degraded. In most cases, they involve the installation of structures such as sluices that enable responsive and precise adaption of local water levels to suit the requirements of specific habitats and/or species. Understanding the impacts of these initiatives and improving our ability to predict the performance of these approaches in the context of future climate change is required in order to: inform management and underpin effective schemes and strategies to achieve the required goals; avoid undesirable outcomes; and direct the often-limited resources available to wetland management and conservation practitioners.

Hydrological processes influence the edaphic and biological characteristics of aquatic and wetland systems. Anthropogenic interventions for a range of management and conservation purposes can significantly modify the hydrology of these environments and their wider catchment (Baker *et al.,* 2009; Mitsch and Gosselink, 2015). Unforeseen impacts may arise from hydrological modifications driven by conservation-oriented management practices. For example, raising water levels or diverting drainage channels to establish and maintain conditions for target plant and animal species in one part of a site may have unwanted consequences such as the creation of undesirable high-water tables or flooding in other areas (Thompson *et al.,* 2004). As a result, hydrological modelling studies that can effectively capture the impacts of both management and climate change on freshwater systems can be very useful in planning effective interventions (e.g., Thompson *et al.,* 2017).

This study investigates the impacts of projected climate change and hydrological management on the Sheskinmore Lough system in County Donegal, northwest Ireland (Figure 1). The Sheskinmore catchment drains a peat-covered granite landscape, and two small rivers enter Sheskinmore Lough, which has formed in the back-barrier of a coastal dune system. The lough and its surrounding wetland are low-lying and shallow, but beyond the reach of tidal waters. The geomorphology and environmental context is typical of west coast sedimentary systems, where sediment dynamics over centuries to millennia have led to the development of dunes. These act to block freshwater flows at the coast, which in turn form shallow marginal freshwater wetlands. The international importance of the habitats and species within the lough and wetland are recognised through the EU Habitats and Birds Directives. Although the National Parks and Wildlife Service (NPWS) has managed water levels since 2005, using a sluice on the lake's outflow, no assessment of system ecohydrology has informed this management.

This study develops a MIKE SHE/MIKE 11 model of the Sheskinmore catchment. Modelling the hydrology of the Sheskinmore system is undertaken to establish the long-term behaviour of water levels and their effects on the ecology of the lake and wetland system in the future. Climate change scenarios were developed using the UKCIP09 probabilistic projections and used to perturb the meteorological inputs to the model. Results are compared to baseline conditions provided by the model. Alternative operation of the sluice used to maintain water levels under baseline and scenario climates are also simulated.

Methods

The MIKE SHE / MIKE 11 model

MIKE SHE is a deterministic, fully-distributed and physically-based modelling system based on the Système Hydrologique Européen (SHE) model (Abbott *et al.,* 1986; DHI, 2005; Refsgaard *et al.,* 2010). The modelling system has been applied at a wide range of scales, from catchments and wetlands less than 10km^2 in area (Thompson *et al.,* 2004; Thompson, 2012), to major international river basins spanning thousands of square kilometres (Andersen *et al.,* 2001; Thompson *et al.,* 2013). It has been used to study a variety of water resource and environmental problems under diverse climatological and hydrological regimes (Refsgaard and Storm, 1995; Butts *et al.,* 2005; Zhang *et al.,* 2008; Refsgaard *et al.,* 2010). The modelling system comprises unsaturated and saturated zones integrated with overland flow into a complete dynamic system whilst maintaining interactions between the various components of the hydrological cycle (Abbott *et al.,* 1986; Graham and Butts, 2005; Refsgaard *et al.,* 2010). The model spatially distributes catchment characteristics and climate variables through an orthogonal grid network, comprising grid cells that extend in equal-sized columns both horizontally and vertically (Graham and Butts, 2005). MIKE 11, a one-dimensional hydraulic model, can be coupled to MIKE SHE to simulate stream and river networks and includes the ability to represent hydraulic structures, including weirs, sluices and culverts (Havnø *et al.,* 1995; Thompson *et al.,* 2004; Duranel, 2015).

A nested approach was employed for the Sheskinmore model. A MIKE SHE / MIKE 11 model of the wider 22km^2 catchment (70m × 70m grid resolution) encompassed the Duvoge and Abberachrin river catchments to the east and the dune barrier to the west (Figure 1). Sheskinmore Lough, its wetland and immediate surroundings (6km^2) was modelled at a higher resolution (40m × 40m). The larger model provided boundary conditions (groundwater head elevations and river inflows to the smaller model).

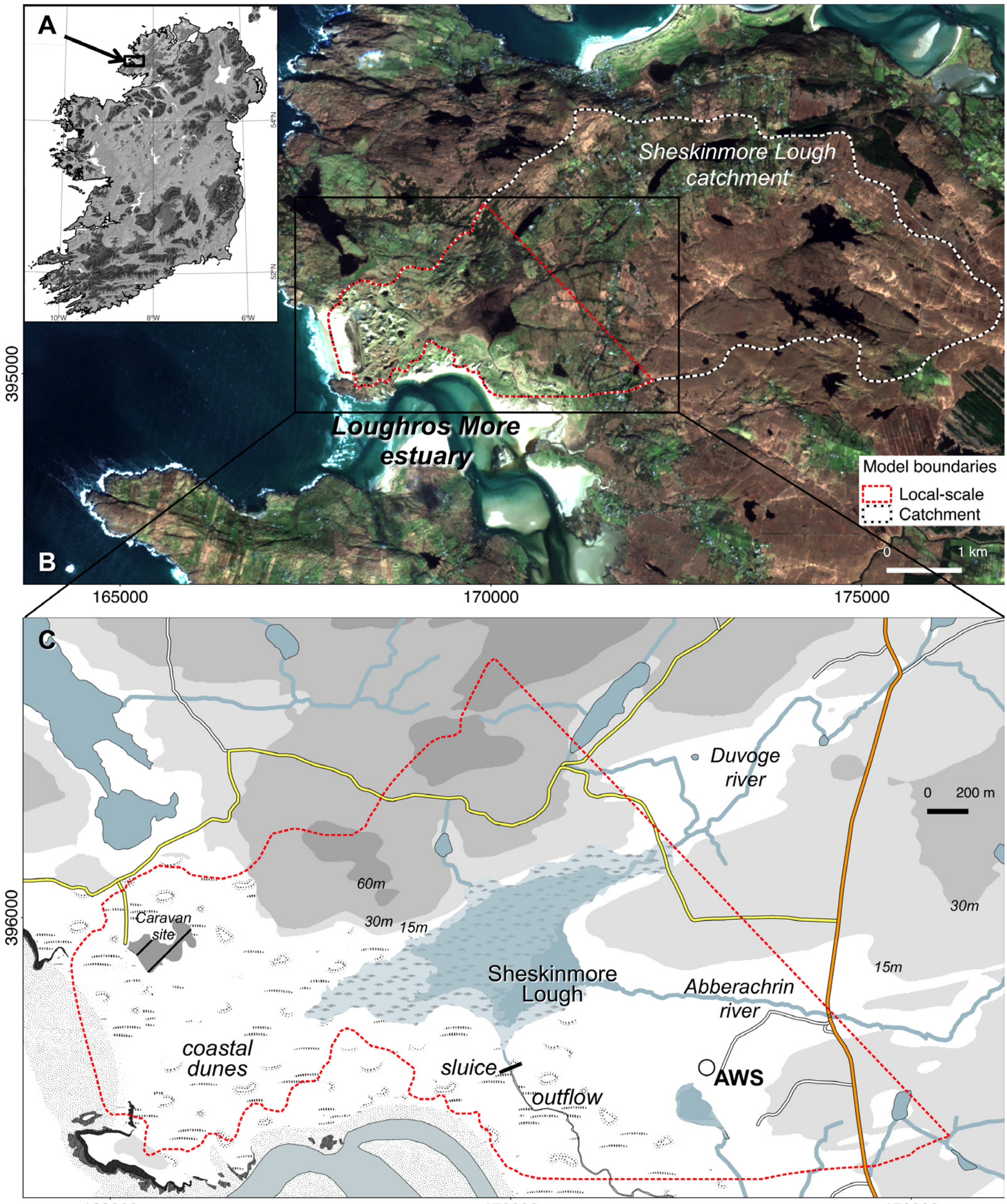

Figure 1 The Sheskinmore Lough system, defining the catchment (22.19km^2) and local (5.94km^2) scale model boundaries and other features mentioned in the text. Grid coordinates are referenced to Irish Grid.

The models were forced with meteorological data from an on-site automated weather station (AWS; Davis Vantage Pro2). Hourly precipitation and evapotranspiration (Penman-Monteith) from the AWS were converted to daily totals for model input. Comparison with regional Met Éireann data (Malin Head, Finner and Ballyhaise stations) revealed precipitation underestimation by the AWS of approximately 33%, but other variables were in good agreement. Under-catch in consumer weather stations has been noted before, often associated with tipping bucket biases, high wind speed effects, and differences in rain gauge depth and mounting position (Medlin *et al.,* 2007; Burt, 2012; Bell *et al.,* 2015). Therefore, daily precipitation data were corrected through multiplication by a transfer factor of 1.33. Daily precipitation and evapotranspiration were uniformly distributed across both model domains based on the assumption of negligible lapse rates due to the limited elevation range of the catchment. Water levels were recorded in the inflows and lough at hourly intervals using Rugged TROLL 100 non-vented (absolute) water level loggers corrected for atmospheric pressure using a Rugged BaroTROLL Data Logger installed at the AWS site, recording at the same temporal interval.

Topography, interpolated to the resolution of the two model domains, was derived from map contours, spot heights and Shuttle Radar Topography Mission 1-arc second data (SRTM, NASA) across the wider catchment, integrated with high resolution dGPS survey data (1-5m spatial resolution, cm-level vertical precision) across the dune, lake and wetland. Vegetation distribution, (peatland, wet grassland, reedbed, sand dune and wetland) mapped as part of a wider field survey (Gardner, 2016) was also resampled to the grid resolution of the two models. Leaf area index (LAI) and root depths were defined for each vegetation class using the literature (Dittmer, 1959; Boggie and Knight, 1960; Sorrel *et al.,* 2000; Bradford and Acreman, 2003; Lalke-Porczyk and Donderski, 2004). In the absence of arable crops and deciduous woodland, LAI and root depth were temporally constant with trial runs demonstrating that plausible small monthly variations had negligible impact on model results. Given the relative rarity of observed overland flow, a uniform Manning M value of $10m^{1/3}s^{-1}$ was specified throughout the model domain (Aldridge and Garrett, 1973; Phillips and Tadayon, 2007) and trial runs demonstrated the insensitivity of the model to this term.

Peat covers granite bedrock or glacial till across most of the Sheskinmore Lough catchment. This lower peat unit is compact and relatively impermeable. In contrast, the drape of calcareous dune sand to the west and southwest has significantly higher permeability. Therefore, the unsaturated zone was spatially discretised as sand or peat based on aerial photography and field observations. The initial hydraulic parameters applied in the unsaturated zone were derived from the literature (Mualem, 1976) and subsequently modified during calibration. In the absence of detailed geological information, a uniform 3m thick peat layer was specified for the saturated zone, simulated using the 3D finite difference method. A surface sand layer of variable thickness was defined based on topography and field observations covering areas of the catchment where sand was observed during field surveys. A zero-flow boundary was specified around the unsaturated zone of the larger model on the assumption that the groundwater divide follows the topographic divide. This was replicated in lower part of the smaller model with upper boundary specified as a time varying head abstracted from the larger catchment model.

The MIKE 11 model that was dynamically coupled to the larger MIKE SHE model comprised three branches; the Duvoge and Abberachrin rivers and the channel downstream of their junction (total branch length: c. 14km long). The upstream parts of the first two branches were excluded when MIKE 11 was coupled to the smaller, higher resolution MIKE SHE model. Cross-sections were based on dGPS field surveys and recent aerial photography. A leakage coefficient of $0.01Ls^{-1}$ and a Manning's n of 0.02 were applied throughout the model to represent the sandy peat-lined (Langhoff *et al.,* 2001) and mixed sediment bed (silt and cobbles) channels (Chow, 1959; Phillips and Tadayon, 2007). When coupled to the catchment-wide MIKE SHE model, zero flow hydrodynamic boundaries were applied to the sources of the Abberachrin and Duvoge rivers. Inflow boundaries were specified when the smaller MIKE 11 model was coupled to the higher resolution MIKE SHE model. In this case, simulated discharges at the relevant points from the larger model were specified.

A constant water level boundary just above the bed for the lowest cross section was specified at the downstream end of the MIKE 11 network to ensure water was discharged from the model and to prevent the river drying out (Thompson *et al.,* 2009). A global time-varying hydrodynamic evapotranspiration boundary (using the AWS data) was applied throughout the MIKE 11 model. A control structure, represented as a time-varying overflow gate, was specified at the location of the sluice on the outflow from Sheskinmore Lough. This enabled opening and closing of the sluice in accordance with current management practices with the sequencing of sluice opening and closing provided by NPWS.

Model calibration and validation

The simulation period (18 June 2012 – 17 June 2014) was divided equally (i.e., the split sample approach; Klemes, 1986) for calibration and validation. For both periods it was necessary to use the first three months as a model spin-up period. The MIKE SHE maximum time step was defined as 24 hours whilst a shorter MIKE 11 time step of 30 minutes was specified for computational stability reasons. Initially, the larger catchment-scale model was calibrated against estimates of daily discharge for the Abberachrin and Duvoge rivers upstream of Sheskinmore Lough. These were based on discrete flow gauging surveys (undertaken in 2012 and 2013) and comparison with publicly available discharge data from the neighbouring Owenea catchment (Office of Public Works, 2014) that is similar in geological characteristics but larger in area. These comparisons confirmed that weighting the Owenea record by catchment area could provide an estimate of discharge for the Abberachrin and Duvoge rivers. Calibration was performed using a manual iterative procedure, and each run was assessed based on a graphical comparison of observed and simulated discharge and widely used statistical measures of model performance: the correlation coefficient (R) (Weglarczyk, 1998; Yang *et al.,* 2002)

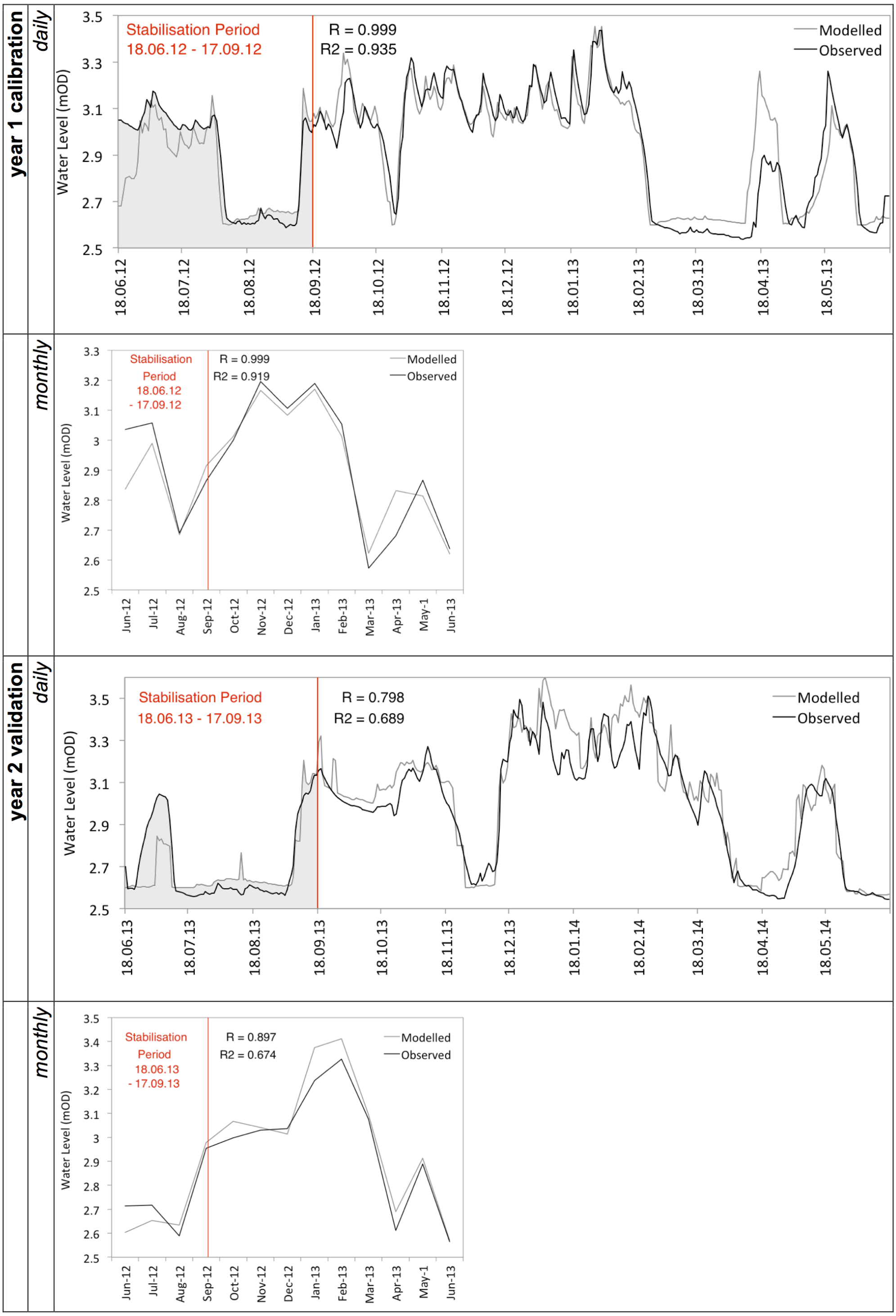

Figure 2 Comparison of daily and monthly observed and simulated lake water level for the local-scale model for year 1 (top) and year 2 (bottom).

and the Nash-Sutcliffe coefficient (R2; Nash and Sutcliffe, 1970; Thompson *et al.,* 2004). Model performance was validated using the same approach (R = 0.999 and R2 = 0.935 (daily); R = 0.999 and R2 = 0.919 (monthly) (Henriksen *et al.,* 2008)). Subsequently, using the approach described above, groundwater head and river flow boundaries for the smaller model were abstracted from this calibrated/validated model and a second validation performed using mean daily water level observations for Sheskinmore Lough (derived from hourly records from the water level logger installed within the lake).

The local-scale model is generally successful at reproducing the observed daily and mean monthly lake water level despite the flashy nature of the catchment response to precipitation and sluice operation (Figure 2). After the warm up period, the model achieves good sequencing of peak water level when the sluice is closed, although the magnitudes of the largest peaks are largely underestimated. Model results for the validation period show relatively poor sequencing of peak water level when the sluice is closed (some of the largest peaks are overestimated by 7%), suggesting the sluice may not have been fully closed. The troughs in daily water level when the sluice is open are generally estimated well. The statistical measures of model performance confirm the ability of the local scale model to simulate lake water level during the calibration period. Based on the Henriksen *et al.* (2008) classification, the model achieves *Excellent* performance at simulating daily water level (R = 0.999; R2 = 0.935) and monthly water level (R = 0.999; R2 = 0.919). Performance for the validation period is *Very Good* for both daily (R = 0.798; R2 = 0.689) and monthly (R = 0.897; R2 = 0.684) water level.

Development of climate change scenarios

The impacts of climate change on Sheskinmore Lough were assessed by perturbing the model's original meteorological inputs using climate change scenarios. Other model parameters, such as those representing land cover, remained unchanged, an approach that is widely used in hydrological modelling assessments of climate change (Fowler and Kilsby, 2007; Johnson *et al.,* 2009; Kingston *et al.,* 2011; Singh *et al.,* 2010; Thompson, 2012). Scenarios were based on the 2009 UK Climate Projections (UKCP09) following the approach used in similar studies (e.g., Bell *et al.,* 2012; Afzal *et al.,* 2015). UKCP09 provides probabilistic projections for atmospheric variables under three emissions scenarios (low, medium and high) that correspond to the B1, A1B and A1FI scenarios in the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000; Jenkins *et al.,* 2009). Projections for atmospheric variables are provided as 30-year time slices in the form of a probability distribution function designed to represent future climate uncertainties (Thompson, 2012). Changes in atmospheric variables are available for monthly, seasonal and annual average periods and are expressed relative to a 30-year baseline period (1961-1990).

Here, projections for the three emissions scenarios for the 2050s (2040-2069) and 2080s (2070-2099) were selected to align with long-term conservation management planning. Monthly changes in precipitation (%) and mean temperature (°C) were abstracted for probabilities between the 10% and 90% levels in 20% increments for northwest Ireland.

This accommodates the central estimate of change (i.e., the change that is as likely as not to be exceeded: 50% probability level), bounded by the changes that are very likely to be exceeded (10% level) and those that are very unlikely to be exceeded (90% level). A total of 30 scenarios were developed comprising five different probabilities (10%, 30%, 50%, 70%, 90%) for each of the three emissions scenarios across the two time slices. The daily precipitation and temperature records from the Sheskinmore AWS were then perturbed using the monthly UKCP09 delta factors. Penman-Monteith evapotranspiration was recalculated using the perturbed temperatures (Zotarelli *et al.,* 2010). Given the comparatively weaker performance for the validation period, the calibration period (18 June 2012 – 17 June 2013) was used in this climate change analysis. Simulated climate change results were compared with those for the observational period (i.e., the baseline). As the simulation period falls outside the 30-year UKCP09 baseline period (1961-1990), results are likely to be representative of conditions at the latter part of each time slice (Thompson *et al.,* 2009; Thompson, 2012).

Sluice management scenarios

Management of the sluice on the outlet of Sheskinmore Lough is used to maintain specific lake water levels for the benefit of some aquatic species. Impacts of the sluice structure on system hydrology was explored through three scenarios: the sluice varied *as is*, i.e., opened and closed throughout the year in response to changing water levels; the sluice left *fully open* at all times; and the sluice left *fully closed* at all times. These scenarios were simulated by changing the elevation of the overflow gate included within the MIKE 11 model. This was initially undertaken for the baseline climate and subsequently the combined influence of all the climate change scenarios and the three-sluice management scenario was simulated.

Results

Modelled hydrological response to climate change

The magnitude of change in climate parameters increases with progressively higher emissions scenarios, and those associated with precipitation are largely greater than for evapotranspiration (Figure 3). Mean annual precipitation is likely to increase (70% and 90% probability levels) relative to the baseline for all three emissions levels for the 2050s and 2080s. At the 10% and 30% probability levels projected mean annual precipitation is below the baseline in both time slices and for all emissions scenarios. Central estimates of change (50% probability level) are associated with declines of between 3.3% and 14.5% for the 2050s and between 2.0% and 14.4% for the 2080s. However, there is an overwhelming trend towards enhanced winter precipitation, with declines limited to the 10% probability level for all scenarios. Summer precipitation is primarily projected to decline by 2050 and 2080.

Potential evapotranspiration increases for all probability levels and emissions scenarios for both the 2050s and 2080s time slices. The central estimates of change (50% probability level) for the 2050s are increases of 18.8-22.5% from an annual baseline of 438.2mm, increasing to 22.7-30.6 % for the 2080s. Seasonal changes in evapotranspiration reflect the annual trend, increasing above the baseline for all scenarios. The likely increases in winter evapotranspiration, however, display a much larger range than those projected for the summer across both the 2050s and 2080s.

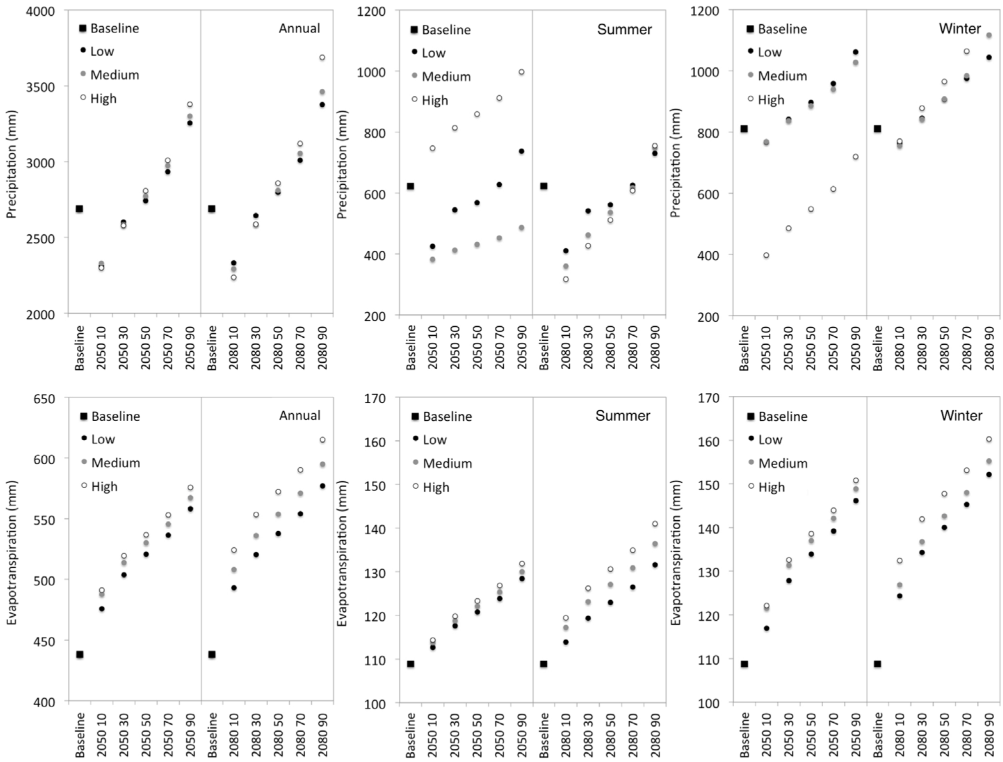

Figure 3 Projected mean absolute annual, summer (June-August) and winter (December-February) catchment precipitation and evapotranspiration for the baseline scenario at probabilities between 10% and 90% for each emissions scenario (Low, Medium, High) for the 2050s and 2080s. Note the different y-axis scales.

The mean monthly water levels in Sheskinmore Lough for the baseline and each climate change scenario are shown in Figure 4. From low to high emissions scenarios there is a general positive trend towards higher projected mean water levels throughout the year in both the 2050s and 2080s. However, there is more uncertainty associated with projected monthly, annual and seasonal water levels in 2080. Mean monthly water level is projected to rise by the greatest degree in winter, with suggested increases by 2050 and 2080. November in particular experiences the most notable increase, for example a rise by 255mm under 2050H90 and 288mm under 2080H90, with distinct but more variable scales of increase in December and January. During the majority of the spring and summer months, water level is projected to decline. The largest declines are projected in June (279mm) and July (293mm under 2050H10, and 288mm under 2080H10); however, these amounts are very likely to be exceeded.

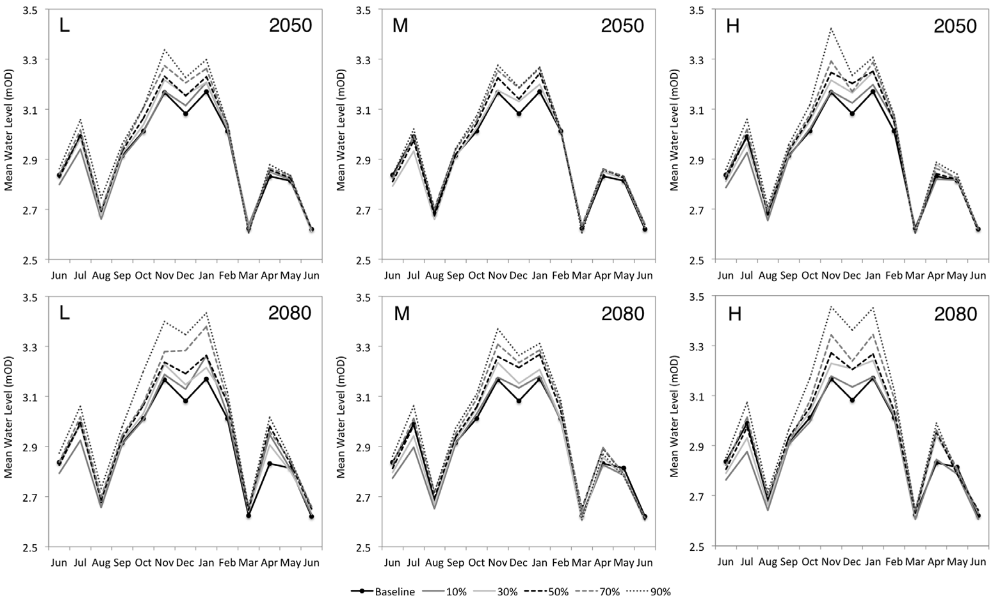

Figure 4 Projected mean monthly water level in Sheskinmore Lough for the baseline scenario at probabilities between 10% and 90% for each emissions scenario (L = Low, M = Medium, H = High) for the 2050s and 2080s.

Modelled hydrological response sluice management

Simulated mean daily water level in Sheskinmore Lough clearly shows the influence of variations in sluice settings under baseline climate conditions (Figure 5). The *as is* scenario exhibits large shifts in water level from an average level of 3.1mOD when the sluice is closed to an average level of 2.6mOD when the sluice is open. Under the *fully open* scenario, water levels fluctuate by <10cm around the lower (2.6mOD) average elevation. The shallow, flat topography of the Sheskinmore Lough system means that a drop in lake level from 2.65mOD to 2.55mOD equates to a 30% reduction in open water area. In contrast, when *fully closed*, water levels fluctuate more significantly (c. 80cm) around the higher (3.1mOD) average water level.

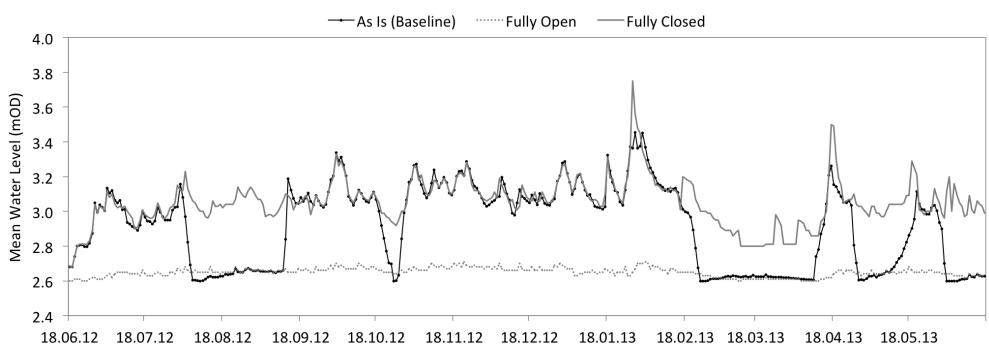

Figure 5 Projected mean daily water level in Sheskinmore Lough for the *as is*, *fully open* and *fully closed* scenarios under the baseline (*as is*) climate conditions.

Modelled hydrological response to sluice operation and climate change

Integration of hydrological management with climate change scenarios shows that mean monthly water levels are driven by the influence of the sluice rather than climate change (Figure 6). Mean monthly water levels currently vary by up to 0.55m under the *as is* management scenario, which is projected to vary by as much as 0.82m under 2080H90. If the sluice were *fully closed*, however, the range in mean monthly water levels would change from 0.39m to 0.6m under this extreme scenario. The *fully open* scenario exhibits an even smaller range, varying by up to just 0.07m in the current climate and by up to 0.08m under 2080H90.

Under the climate change scenarios, the largest obvious difference between the two scenarios is the retention of relatively high water levels in summer for the *fully closed* scenario although the inter-climate change scenario variation at this time of year is smaller than in the summer. Under the *fully open* scenario inter-climate change scenario variations are very small. Minor (<0.04m) declines from the baseline are projected for summer, autumn and winter at the 10% probability level. Little change is projected at the 50% probability level, and only at the 90% probability level do water levels increase, primarily during the winter and spring. Again, the magnitude of these changes is small (<0.04m).

The combined effect of future climate change and hydrological management on the lake and wetland system is shown in Figure 7. Here, median, low and high water levels (50^{th}, 10^{th} and 90^{th} percentiles respectively) predicted using the Medium emissions scenario and 90% probability level are visualised as wetted area. These show the likely extent of wet ground and open water under the different management scenarios. The results show that the impact of management on the extent of the water body, and annual range in this, is far greater than that associated with predicted climate change through to 2080. In all management scenarios, small changes in water level could lead to a slight expansion in the water body. But if sluice management shifted to either *fully open* or *fully closed*, this would lead, respectively, to a significant contraction or expansion of the water body, and an important reduction in annual water level variation.

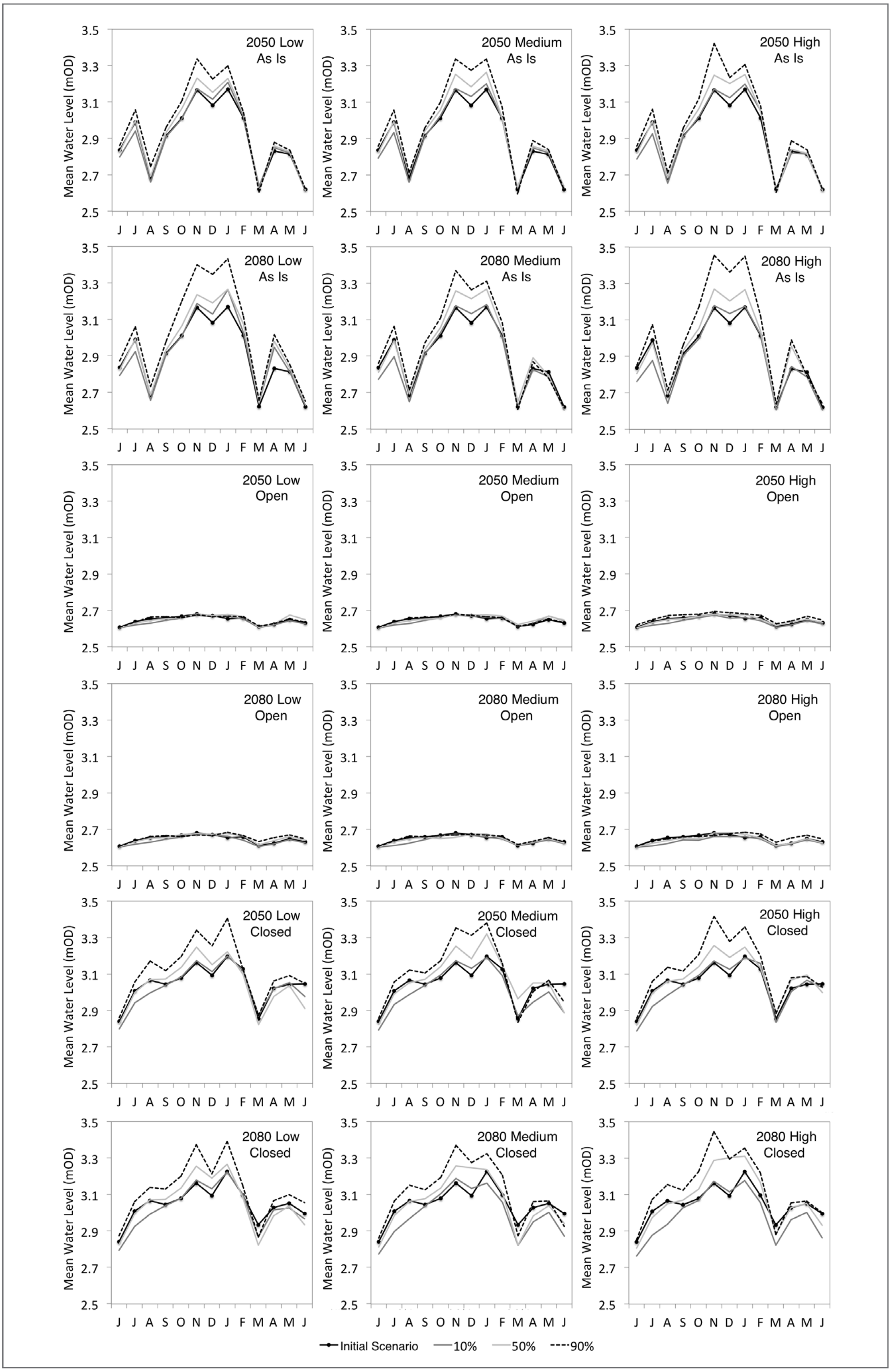

Figure 6 Projected mean monthly water level in Sheskinmore Lough under the three initial management scenarios (*as is*, *fully open*, *fully closed*) in the current climate, and also under the future climate change emissions scenarios (L = Low, M = Medium, H = High) at probabilities between 10% and 90% for the 2050s and 2080s.

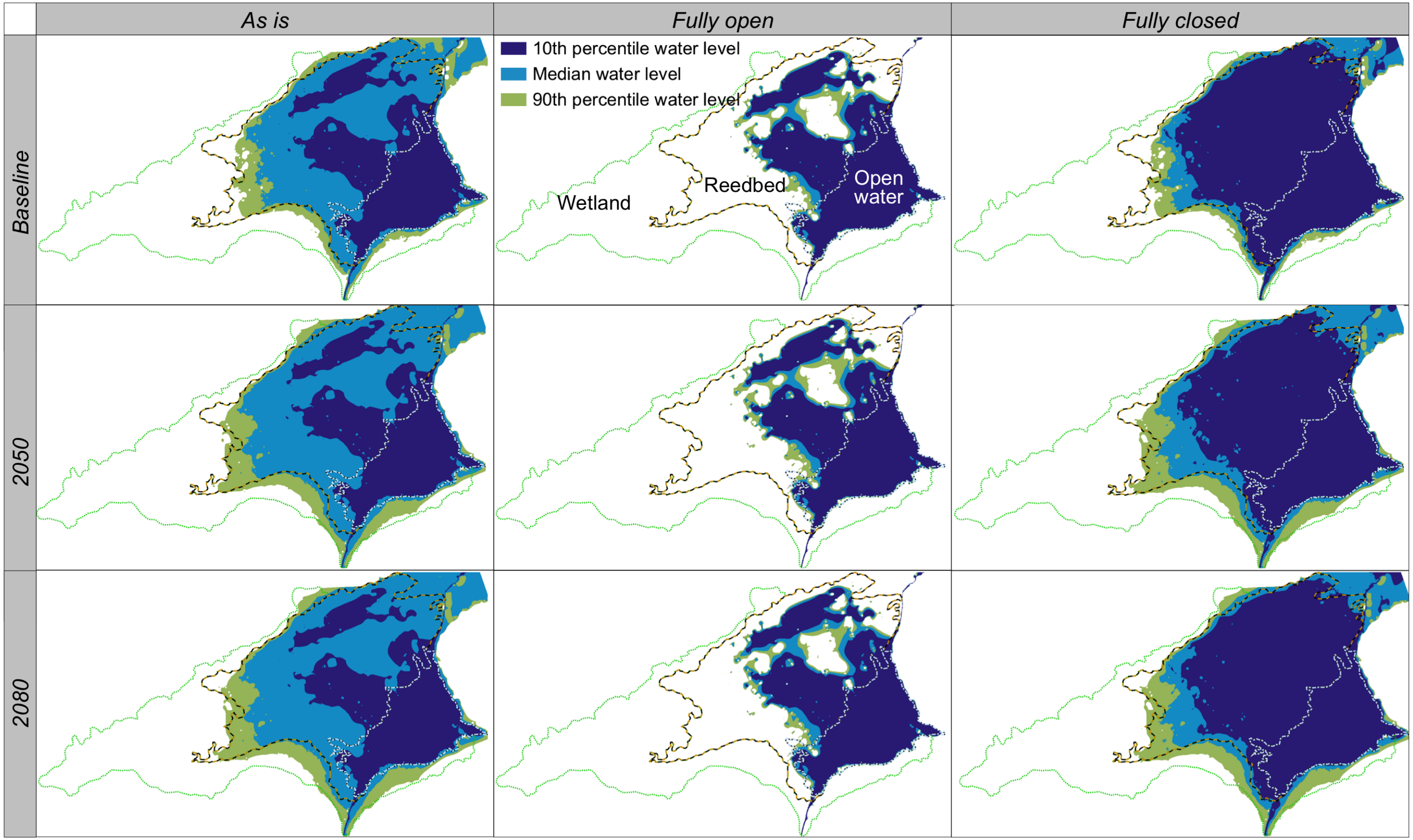

Figure 7 Impacts of future climate change and hydrological management on the wetted area of the Sheskinmore Lough and wetland system for scenarios based on the median, 10th and 90th percentile modelled lake water levels for each management scenario (*as is*, *fully open* and *fully closed*) under the Medium emissions scenario (90% probability level) for the 2050s and 2080s. Note the contemporary open water, reedbed and wetland habitats are delineated.

Discussion

Ecological responses to climate change

The results of this study have shown that the lake and wetland system at Sheskinmore Lough will be significantly impacted in the future by both climate change and any modification to sluice management. These changes are shown here to force distinct changes in the hydrological regime, which have undoubtedly impacted the sensitive aquatic ecosystems since sluice installation, and likely continue to do so into the future. In addition, indirect impacts to overland and groundwater flow are also important for the future sustainability of wider catchment habitats (Acreman *et al.,* 2013). Great uncertainties still remain, however, regarding the magnitude and extent of any climate-related hydrological changes (Thompson *et al.,* 2009), and hence their likely associated ecological impacts.

Hydrological modelling of the Sheskinmore Lough system shows that climate change has a noticeable impact on site water levels when contemporary hydrological management is unaltered. The extreme changes lead to an increase in mean annual lake water levels of 0.12m under 2080H90. It should be noted that these maximums, simulated at the 90% probability level, are very unlikely to be exceeded. Seasonal variation was also apparent in the modelling results, with lake level predicted to increase by up to 0.08m (2080H10) during autumn and winter, and decrease by as much as 0.12m (2080H10) during spring and summer. However, it is very likely that all of these amounts will be exceeded. Under the 2050H90 and 2080H90 scenarios, lake level increases by up to 0.15m in the autumn and 0.17m in the winter. In the spring and summer, under the same scenarios, lake level increases are unlikely to exceed 0.08m, and water levels are more than likely to decrease during the spring and summer (up to 0.06m) due to enhanced evapotranspiration caused by increased temperatures.

The simulations show that under current management intra-annual water level fluctuations are likely to increase over time. This will have a number of impacts on the ecology of the lake and wetland system at Sheskinmore Lough. Lake biota respond differently to changes in water level, and evidence shows that just small changes can result in large shifts in plant community composition (Coops *et al.,* 2003; Mjelde *et al.,* 2013). For example, littoral helophyte communities, including *Equisetum fluviatile*, *Carex* spp., and *Phragmites australis* found at Sheskinmore can be completely dependent on minor water level fluctuations to expose substrates for germination or flood seedlings (Wantzen *et al.,* 2008; Mjelde *et al.,* 2013). High water levels in winter may limit submersed plant expansion, whereas lower spring lake levels may encourage their expansion. At Sheskinmore Lough, it is the spring water levels that will most likely impact macrophyte dispersal, expansion and community composition, especially in the shallowest, littoral zone.

Disturbance from intra-annual water level fluctuations can cause mortality of aquatic plants through heating and desiccation in summer and reduced light penetration due to enhanced inundation in winter (Blindow, 1992; Irwin and Noble, 1996). Desiccation and inundation tolerance determine the distribution of littoral species (Mjelde *et al.,*

2013) including *Juncus bulbosus*, *Littorella uniflora* and *Equisetum fluviatile*, found along the aquatic-terrestrial transition zone around Sheskinmore Lough. When water depths across the system reach a maximum, inundation through flooding of the lake fringe in turn prevents respiration, reduces light levels required for photosynthesis, and initiates chemical changes (Middleton, 1995). The effects are consistent with disturbance factors that increase resource availability, cause the removal of dominant species and delay successional processes (Sousa, 1984). However, disturbance can also promote colonisation by a new suite of plant species (Salisbury, 1970; Mooij *et al.,* 2005).

A number of studies have identified climate-induced intra-annual water level fluctuations as a key disturbance factor in terms of hydrological influence on littoral vegetation dynamics (Gasith and Gafny, 1990; Irwin and Noble, 1996; Hroudova and Zakravsky, 1999; Abrahams, 2008). According to Grime (1979), the key mechanism linking climate change-induced increased water level fluctuations with impacts on lake shoreline communities is likely to be the disturbance regime generated by repeated drawdown and re-flooding along lake shorelines. Changes in species composition within Sheskinmore Lough shoreline habitats subject to increased water level fluctuations from climate change are likely to be dominated by a loss of competitive and stress-tolerant species with increasingly ruderal vegetation types and expanding areas of bare substrate. This will have significant impacts on the nature conservation value, ecosystem functioning and ecological services provided by the lake habitat.

In a study of Great Lakes wetlands, Mortsch (1998) concluded that an increased frequency and duration of low water levels produced by climate change, together with changes in the timing and amplitude of seasonal water levels, would affect wildlife, waterfowl and fish habitats, water quality, wetland area and vegetation diversity. However, other studies suggest that lakes suffering a decline in biodiversity through artificial stabilisation of water levels can experience a reversal of these adverse impacts (Wilcox and Meeker, 1991; Hill *et al.,* 1998). Similarly, Abrahams (2008) suggests that lakes that have become dominated by extensive stands of large competitive species could, with increased water-level fluctuations, develop greater species diversity through the creation of niches for less competitive species. At Sheskinmore, the projected increases in intra-annual water level fluctuations in the 2050s and 2080s under the three emissions scenarios are likely to be sufficient to enhance disturbance regimes, especially along the lake fringe.

Whatever the resulting emissions scenario in the 2050s and 2080s, climate change is likely to have an impact on the ecology of Sheskinmore Lough and similar west Ireland coastal sedimentary lake-wetland systems, especially the species and communities of the lake fringe and littoral zone. The contemporary system has been experiencing an altered hydrology since 2005 if not before, but in combination with other land management practices, for example, poaching by grazing of cattle around the lake fringe, the consequences of climate change are likely to be enhanced. Therefore, conservation management of the lake shoreline and littoral zone should focus on three key areas: water level management, maximising favourable substrate conditions and shoreline topography, and encouraging vegetation establishment (Abrahams, 2008). These will allow the adverse impacts of increased disturbance to be mitigated and enhance fertility in these areas so that biodiversity can be maintained despite the effects of climate change.

Ecological responses to hydrological management

The projected increases in climate change-driven intra-annual water level fluctuations in the 2050s and 2080s are likely to be altered through hydrological management using the existing sluice. Although natural water level fluctuations have the ability to maximise abiotic and biotic productivity and diversity necessary for species survival (Gafny *et al.,* 1992; Gafny and Gasith, 1999; Wantzen *et al.,* 2008), Turner *et al.* (2005) and Wagner and Falter (2002) stress that lake level manipulations, specifically where water levels are kept constant for extended periods, can result in decreased species diversity. Since aquatic biota have evolved in accordance with specific natural water level fluctuations, deviations from these patterns may exceed tolerance thresholds and dramatically alter community composition and diversity, especially in littoral areas (Sparks *et al.,* 1998; Bond *et al.,* 2008).

Hydrological management at Sheskinmore Lough to date has altered the natural hydrology of the lake and wetland system. Modelling shows that the sluice has two key impacts on water levels under current climate conditions. First, when *fully closed* (or when closed during the *as is* scenario) the sluice maintains mean monthly baseline water levels at elevations between 2.84mOD and 3.23mOD (0.39m range). When *fully open* (or when open during the *as is* scenario), mean monthly lake level ranges between 2.6mOD and 2.7mOD (0.1m range). Arguably, without the sluice, it is likely that the open water environment of the lake would not persist throughout the year. Although intra-annual fluctuations occur at these contrasting lake levels, they are eclipsed by the fluctuations imposed by the operation of the sluice during the *as is* scenario, which produces water level ranges of up to 0.85m. Second, the shifts in water level when the sluice is opened or closed occur extremely rapidly. When opened after a period of closure, rapid drawdown reduces water levels by up to 0.85m in less than seven days. Equally, closure of the sluice following an open period leads to a rapid rise in lake level of 0.85m in just five days.

Modified water level fluctuations have a number of potential impacts. Coops *et al.* (2003) observed that shallow lakes in The Netherlands have degraded due to pollution, eutrophication and modified water level fluctuations. This often results in deterioration of emergent vegetation along lake shorelines, with negative effects on food chains and desiccation of adjoining wetland areas (Ter Heerdt and Drost, 1994; Coops and Hosper, 2002). Hydrologically manipulated lakes are more sensitive to climate-driven changes in hydrology than natural, open lakes (Street, 1980; Kebede *et al.,* 2006), and climate change is beginning to force a rethink of water management in such systems (Coops *et al.,* 2003).

Only since the late 1990s have aquatic ecologists begun to recognise the importance of water level fluctuations for temperate lake ecosystems (Wilcox and Meeker, 1991; Wagner and Falter, 2002; Wantzen *et al.,* 2008). The hydrology environmental standards for lakes within the Water Framework Directive (WFD), for example, proposed a maximum permissible drawdown figure of 1m for macrophytes (Gosling and Hatton-Ellis, 2004). However, conflicting drawdown figures in the wider literature indicate the maximum water level range that lake biota can withstand is fairly arbitrary. Such figures are arguably largely dependent on lake morphology and should be used with caution, especially when applied to shallow lakes. For example, a 1m drawdown in a deep lake with steep sides would have little impact on the littoral habitat; however, in a shallow lake with gradual marginal inclines the impact could be significant. Indeed, determining the optimum or threshold water level fluctuation range of a lake system, especially a shallow one, requires system-specific tailoring.

In the case of Sheskinmore Lough, modelling has revealed that the current natural amplitude of water level fluctuations (i.e., when the sluice is *fully open* and when open during the *as is* scenario) is very small, at just 10cm. However, sluice operation increases this range by as much as 90cm. The shallow (<1.5m depth), flat (depths are mostly between 0.25m and 0.75m) morphology of Sheskinmore Lough means that sluice closure following a prolonged dry period (such as that observed from February to April in 2013) when lake level falls to absolute minimum (30cm in the deepest areas), results in the open water area of the lake increasing by as much as 80% following sluice closure (Figure 7).

Large, manipulated shifts in lake level fluctuations have a number of ecological implications for Sheskinmore Lough. First, raising water levels by up to 0.85m can noticeably alter the underwater light climate, especially in the deeper areas of the lake. Species that cannot withstand the lower light intensities associated with these increased depths are less likely to survive. Equally, they are more likely to be out-competed by species that thrive under lower light conditions. One such species is the rare submerged macrophyte *Najas flexilis*, which is listed in the SAC designation for Sheskinmore. It thrives at depths of up to 9m (Preston and Croft, 2001; Roden, 2002; Rostk and Schmidt, 2015), but is rarely associated with depths <1m, which dominate (85%) Sheskinmore Lough. Therefore, it is likely to be compromised when the lake level falls during periods of sluice opening over the summer months and would presumably not survive if natural conditions resumed (i.e., if the sluice were removed). Second, altering the overall lake water level can dramatically change the spatial distribution of erosion and deposition zones (Wantzen *et al.,* 2008).

The low-lying topography of coastal sedimentary lakes enhances the disturbance potential in the littoral and shallow areas. Even small changes in lake level produce significant shifts in lake extent. At Sheskinmore, lower water levels when the sluice is open exposes a greater area (up to 80%) of lakebed to wind and wave erosion, and cattle trampling. Frequent high wind speeds in northwest Ireland, combined with the loose, soft sandy sediments of these coastal sedimentary systems, mean the majority of macrophytes within the shallow areas of Sheskinmore Lough are likely to be impacted when the sluice is open, especially during winter when storms are generally more intense. Disturbance of lakebed sediments reduces the likelihood of germination and survival of macrophytes, especially those with shallow roots. Charophytes on the other hand do not possess roots and are fixed to the substrate via rhizoids (Hrivnak *et al.,* 2001; Van den Berg *et al.,* 2001; Van Nes *et al.,* 2002). Therefore, they are likely to fare better in these areas as they can be mobile with the sediment.

Low water levels during the spring and summer (when the sluice is open) also expose the littoral habitats to poaching by grazing cattle. High water levels in the wetland to the west (up to 30cm depth) during sluice closure, however, are likely to increase poaching by grazing cattle and horses due to increased access to freshwater. Although a certain amount of poaching disturbance can be beneficial for biodiversity, and grazing of emergent vegetation is an important part of freshwater habitat management to control encroachment of marginal vegetation, too much poaching is likely to exceed the tolerance levels of the majority of aquatic macrophytes. Complete absence of grazing by livestock on the other hand is generally regarded as detrimental to the biodiversity of marginal aquatic ecosystems (Oliver, 2007).

Hydrological management appears to have a distinct impact on *Phragmites australis* coverage. During the modelled period, the sluice was opened for an extended period (February to April 2013) followed by repeated shorter intervals throughout the rest of the year. Studies have shown that artificially lowering of spring and summer water levels enhances the growth of *Phragmites australis*, which benefits from a competition-free environment during early summer when water depths are minimal (<30cm) (Van den Brink *et al.,* 1993; Keto *et al.,* 2002; Hellsten *et al.,* 2006). In addition, Keto *et al.* (2008) and Weisner (1987) found that regulation of lake water at low levels provides optimal growth areas for *Phragmites australis* as wave exposure enhances oxygen saturation within sediments. Schmieder *et al.* (2004) and Nechwatal *et al.* (2008) both document the degradation of *Phragmites australis* following early spring floods when water levels are high. Extreme floods significantly reduce the oxygen supply to *Phragmites australis* rhizomes and submerged shoots, an impact that is becoming more widely accepted as a major factor in reed dieback (Koppitz, 2004; Ostendorp *et al.,* 2003; Dienst *et al.,* 2004). Therefore, opening the sluice for several extended periods is likely to have had a significant impact on the rigour of the *Phragmites australis* reedbed. As submerged vegetation within Sheskinmore Lough is relatively sparse and competition in the littoral zone consequently low, shallow water depths are likely to favour the expansion of *Phragmites australis* stands.

Projected lower spring and summer water levels, especially when the sluice is open, will reduce the area across the lake and wetland system suitable for waterfowl by approximately 80%. The short periods when the sluice was closed in spring and summer reveal that water levels during this time are raised to levels sufficient for breeding waders, but the lake fringe and wetland habitat may be vulnerable to excessive flooding during extreme rainfall events. Ausden (2014) suggests allowing an increased rate of drawdown during spring and summer, while encouraging flooding in winter. In the case of waders, areas might still remain wet enough during the breeding season, despite a greater rate of drawdown. If applied at Sheskinmore Lough, this approach would centre around accommodating, rather than resisting, changes in hydrology that occur as a result of climate change (Hoffmann, 1958; Valverde, 1958; Ausden, 2014). In order for this approach to work effectively, careful operation of the sluice would be required to ensure lake levels were not too low for too long during the spring and summer period. In addition, winter water levels should not be too high for too long. In the context of just one protected species, this approach would also have an important effect on the rare, protected whorl snail, *Vertigo geyeri*, which depends on summer groundwater levels within the wetland being maintained at or close to the ground surface (Cameron *et al.,* 2003; Holyoak, 2005).

Relative impacts of climate change and management on system ecohydrology

As discussed previously, moderate water level fluctuations tend to have a positive effect on species diversity and the conservation value of shoreline vegetation. The extreme fluctuations observed and projected under the *as is* and *fully closed* hydrological management scenarios, however, have revealed that hydrological management is more likely to have a more significant ecological impact than climate change when the two factors are examined independently. What is less clear, due to inherent uncertainties in climate change scenarios, is how the potential impacts of the sluice via hydrological management will be exacerbated or suppressed under future climate change. If water levels at Sheskinmore Lough have already reached an ecological threshold range under current conditions, then climate change has the potential to disrupt lake water levels to a point where this ecological tolerance threshold may be exceeded.

The likely future ecohydrological impacts from the combined influence of climate change and hydrological management on shallow coastal lake and wetland systems are summarised in Figure 8. The factors selected provide a simplified snapshot of potential future impacts at Sheskinmore Lough. The summary includes those flora and fauna that are most dependent on the lake and wetland system and, therefore, are most vulnerable to future changes, but does not capture the complete biodiversity of the site. The extreme fluctuations observed and projected under hydrological management scenarios (*as is* and *fully closed*), have shown that hydrological management arguably has a more significant ecological impact than climate change when the two factors are examined independently. Hydrological managers will need to consider a wider range of potential impacts and species requirements when developing future management strategies for Sheskinmore Lough and similar systems elsewhere in Ireland.

Climate change is beginning to force hydrological managers in wet temperate regions, such as northwest Ireland, to adjust water level management schemes so that they are more sensitive and, ultimately, more adaptable to future changes. Therefore, future management should allow a degree of water level fluctuation combining ecosystem rehabilitation with hydrological functions (Coops and Hosper, 2002). For example, the sluice could be modified to allow for more controlled water level management by allowing variable (i.e., smaller) volumes of water to pass through the sluice structure. To date, ecohydrological research has focused primarily on climate change prediction,

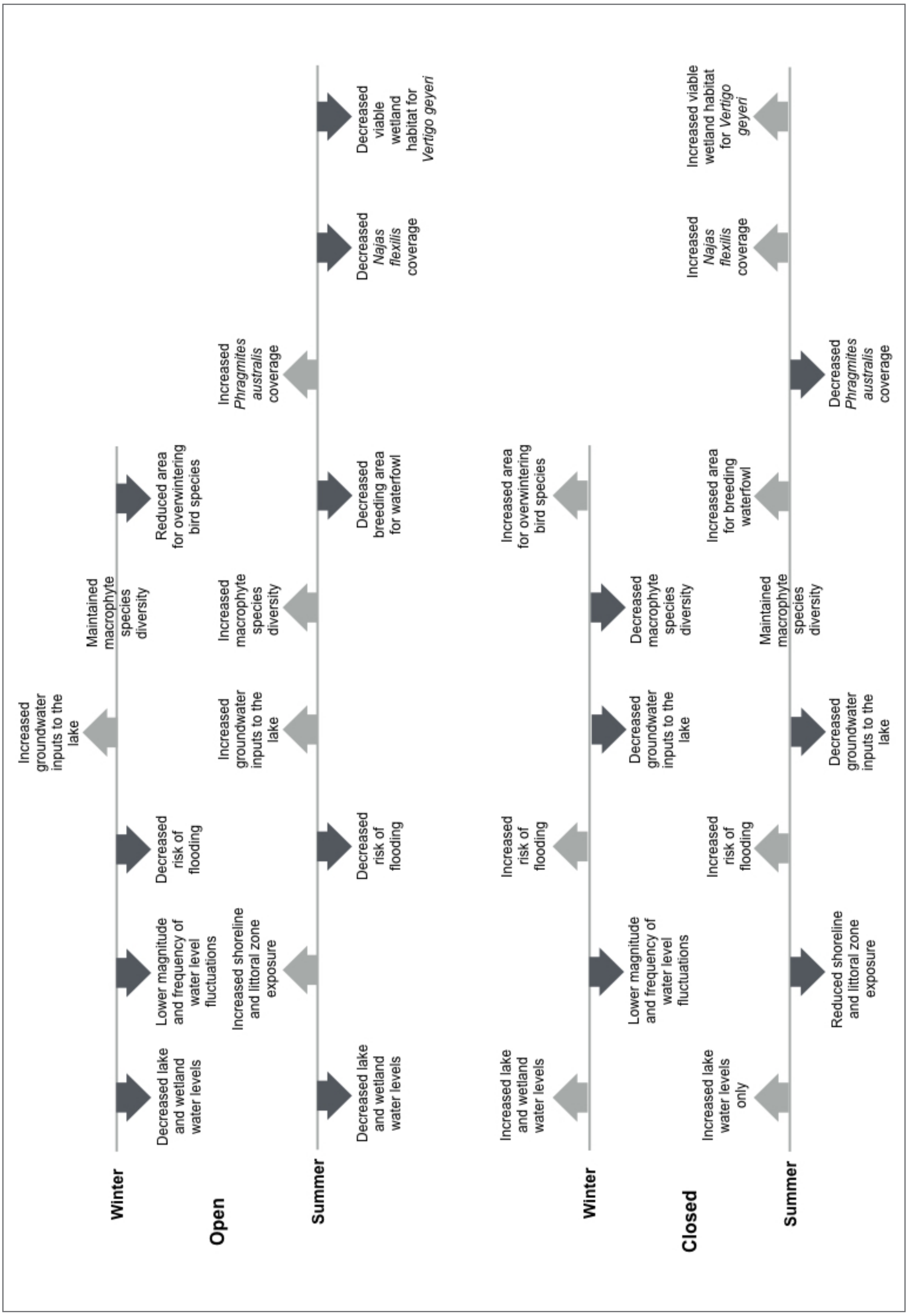

Figure 8 Summary of the likely future ecohydrological impacts per season and sluice status from the combined influence of climate change and hydrological management at Sheskinmore Lough.

impact assessment and mitigation, and there has been little attempt to develop practical adaptation methods to reduce potential climate change impacts on lakes and wetland systems (Hulme, 2005; Abrahams, 2008; Ausden, 2014). Such measures could increase the flexibility of management of important sites such as Sheskinmore Lough, enhancing the possibilities for complex ecosystems to adapt to change and reduce the additional pressures of non-climate related impacts (Abrahams, 2008; Ausden, 2014). A non-interventionist approach can be taken, accepting the changes to environments that will occur and allowing new habitats and communities to develop without substantial input. In many cases, however, a more appropriate approach is required, in order to implement active management strategies to ensure that the most severe effects of climate change are mitigated, as long as they facilitate beneficial adaptation to altered hydrologic regimes (Van Dam *et al.,* 2002). The question of sea-level rise impacts is beyond the scope of this work, particularly given the lack of evidence for contemporary sea-level rise in northwest Ireland. Although rising sea-levels in the future might influence the hydrology of this lake-wetland system, it is saline intrusion into groundwater that is of concern in many coastal lowland freshwater systems (Hiscock & Tanaka 2006; Sonnenborg *et al*. 2012).

Conclusions

The ability to predict future hydrological conditions and their potential impacts upon aquatic systems is vital if conservation management is to be successful and sustainable in the long-term. Modelling has revealed that hydrological management, specifically in the form of sluice operation, has had a dramatic effect on the ecohydrology of Sheskinmore Lough. When combined with climate change, these effects are even greater during periods when the sluice is closed. Under current sluice management, climate change is predicted to increase the magnitude of water level fluctuations by the end of the current century. From low to high emissions scenarios, there is a general positive trend towards higher projected mean water levels throughout the year in both the 2050s and 2080s, except during June, July and August when water levels are likely to decrease. However, there is more uncertainty associated with projected lake levels in the 2080s.

The projected increases in climate change-induced intra-annual water level fluctuations in the 2050s and 2080s are likely to be exacerbated by hydrological management. Modelling has shown that sluice operation has two key effects: generating artificially large ranges in water levels, and rapid drawdown and inundation rates, that have the potential to threaten lake systems with a number of negative impacts. Variations in water level are far greater under the *as is* scenario in comparison to the *fully closed* and, in particular, the *fully open* scenarios. On the whole, large lake level fluctuations are likely to have a number of detrimental ecological implications for Sheskinmore Lough as deviations from natural patterns exceed tolerance thresholds and dramatically alter community composition and diversity.

The extreme fluctuations observed and projected due to the operation of the sluice revealed that hydrological management has a more significant ecological impact on site biota than climate change, when the two factors are examined independently. When combined, impacts from both of these anthropogenic forces on the ecohydrology of the site together present the greatest overall threat. These findings are particularly concerning given the paucity of research on shallow coastal lake systems, and, in particular, their hydrological regime and functions. In the case of Sheskinmore Lough, modelling has revealed that the natural amplitude of water level fluctuations (i.e., when the sluice is fully open) is very small (10cm), which in itself can change the open water area by around 30% due to the shallow, flat morphology. Sluice closure, following a prolonged dry period, results in the open water area of the lake increasing by as much as 90%.

Water level changes are likely to have a number of impacts on the ecology of Sheskinmore Lough, leading to shifts in plant community composition and loss of species with specific water level regime requirements. This will have significant impacts on the nature conservation value, ecosystem functioning and ecological services provided by the lake habitat. The variety of biota under threat at Sheskinmore Lough, means hydrological managers need to consider all of the potential impacts, the array of vulnerable species, the specific ecohydrologies they depend on, and the overall biodiversity of the site, when developing future management strategies. From birds to snails and from rare plants to prolific invaders, a delicate balance between hydrological management for the maximisation of current biodiversity and hydrological management to enhance ecological resilience must be achieved going forwards.

Acknowledgements

We would like to express our sincere thanks to the National Parks and Wildlife Service (NPWS), especially to Tim Roderick, Emer Magee and Andrew Speer for their on-going assistance throughout the study. Thanks must also go to the Sheskinmore landowners for granting access: including Seamus Meehan, Michael Kennedy, Aidan Campbell, and BirdWatch Ireland. Finally, we would like to thank our various colleagues, friends and family for all of their help and support: Amanda Robinson, Arnaud Duranel, Barbara Gardner, David Maher-McWilliams, Malcolm McClure, Kasey Bolles and Stephanie Goodrich. We are grateful to the reviewers for their helpful points to improve the paper.

References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J., 1986. An Introduction to the European Hydrological System – Système Hydrologique Européen 'SHE', 1: History and philosophy of a physically based distributed modelling system. *Journal of Hydrology*, 87, 45-59.

Abrahams, C., 2008. Climate change and lakeshore conservation: a model and review of management techniques. *Hydrobiologia*, 613, 33-43.

Acreman, M.C., Blake, J.R., Mountford, O., Stratford, C., Prudhomme, C., Kay, A., Bell, V., Gowing, D., Rothero, E., Thompson, J., Hughes, A., Barkwith, A. and van de Noort, R., 2013. *Guidance on using the Wetland Toolkit for Climate Change: A contribution to the Wetland Vision Partnership*. Wallingford, UK, Centre for Ecology and Hydrology, 1-75.

Afzal, M., Gagnon, A.S. and Mansell, M.G., 2015. The impact of projected changes in climate variability on the reliability of surface water supply in Scotland. *Water Science and Technology*, 15, 736-745.

Aldridge, B.N. and Garrett, J.M., 1973. Roughness coefficients for stream channels in Arizona. US Geological Survey Open-File Report, 1-87.

Andersen, J.A., Refsgaard, J.C. and Jensen, K.H., 2001. Distributed hydrological modelling of the Senegal River Basin—model construction and validation. *Journal of Hydrology*, 247, 200-214.

Ausden, M., 2014. Climate Change Adaptation: Putting Principles into Practice. *Environmental Management*, 54, 685-698.

Baker, C., Thompson, J.R. and Simpson, M., 2009. Hydrological dynamics I: Surface waters, flood and sediment dynamics. In E.B. Maltby and T. Barker, (Eds). *The Wetlands Handbook*. Chichester, Wiley-Blackwells, 120-168.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, IPCC Secretariat.

Bell, S., Cornford, D. and Bastin, L. 2015. How good are citizen weather stations? Addressing a biased opinion. *Weather*, 70, 75-84. doi:10.1002/wea.2316

Bell, V.A., Kay, A.L., Cole, S.J., Jones, R.G., Moore, R.J. and Reynard, N.S., 2012. How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *Journal of Hydrology*, 442, 89-104.

Blindow, I., 1992. Long and short-term dynamics of submerged macrophytes in two shallow eutrophic lakes. *Freshwater Biology*, 28, 15-27.

Boggie, R. and Knight, A.H., 1960. Studies of root development in a grass sward growing on deep peat using radioactive tracers. Aberdeen, Macaulay Institute for Soil Research, 133-136.

Bond, R.B., Lake, P.S. and Arthington, A.H., 2008. The impacts of drought on freshwater ecosystems: An Australian perspective. *Hydrobiologia*, 600, 3-16.

Bradford, R.B. and Acreman, M.C., 2003. Applying MODFLOW to wet grassland in-field habitats: A case study from the Pevensey Levels, UK. *Hydrology and Earth Sciences*, 7, 43-55.

Burt, S. 2012. The Weather Observer's Handbook. Cambridge University Press.

Butts, M.B., Dubicki, A., Stronska, K., Jørgensen, G., Nalberczynski, A., Lewandowski, A. and van Kalken, T., 2005. Flood forecasting for the Upper and Middle Odra River Basin. Accepted for publication. In: Flood Risk Management in Europe: Innovation in Policy and Practice, Advances in Natural and Technological Hazards Research Series.

Cameron, R.A.D., Colville, B., Falkner, G., Holyoak, G.A., Hornung, E., Killeen, I.J., Moorkens, E.A., Pokryszko, B.M., Von Proschwitz, T., Tattersfield, P. and Valovirta, I., 2003. Species accounts for snails of the genus *Vertigo* listed in Annex II of the Habitats Directive. In: M.C.D. Speight, E.A. Moorkens and G. Falkner, (Eds), Proceedings of the Workshop on Conservation Biology of European *Vertigo* species. Dublin, April 2002. Heldia 5, Sonderheft 7, 151-170.

Chow, V.T., 1959. *Open-channel hydraulics.* New York, McGraw-Hill.

Coops, H. and Hosper, S.H., 2002. Water-level Management as a Tool for the Restoration of Shallow Lakes in the Netherlands. *Lake and Reservoir Management*, 18, 293-298.

Coops, H., Beklioglu, M. and Crisman, T.L., 2003. The role of water-level fluctuations in shallow lake ecosystems – workshop conclusions. *Hydrobiologia*, 506, 23-27.

DHI, 2005. MIKE SHE, An Integrated Hydrological Modelling System: User Guide. Horsholm, Denmark, DHI Water & Environment.

Dienst, M., Schmieder, K. and Ostendorp, W., 2004. Dynamik der Schilfrohrichte am Bodensee unter dem Einfluß von Wasserstandsvariationen. *Limnologica*, 34, 29-36.

Dittmer, H.J., 1959. A study of the root system of certain sand dune plants in New Mexico. *Ecology*, 40, 265-273.

Duranel, A.J., 2015. Hydrology and hydrological modelling of acidic mires in Central France. London, University College London, PhD Thesis.

Fowler, H.J. and Kilsby, C.G., 2007. Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change*, 80, 337-367.

Gafny, S. and Gasith, A., 1999. Spatially and temporally sporadic appearance of macrophytes in the littoral zone of Lake Kinneret, Israel: Taking advantage of a window of opportunity. *Aquatic Botany*, 62, 249-267.

Gafny, S., Gasith, A. and Goren, M., 1992. Effect of water level fluctuation on shore spawning of Mirogrex terraesanctae (Steinitz), (Cyprinidae) in Lake Kineret, Israel. *Journal of Fish Biology*, 41, 863-871.

Gardner, E.A., 2016. The ecohydrology and conservation of a coastal sedimentary lake and wetland system: Sheskinmore Lough, Donegal, Ireland. PhD Thesis. London, University College London.

Gasith, A. and Gafny, S., 1990. Effects of water level fluctuation on the structure and function of the littoral zone. In: M.M. Tilzer and C. Serruya, (Eds), Large Lakes: Ecological Structure and Function. New York, Springer-Verlag.

Gosling, R. and Hatton-Ellis, T., 2004. A proposal for amending the hydrology environmental standards for lakes. UKTAG Report.

Graham, D.N. and Butts, M.B., 2005. Flexible, integrated watershed modelling with MIKE SHE. In: V.P. Singh and D.K. Frevert, (Eds), *Watershed Models*, Boca Raton, CRC Press, 245-272.

Grime, J.P., 1979. *Plant Strategies and Vegetation Processes*. Chichester, Wiley.

Havnø, K., Madsen, M.N. and Dørge, J., 1995. MIKE 11: A generalised river modelling package, in Computer Models of Watershed Hydrology. In: V.P. Singh, 1995, (Ed), Colorado, Water Resources Publications, 809-846.

Hellsten, S., Keto, A., Suoraniemi, M. and Partanen, S., 2006. Long term changes in the aquatic vegetation of Lake Paijanne, Southern Finland. *Verhandlung International Verein Limnology*, 29, 1167-1173.

Henriksen, H.J., Troldborg, L., Højberg, A.J. and Refsgaard, J.C., 2008. Assessment of exploitable groundwater resources of Denmark by use of ensemble resource indicators and a numerical groundwater-surface water model. *Journal of Hydrology*, 348, 224-240.

Hill, N.M., Keddy, P.A. and Wisheu, I.C., 1998. A hydrological model for predicting the effects of dams on the shoreline vegetation of lakes and reservoirs. *Environmental Management*, 22, 723-736.

Hiscock, K. and Tanaka, Y., 2006. Potential impacts of climate change on groundwater resources: From the high plains of the US to the flatlands of the UK. *National Hydrology Seminar*, 19-25.

Hoffmann, L., 1958. An ecological sketch of the Camargue. *British Birds*, 51, 321-349.

Holyoak, GA., 2005. Widespread Occurrence of *Vertigo geyeri* (Gastropoda: Vertiginidae) in North and West Ireland. *The Irish Naturalists' Journal*, 28, 141-150.

Hrivnak, R., Otahelova, H. and Husak, S., 2001. *Nitella mucronata* and *N. translucens* – contribution to occurrence and ecology in Slovakia. *Biologia*, 56, 13-15.

Hroudova, Z. and Zakravsky, P., 1999. Vegetation dynamics in a fishpond littoral related to human impact. *Hydrobiologia*, 415, 139-145.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S., 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Norwich, University of East Anglia, UK, Tyndall Centre for Climate Change Research, School of Environmental Sciences.

Hulme, P.E., 2005. Adapting to climate change: is there scope for ecological management in the face of a global threat? *Journal of Applied Ecology*, 42, 784-794.

IPCC, 2000. Special Report on Emissions Scenarios (SRES): A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, UK, Cambridge University Press.

Irwin, E.R. and Noble, R.L., 1996. Effects of reservoir drawdown on littoral habitat: assessment with on-site measures and Geographic Information Systems. *American Fisheries Society Symposium*, 16, 324-331.

Jenkins, G.J., Murphy, J.M., Sexton, D.M.H., Lowe, J.A., Jones, P. and Kilsby, C.G., 2009. UK Climate Projections: Briefing Report. Met Office Hadley Centre, Exeter, UK.

Johnson, A.C., Acreman, M.C., Dunbar, M.J., Feist, S.W., Giacomello, A.M., Gozlan, R.E., Hinsley, S.A., Ibbotson, A.T., Jarvie, H.P., Jones, J.I., Longshaw, M., Maberly, S.C., Marsh, T.J., Neal, C., Newman, J.R., Nunn, M.A., Pickup, R.W., Reynard, N.S., Sullivan, C.A., Sumpter, J.P. and Williams, R.J., 2009. The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. *Science of the Total Environment*, 407, 4787-4798.

Kebede, S., Travi, Y., Alemayehu, T. and Marc, V., 2006. Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology*, 316, 233-247.

Keto, A., Hellsten, S. and Eloranta, P., 2002. Notes on the ecology of common reed in Lake Paijanne, Finland. *Verhandlung International Verein Limnology*, 28, 586-590.

Keto, A., Tarvainen, A., Marttunen, M. and Hellsten, S., 2008. Use of the water-level fluctuation analysis tool (Regcel) in hydrological status assessment of Finnish lakes. *Hydrobiologia*, 613, 133-142.

Kingston, D.G., Thompson, J.R. and Kite, G., 2011. Uncertainty in climate change projections of discharge for the Mekong River Basin. *Hydrology and Earth System Sciences Discussions*, 7, 5991-6024.

Klemes, V., 1986. Operational testing of hydrological simulation. *Hydrological Sciences Journal*, 31, 31-24.

Koppitz, H., 2004. Effects of flooding on the amino acid and carbohydrate patterns of *Phragmites australis*. *Limnologica*, 34, 37-47.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z. and Shiklomanov, I.A., 2007. Freshwater resources and their management. In: M.L.Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, CE., (Eds), 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, Cambridge University Press, 173-210.

Lalke-Porczyk, E. and Donderski, W., 2004. The role of bacteria growing on the root system of the common reed (Phragmites australis [Cav.] Trin. Ex Steudel) in the Metabolism of Organic Compounds. *Polish Journal of Environmental Studies*, 14, 57-64.

Langhoff, J.H., Christensen, S. and Rasmussen, K.R., 2001. Scale dependent hydraulic variability of a stream bed on an outwash plain. *Impact of Human Activity on Groundwater Dynamics*, 269, 205-212.

Maltby, E.B., Ormerod, S., Acreman, M.C., Blackwell, M., Durance, I., Everard, M., Morris, J., Spray, C., Biggs, J., Boon, P., Brierley, B., Brown, L., Burn, A., Clarke, S., Diack, I., Duigan, C., Dunbar, M., Gilvear, D., Gurnell, A., Jenkins, A., Large, A., Maberly, S., Moss, B., Newman, J., Robertson, A., Ross, M., Rowan, J., Shepherd, M., Skinner, A., Thompson, J.R., Vaughan, I. and Ward, R., 2011. Freshwaters – Openwaters, Wetlands and Floodplains in The UK National Ecosystem Assessment Technical Report. UK National Ecosystem Assessment, UNEP-WCMC, Cambridge, 295-360.

McGrath, R., Wang, S., Nolan, P., Nishimura, E., Semmler, T., Sweeney, C. and Lynch P., 2005. Climate Change: Regional Climate Model Predictions for Ireland. Johnston Castle, Wexford, Environmental Protection Agency Report, 1-45.

Medlin, J.M., Kimball, S.K. and Blackwell, K.G., 2007. Radar and rain gauge analysis of the extreme rainfall during Hurricane Danny's 1997 Landfall. Monthly Weather Review, 135, 1869-1888.

Middleton, B.A., 1995. Seedbanks and species richness potential of coal slurry ponds reclaimed as wetlands. *Restoration Ecology*, 34, 311-318.

Mitsch, W.J. and Gosselink, J.G., 2015. *Wetlands*. New York, Wiley.

Mjelde, M., Hellsten, S. and Ecke, F., 2013. A water level drawdown index for aquatic macrophytes in Nordic lakes. *Hydrobiologia*, 704, 141-151.

Mooij, W.M., Hulsmann, S., De Senerpont Domis, L.N., Nolet, B.A., Bodelier, P.L.E., Boers, P.C.M., Dionisio Pires, L.M., Gons, J.J., Ibelings, B.W., Noordhuis, R., Portielje, R., Wolfstein, K. and Lammens, E.H.R.R., 2005. The impact of climate changes on lakes in the Netherlands: a review. *Aquatic Ecology*, 39, 381-400.

Mortsch, L.D., 1998. Assessing the Impact of Climate Change on the Great Lakes Shoreline Wetlands. *Climatic Change*, 40, 391-416.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12, 513-522.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T.P., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R. and Wood, R.A., 2009. UK Climate Projections Science Report: Climate change projections. Exeter, UK, Met Office Hadley Centre.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, Part 1: A discussion of principles. *Journal of Hydrology*, 10, 282-290.

Nechwatal, J., Wielgoss, A. and Mendgen, K., 2008. Flooding events and rising water temperatures increase the significance of the reed pathogen *Pythium phragmitis* as a contributing factor in the decline of *Phragmites australis*. *Hydrobiologia*, 613, 109-115.

Office of Public Works, 2014. Hydro-Data Ireland Website: Estimated Flow Data for Owenea River. http://www.opw.ie/hydro/index.asp?mpg=dmf.asp%3Fid%3D38001. [Accessed 16th July 2014].

Oliver, G.A., 2007. Coastal Lagoons: Conservation Status Assessment Report. Dublin, Dúchas.

Ostendorp, W., Dienst, M. and Schmieder, K., 2003. Disturbance and rehabilitation of lakeside *Phragmites* reeds following an extreme flood in Lake Constance (Germany). *Hydrobiologia*, 506, 687-695.

Phillips, J.V. and Tadayon, S., 2007. Selection of Manning's Roughness Coefficient for Natural and Constructed Vegetated and Non-Vegetated Channels, and Vegetation Maintenance Plan Guidelines for Vegetated Channels in Central Arizona. Virginia, US Geological Survey, 1-49.

Preston, C.D. and Croft, J.M., 2001. *Aquatic Plants in Britain and Ireland*. Colchester, Harley Books.

Refsgaard, J.C. and Storm, B., 1995. MIKE SHE. In: V.P. Singh, (Ed), Computer Models of Watershed Hydrology. Highland Ranch, Colorado, Water Resources Publications: 809-846.

Refsgaard, J.C., Storm, B. and Clausen, T., 2010. Système Hydrologique Europeén (SHE): review and perspectives after 30 years development in distributed physically-based hydrological modelling. *Hydrology Research*, 41, 355.

Roden, C., 2002. The distribution of *Najas flexilis* in County Donegal. Dublin, Dúchas.

Rostk, W. and Schmidt, W.L.E., 2015. West of Ardara/Maas Road SAC Conservation objectives supporting document: *Najas flexilis*. NPWS Survey Report, 1-25.

Salisbury, E.J., 1970. The pioneer vegetation of exposed muds and its biological features. *Philosophical Transactions of the Royal Society of London Series B*, 259, 207-255.

Schmieder, K., Dienst, M., Ostendorp, W. and Johnk, K., 2004. Effects of water level variations on the dynamics of the reed belts of Lake Constance. *Ecohydrology and Hydrobiology*, 4, 469-480.

Singh, C.R., Thompson, J.R., French, J.R., Kingston, D.G. and Mackay, A.W., 2010. Modelling the impact of prescribed global warming on water resources of headwater catchments of the Irrawaddy River and their implications for Loktak Lake, northeast India. *Hydrology and Earth System Sciences*, 14, 1745-1765.

Sorrel, B.K., Mendelssohn, I.A., McKee, K.L. and Woods, R.A., 2000. Ecophysiology of wetland plant roots: A modelling comparison of aeration in relation to species distribution. *Annals of Botany*, 86, 675-685.

Sousa, W.P., 1984. The role of disturbance in natural communities. *Annual Review of Ecology and Systematics*, 15, 353-391.

Sonnenborg, T.O., Hinsby, K., van Roosmalen, L. and Stisen, S., 2012. Assessment of climate change impacts on the quantity and quality of a coastal catchment using a coupled groundwater–surface water model. *Climatic Change*, 113(3-4), 1025-1048.

Sparks, R.E., Nelson, J.C. and Yin, Y., 1998. Naturalization of the flood regime in regulated rivers. *BioScience*, 48, 706-720.

Street, F.A., 1980. The relative importance of climate and local hydrogeological factors in influencing lake-level fluctuations. *Palaeoecology of Africa*, 12, 137-158.

Sweeney, J. Brereton, T., Byrne, C., Charlton, R., Emblow, C., Fealy, R., Holden, N., Jones, M., Donnelly, A., Moore, S., Purser, P., Byrne, K., Farrell, E., Mayes, E., Minchin, D., Wilson, J. and Wilson, J., 2003. *Climate Change: Scenarios & Impacts for Ireland*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland, 229.

Ter Heerdt, G.N.J. and Drost, H.J., 1994. Potential for the development of marsh vegetation from the seed bank after a drawdown. *Biological Conservation*, 67, 1-11.

Thompson, J.R., 2012. Modelling the impacts of climate change on upland catchments in southwest Scotland using MIKE SHE and the UKCP09 probabilistic projections. *Hydrology Research*, 43, 507-530.

Thompson, J.R., Gavin, H., Refsgaard, A., Refstrup Sørenson, H. and Gowing, D.J., 2009. Modelling the Hydrological Impacts of Climate Change on UK Lowland Wet Grassland. *Wetlands Ecology and Management*, 17, 503-523.

Thompson, J.R., Green, A.J., Kingston, D.G. and Gosling, S.N., 2013. Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *Journal of Hydrology*, 486, 1-30.

Thompson, J.R., Iravani, H., Clilverd, H.M., Sayer, C.D., Heppell, C.M. and Axmacher, J.C., 2017. Simulation of the hydrological impacts of climate change on a restored floodplain. *Hydrological Sciences Journal*, 62, 2482-2510.

Thompson, J.R., Refstrup Sørenson, H., Gavin, H. and Refsgaard, A., 2004. Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in Southeast England. *Journal of Hydrology*, 293, 151-179.

Turner, M.A., Huebert, D.B., Findlay, D.L., Hendzel, L.L., Jansen, W.A., Bodaly, R.A., Armstrong, L.M. and Kasian, S.E.M., 2005. Divergent impacts of experimental lake-level drawdown on planktonic and benthic plant communities in a boreal forest lake. *Canadian Journal of Fisheries and Aquatic Sciences*, 62, 991-1003.

Valverde, J.A., 1958. An ecological sketch of the Coto Donana. *British Birds*, 51, 1-23.

Van Dam, R., Gitay, H. and Finlayson, M., 2002. Climate Change and Wetlands: Impacts, Adaptation and Mitigation: Ramsar COP8 DOC. 11 Information Paper. Ramsar Convention Bureau.

Van den Berg, M.S., Coops, H. and Simons, J., 2001. Propagule bank buildup of *Chara aspera* and its significance for colonization of a shallow lake. *Hydrobiologia*, 462, 9-17.

Van den Brink, F.W.B., van der Velde, G. and bij de Vaate, A., 1993. Ecological aspects, explosive range extension and impact of a mass invader, *Corophium curvispinum* Sars, 1895 (Crustacea: Amphipoda), in the Lower Rhine (The Netherlands). *Oecologia*, 93, 224-232.

Van Nes, E.H., Scheffer, M., Van den Berg, M.S. and Coops, H., 2002. Dominance of charophytes in eutrophic shallow lakes – when should we expect it to be an alternative stable state? *Aquatic Botany*, 72, 275-296.

Wagner, T. and Falter, M.C., 2002. Response of an aquatic macrophyte community to fluctuating water levels in an oligotrophic lake. *Lake and Reservoir Management*, 18, 52-65.

Wantzen, K.M., Rothhaupt, K-O., Mortl, M., Cantonati, M., Toth, L.G. and Fischer, P., (Eds) 2008. Ecological effects of water-level fluctuations in lakes. *Developments in Hydrobiology*, 204, 21-31.

Weglarczyk, S., 1998. The interdependence and applicability of some statistical quality measures for hydrological models. *Journal of Hydrology*, 206, 98-103.

Weisner, S.E.B., 1987. The relation between wave exposure and distribution of emergent vegetation in a eutrophic lake. *Freshwater Biology*, 18, 537-544.

Wilcox, D.A. and Meeker, J.E., 1991. Disturbance Effects on Aquatic Vegetation in Regulated and Unregulated Lakes in Northern Minnesota. *Canadian Journal of Botany*, 69, 1542-1551.

Yang, D.W., Herath, S. and Musiake, K., 2002. A hillslope-based hydrological model using catchment area and width functions. *Hydrological Sciences Journal*, 47, 49-65.

Zhang, Z., Wang, S. and Sun, G., 2008. Evaluation of the MIKE SHE Model for the Application in the Loess Plateau, China. *Journal of the American Water Resources Association*, 44, 1-5.

Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W. and Morgan, K.T., 2010. Step by step calculation of the Penman-Monteith evapotranspiration (FAO-56 Method). University of Florida.