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Understanding the hydrological functioning of a shallow lake system within a coastal karstic aquifer in Wales, UK

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SUMMARY

Bosherston Lakes in west Wales are an internationally important set of linked freshwater lowland lakes which were created by damming tidal creeks in the 18th and 19th centuries. The lakes have an average water depth of 1–3 m, and receive surface water inflows but have an uncertain interaction with the underlying karstic Carboniferous Limestone. This paper describes the application of the Soil Water Assessment Tool (SWAT) to improve the understanding of the hydrological functioning of the lake system. The temporally variable and limited observational data were used within a two-step calibration process. The simulated surface water inflows and groundwater levels were calibrated, followed by the lake volumes (Nash–Sutcliffe (NS) coefficient ranging from 0.67 to 0.74). Finally the simulated lake volumes were validated (NS ranging from 0.56 to 0.74) and the simulated lake outflows demonstrated to be plausible. Simulations reveal that three of the four linked water bodies lose significant water to the underlying aquifer. The simulated water balance demonstrates that the catchment outputs are dominated by evapotranspiration, surface outflow from the lake system to the sea and coastal groundwater discharge, with abstraction and lake evaporation being of lesser importance. The coastal groundwater discharge originates from both leakage from the lakes and previously unrecognised larger scale groundwater flow paths in the limestone aquifer. The study has provided an improved basis for the future hydrological management of the catchment and lakes and has demonstrated the wider utility of SWAT in simulating karstic systems.

Introduction

Freshwater coastal ecosystems are intrinsically vulnerable to environmental degradation given their proximity to the sea, low water volume, generally low elevation and pressures from coastal development, abstraction and agriculture (UNEP, 2006). Shallow lakes respond more directly to prevailing weather conditions than deeper lakes due to their smaller volume and lack of stratification (Gerten and Adrian, 2001; Mooij et al., 2007), and wind–wave action easily penetrates to the lake bottom. As a result, sediment and nutrients in shallow lakes, unlike in deeper lakes, are constantly mixing in or with the water column. The water level regime is an important factor for lake ecosystem functioning and affects conservation values (Coops et al., 2003). Levels naturally fluctuate due to variations in climatic conditions and human activities (Blindlow, 1992), which can cause disturbance for submerged plant communities. Excessive high water levels in the growing season will reduce light availability while low water levels may damage plants due to ice and wave action during winter or desiccation in summer (Coops et al., 2003). There is consequently an increasing need for sustainable water management to contribute to the conservation of these important ecosystems (Janse et al., 2008; Reed et al., 2008; Tatrai et al., 2008). Understanding the hydrological processes controlling the current behaviour of shallow lakes is therefore fundamental to the current and long term management of these ecologically-important waterbodies and to understanding their resilience to future climate change.

The coastal Bosherston Lakes in west Wales, UK (Fig. 1) (51.617 °N, −4.925 °W), are an outstanding shallow marl lake system which has been classified under the European Habitats Directive as a Special Area of Conservation (SAC) due to its habitat of "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.". Charophytes or Stoneworts (Stewart, 2004) are represented by bristly stonewort *Chara hispida* which forms dense beds up to 1 m high, with individual plants up to 3.5 m long, and by variable quantities of *Chara globularis*, *Chara virgata* and *Chara vulgaris*. The lakes are fed by two small streams but it is thought that there is considerable interaction between the lake and the groundwater within the underlying karstic limestone aquifer (Rees and Hinton,

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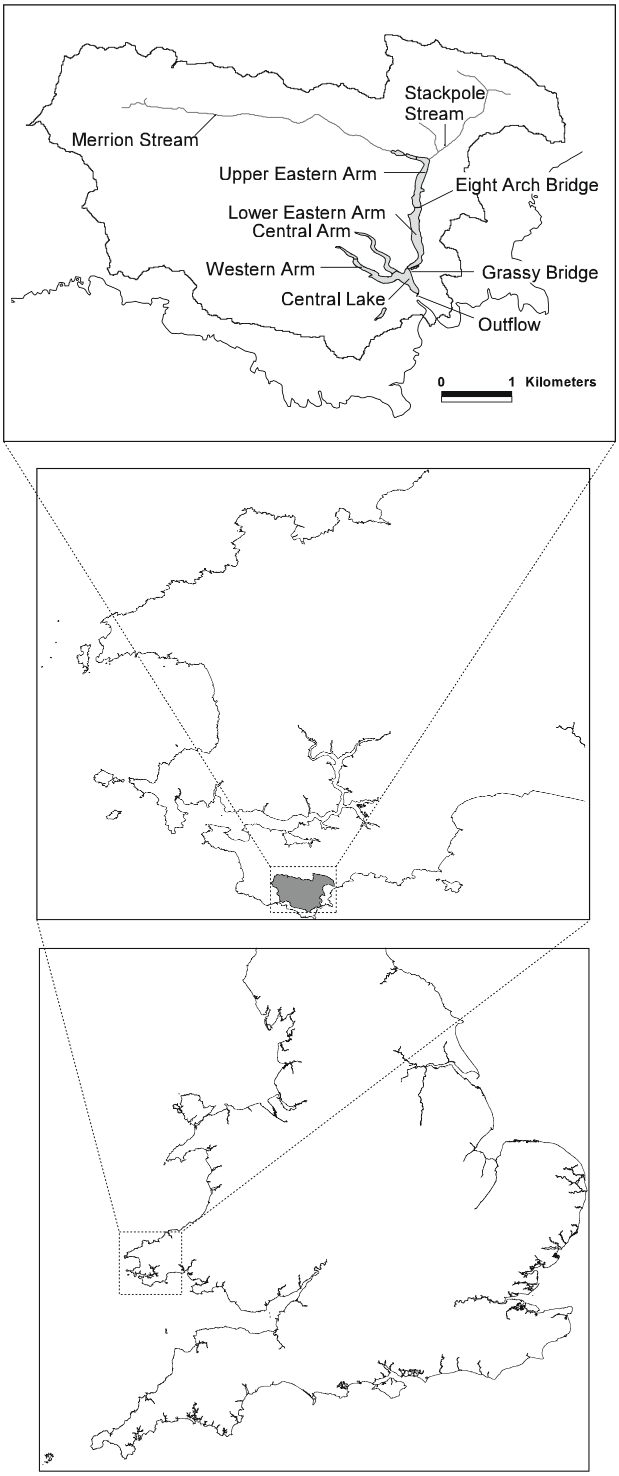

Fig. 1. Bosherston Lakes and catchment.

1989). Given their proximity to the sea and shallow water depths of 1–3 m, there are many threats to this fragile freshwater ecosystem. In particular the lakes are vulnerable to siltation, nutrient enrichment (both through groundwater and surface water inflows) and drought (leading to low water levels). They have a history of catchment eutrophication during the early to late 20th Century with declining water quality due to sewage inputs (now ceased) and increasingly intensive agriculture in the catchment (Rees et al., 1991), but the apportionment of flows and nutrient fluxes to the lake from groundwater and surface water are poorly understood. As a result the system is classified as being in unfavourable condition due to eutrophication and insufficient *Chara* cover (Burgess et al., 2006), although the Central Arm and Western Arm are classified as being in favourable condition. This paper therefore describes the application of the Soil Water Assessment Tool (or SWAT model) to provide a quantitative understanding of the hydrological processes controlling lake water levels, flushing rates and groundwater–surface water interactions, as part of the long term conservation of this internationally important shallow freshwater lake system.

The study area

The lake system

Bosherston Lakes is a system of shallow linked lakes lying close to sea level within the Stackpole National Nature Reserve. The lakes were created during the late 18th and mid 19th centuries by damming the narrow incised tidal creeks that the lake now fills. The Bosherston Lakes system is composed of four water bodies, the Upper and Lower Eastern Arms, the Central Arm and Western Arm–Central Lake (Fig. 1). The four water bodies are separated by stone-walled causeways or dams with sluices or weirs (Eight Arch Bridge, Grassy Bridge Dam and Central Arm Causeway), although hydraulic connection occurs between water bodies when water levels are sufficiently high, generally during the winter.

The lakes are covered by a Nature Reserve Agreement between the Countryside Council for Wales (the Welsh Assembly Government's wildlife conservation authority for Wales) and the owners, the National Trust (a conservation charity). Although the Countryside Council for Wales is responsible for the ecological management of the lakes and their achievement of favourable condition under the Habitats Directive, the Environment Agency (the national environmental regulator) is responsible for the wider water quality and water resources of the catchment.

The catchment

The catchment is generally low lying with all land below 100 m above sea level (masl) (Fig. 2a). The higher land in the north of the catchment, at an elevation of around 30–90 masl, is mostly formed of Devonian age Milford Haven Group (Fig. 2b), which comprises mudstones, siltstones and thin, fine grained sandstones (although there are also subsidiary bands of Carboniferous Lower Limestone Shales and Devonian Skrinkle Sandstone). The primary porosity of the sandstones are low, with in the predominant groundwater flow via fractures. The permeability is limited due in part to the variety of lithologies, with low permeability mudstones, marls and siltstones interbedded with the sandstones (Morris et al., 2000).

The Carboniferous Limestone (Fig. 2b), which is the main aquifer in the area, forms a distinctive coastal plateau of low relief (of around 20–40 masl) in which lie the Bosherston Lakes (Howells, 2006). The Carboniferous Limestone exhibits 'karstic' hydrogeological behaviour by virtue of a combination of high rock solubility and well developed secondary or fracture porosity (Allen et al., 1997). Groundwater flow largely occurs within the localised solutionally-enlarged conduits which provide low resistance pathways for ground water flow and which often short circuit the granular or fracture permeability of the aquifer. Despite the limestone aquifer outcrop continuing beyond the coastline, there is no evidence of significant saline intrusion into the limestone aquifer, although this may partly relate to the paucity of observation boreholes near to the coast. However, a farm located around 400 m from the coast reportedly had to sink 3 boreholes as the first two were saline, but unfortunately the groundwater level and the depths to which the

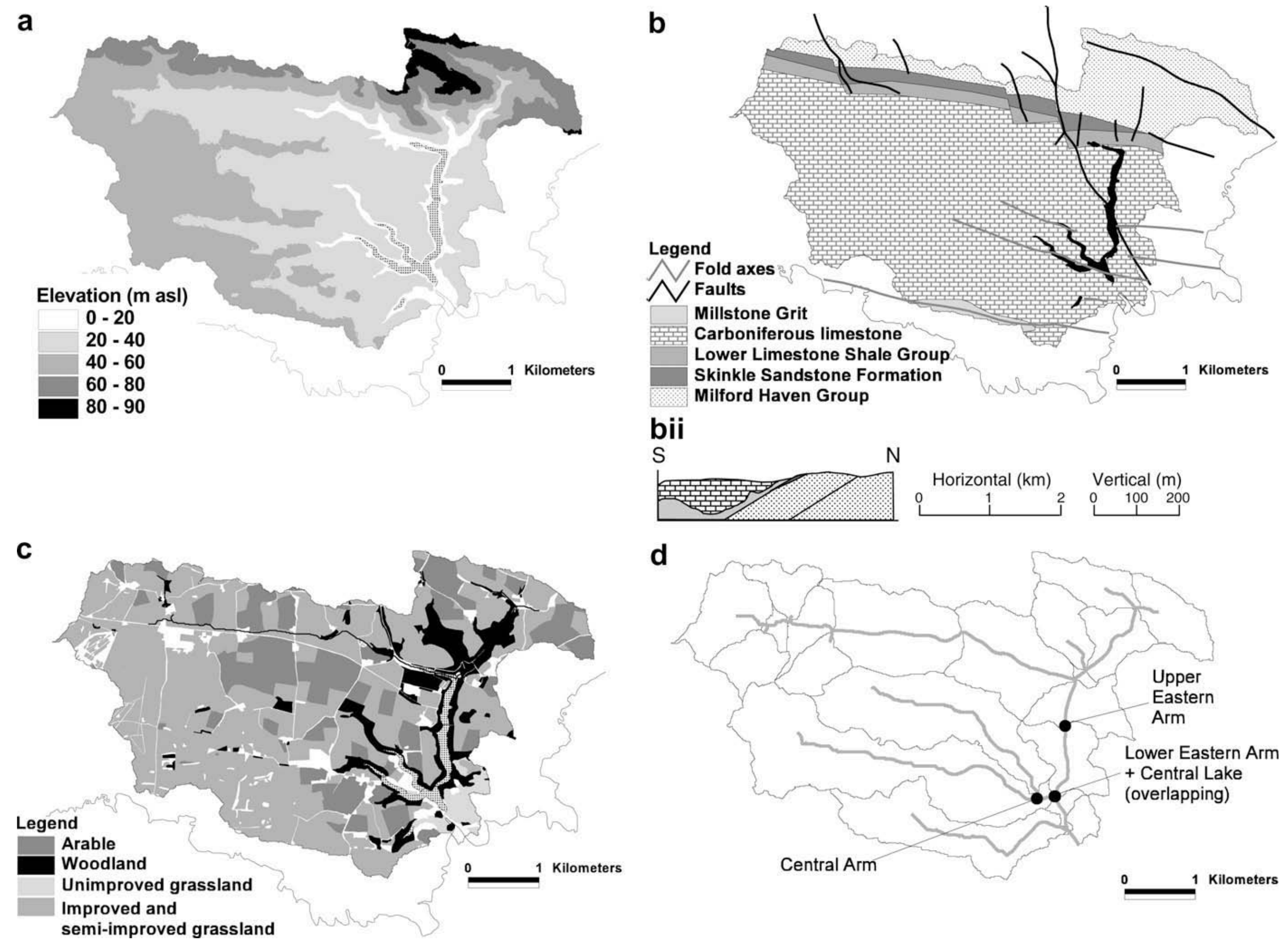

Fig. 2. Bosherston catchment: (a) elevation; (b) bedrock geology, faults and fold axes and generalised cross section; (c) land use; (d) SWAT representation of the catchment and waterbodies (Geological Map Data© NERC 2009; Elevation data© Ordnance Survey 2009).

saline boreholes were drilled are unknown. The only hydrogeological study of south Pembrokeshire was carried out in the 1970s (Howard Humphrey and Sons, 1978) and was able to make only limited comments on the limestone aquifer properties of the area because of the lack of hydrogeological data.

The stream network in the catchment is largely restricted to the northern parts overlying the Milford Haven Group, where the Merrion and Stackpole Streams eventually discharge into the lakes (Fig. 1). In the limestone areas surface waters infiltrate into the dry streambeds or into small sinkholes such that there are no surface water inflows into either the Western or Central Arms of the lake.

The soils are mainly permeable, well drained brown-earth soils, resulting from post-glacial weathering of extensive loess deposits, although Aeolian sand deposits are present near the coast (Rudeforth et al., 1984).

The climate of the area is in general mild and maritime, being influenced by the prevailing south–south westerly winds from the Atlantic Ocean. Annual average rainfall for the period 1970–2006 at the nearby Orielton weather station [51.654°N, −4.957°W], situated 1.5 km from the catchment border (Fig. 3), is 1120 mm. The moist climate of the region suits the growth of grass, and livestock farms are the dominant feature of the landscape. Permanent or temporary grass covers almost two thirds of the catchment (Fig. 2c) to provide grazing and forage for beef, sheep and milk production. Arable crops, mainly barley, form part of the rotation on many farms to provide feed. Apart from the small villages of Bosherston and Stackpole, there is little other urban development.

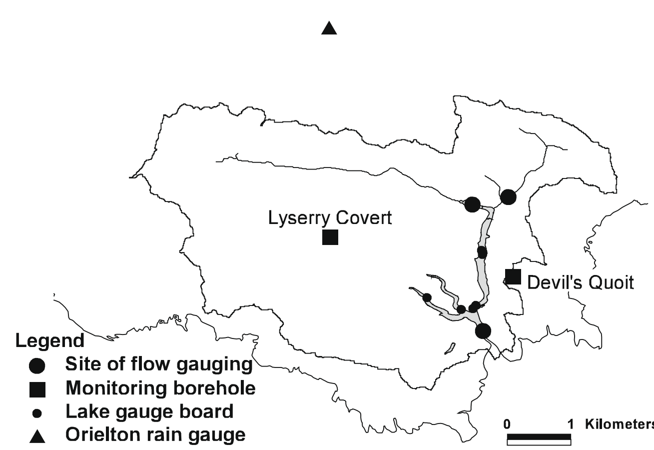

Fig. 3. Location of weather and hydrometric monitoring sites.

Previous unpublished studies into the catchment and lake hydrology have been synthesised by Holman et al. (2009) to form the basis of a conceptual model of the system (Fig. 4).

The model

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) is a physically based, continuous, semi-distributed model which operates on a daily time step and is able to predict the movement of water (and sediment and agricultural chemicals) in complex watersheds with varying soils, land use and management conditions over long periods of time. It includes surface run-off, return flow, percolation, crop growth, irrigation, groundwater flow, and reach routing among other features. Surface run-off is calculated by an improved Soil Conservation Service (SCS) Curve Number approach (Arnold et al., 1998). The percolation component consists of a linear storage with up to ten layers, with the flow rate governed by the hydraulic conductivity and the available water capacity of each layer. For lateral subsurface flow, a kinematic storage model is used. Percolation from the root zone recharges a shallow aquifer (Neitsch et al., 2005), which is also connected to stream flow. The model calculates evaporation from soil and transpiration from plants separately, as described by Ritchie (1972). The actual evaporation is a function of soil water content, plant type and soil depth. Transpiration is computed as a linear function of potential plant evapotranspiration and leaf area index. Canopy storage for each crop is also included. SWAT also contains a plant growth model, which is a simplified version of the plant growth approach of the EPIC model (Williams et al., 1983). It is based on accumulating heat units, harvest index for the partitioning of grain yield, the Monteith approach for potential biomass (Monteith, 1977) and water, nutrient and temperature stress concepts. Tillage systems and agricultural management can be specified for each crop.

SWAT simulates two aquifer in each sub basin – a Shallow Aquifer and a Deep Aquifer. The Shallow Aquifer is considered to be an unconfined aquifer that interacts with the main river in the subbasin, whilst the Deep Aquifer is described as a confined aquifer which is assumed to contribute to streamflow somewhere outside the watershed. Recharge to the Deep Aquifer is a specified proportion of the total recharge on a given day. However, it is important to recognise that, although the Deep Aquifer is described as a confined aquifer in Neitsch et al. (2005), there is no physical or mathematical representation of a deeper confined aquifer in the model, but it is rather a store into which the proportion of recharge that enters can be considered as lost from the system.

Application of SWAT has been widely reported in European catchments, but has been little applied in karstic systems (e.g. see review by Gassman et al., 2007).

Model set-up

Automatic catchment delineation using a 10 m resolution digital elevation model was used to define the 2049 ha Bosherston Lakes catchment (Fig. 2d). In the absence of sufficient groundwater monitoring boreholes, it was assumed that the surface water and groundwater catchments were coincident. Although this is clearly a significant assumption with regard to a karstic limestone aquifer (Goldscheider and Drew, 2007), there is a geological control to the northern boundary of the limestone where it abuts the Milford Haven Group. Twenty subbasins were delineated after manual alterations to allow for the locations and separations of the water bodies within the lake system.

Daily precipitation data were available for 1970–2006 from the Orielton weather station, with data from Stackpole and Milford Haven (both within 10 km) used to fill the few data gaps. Daily Potential Evapotranspiration (PET) data, based on the Penman–Monteith algorithm (Jensen et al., 1990), from 1975 from the European Monitoring Agriculture with Remote Sensing (*MARS*, http://agrifish.jrc.it/marsstat/) system was used after a comparison with the values from the Hargreaves equation (Hargreaves and Samani, 1985) using minimum and maximum daily temperature from the Orielton weather station showed little difference.

Spatial soil data was provided by the Digital National Soil Map of England and Wales (NSRI, 2001). Data on soil physical and chemical characteristics were derived from the *Land Information System* (http://www.landis.org.uk) and Rudeforth et al. (1984). Soil albedo was calculated using NRCS (1999) and soil erodibility factors were calculated using Williams (1995).

Spatial land cover data came from the national Land Cover Map 2000. Within arable land cover classes, rotations linked to soil types were based on Holman et al. (2004), which agreed with the data on individual crops areas within the catchment from national agricultural census data. Two main crop rotations were used – silage–silage–silage–winter wheat–winter barley–maize, and hay–hay–hay–winter wheat–spring barley–potato rotations. Improved grassland was assigned silage (single cut) and grazing based on local practice; whilst the remaining unimproved grassland was assumed to be grazed by sheep. The livestock types and numbers from the census data were also used to calculate livestock composition and densities within the catchment. Vegetation and livestock parameters were defined based on Whitehead (2006), Hough (1990), Agro Business Consultants (2007), Frame (2000), Holman et al. (2004) and Manske (2004). Grassland and arable crops were fertilised according to the recommendations in DEFRA (2000), assuming average nutrient supply status in the soils.

There are two main groundwater abstractions in the catchment providing water for an army camp and a livestock farm. Gillard (2007) estimated the annual average abstraction for the farm at around 146,000 m^3/a based upon number of cattle and their typical consumption by season. Annual abstraction from the army camp is around 176,000 m^3/a, based upon measured monthly abstraction data for 2005.

Each of the four water bodies comprising the lakes were set-up within SWAT as reservoirs and parameterised according to the SWAT target release approach (Neitsch et al., 2005). Using this option the water bodies release water as a function of the desired target storage (based on overflow levels of the weirs), and the number of days to reach a target storage, which permits the representation of the differing flushing rates/residence times of the water bodies. Using available bathymetric data (Holman et al., 2007), the volume at the principal spillway of the Upper Eastern Arm was calculated as 76,000 m^3; for Lower Eastern Arm of 139,000 m^3; Central Arm of 47,000 m^3; and Western Arm–Central Lake of 172,000 m^3.

Calibration/validation data

There are limited hydrological data available in the catchment, with the main source of data being periodic (7–10 day interval) manual measurements of the lake water levels (to the nearest centimetre) at between three and six staff gauges since July 1977 (Fig. 3). Monthly average discharge data for the Merrion and Stackpole streams were available for October 1983 to August 1985, while Rees and Hinton (1989) provides occasional spot measurements of the lake outflow to the sea in 1984 and 1985 and the water levels required for the hydraulic connections of the various lake arms. Daily groundwater levels have also recorded (to the nearest centimetre) by the Environment Agency (the national environmental regulator) at four monitoring boreholes in the catchment since 1997.

Model calibration and validation

Calibration

The temporally variable and limited observational data were used within a two-step calibration process, with the simulated

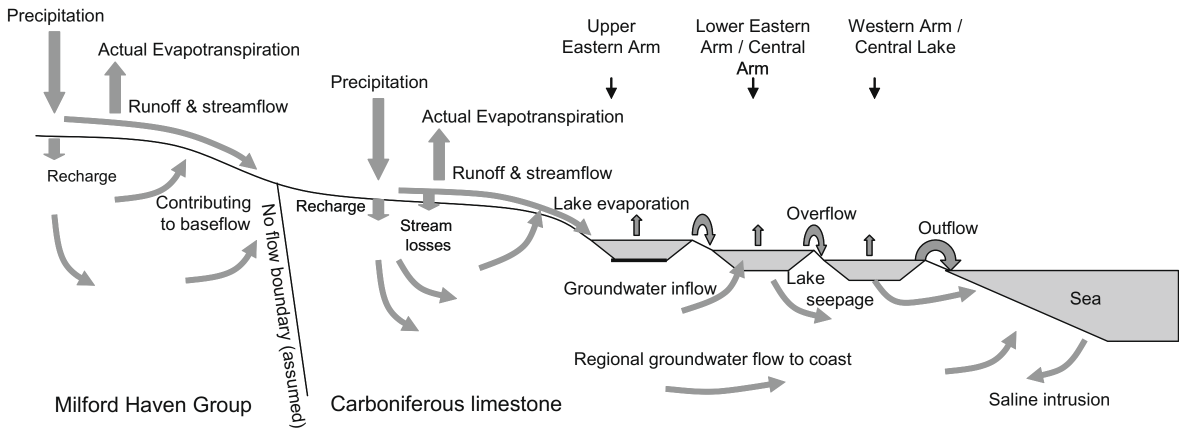

Fig. 4. Conceptual model of the Bosherston Lakes system.

surface water inflows (Fig. 5) and groundwater levels (Fig. 6) calibrated first, followed by the lake volumes. A sensitivity analysis in the Bosherston catchment shows that the simulated stream discharges were particularly sensitive to Curve Number (CN), ALPHA_BF, RCHRG_DP and GW_REVAP, consistent with other studies (e.g. Neitsch et al., 2001). Using the 23 months of monthly average stream discharges in 1983–1985, the calibration of simulated streamflow was carried out for the upper portion of the catchment, crossed by the Merrion and Stackpole Streams. The modelled shallow aquifer storage values were calibrated against observed borehole data for the period 1997–2005, (Fig. 6). In order to provide good volumetric and temporal representation of the stream flows, the calibration resulted in low Curve Numbers – around 45 for the subbasins of the Merrion Stream, which straddle the sandstone and the limestone, and around 55 in the Stackpole Stream subcatchment on the sandstone. Other calibration parameters were:

- ALPHA_BF baseflow recession constant, was decreased to 0.020 days to improve the fit of the recession limbs of the stream hydrographs;
- RCHRG_DP, the Deep Aquifer percolation fraction which defines the proportion of total daily recharge routed to the Deep Aquifer was increased to 0.55 on the northern Limestone subbasins to satisfactorily fit the hydrographs;
- GW_REVAP, which controls the proportion of water which will move from the shallow aquifer to the root zone as a result of soil moisture depletion was increased to 0.20 to account for the important loss of water from the shallow aquifer to overlying the soil layers, particularly within the significant areas of wet woodland.

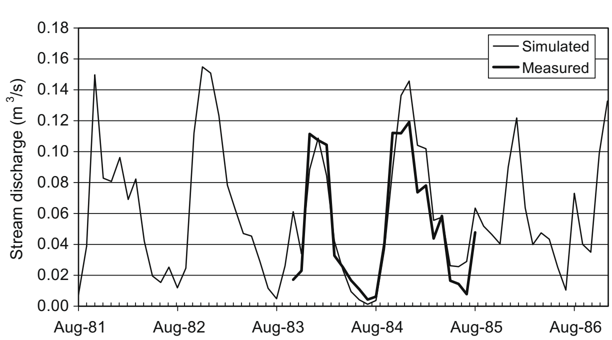

Fig. 5. Measured and simulated average monthly flows in Stackpole Stream during the calibration period.

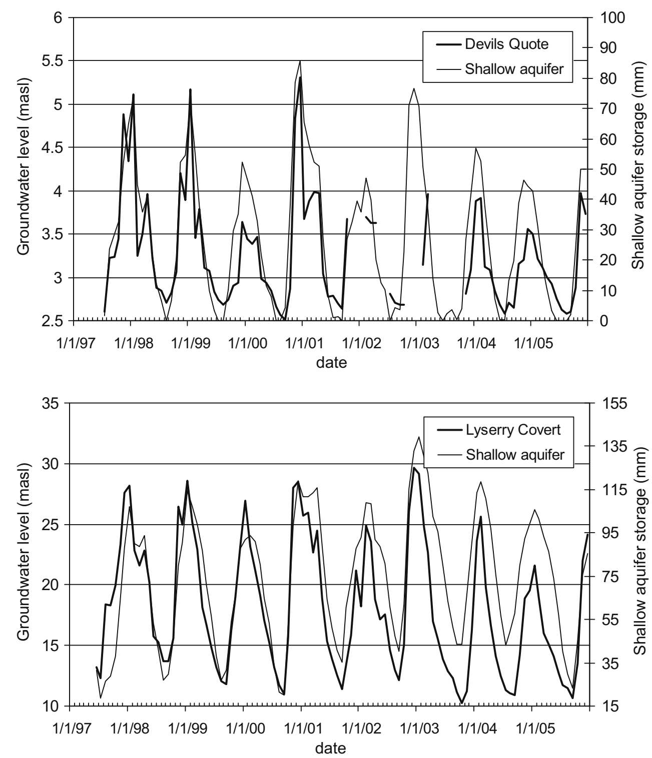

Fig. 6. Comparison of observed groundwater levels and simulated SWAT shallow aquifer storage within the catchment during the calibration period at Devils Quote and Lyserry Covert boreholes.

After completing the initial calibration of the streamflow discharges into the lake system (Fig. 5), the lake levels were calibrated (Fig. 7). The calibration of the lake levels is challenging because of the 'buffering effect' that the lakes provide to the peaks in stream and groundwater spring discharge. For the calibration of the model against lake levels, the period 1995–2005 was used as the lake level data were most frequent during this period. The number of days to reach target storage were calibrated to 2 days for the Upper Eastern Arm, four for the Lower Eastern Arm, five for Central Arm and four for Western Arm and Central Lake, which was consistent with observed water level records. Certain sub-catchments discharge directly into the Western and Central Arm of the lakes through the calcium-rich groundwater springs with no evident surface hydrography – in these sub-catchments the CN was

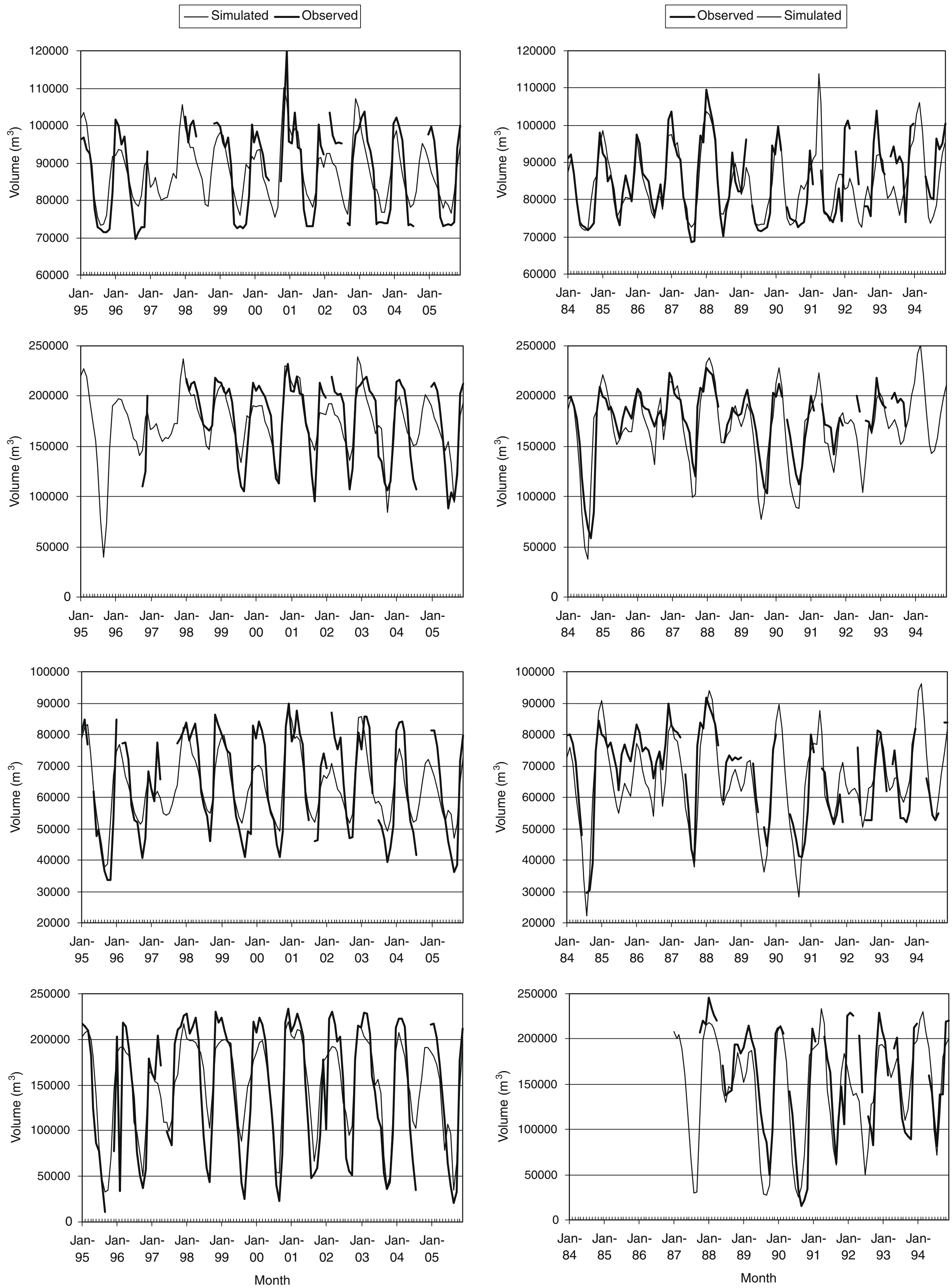

Fig. 7. Simulated and observed lake volumes in the (from top) Upper Eastern Arm; Lower Eastern Arm; Central Arm; Central Lake-Western Arm during the (left) calibration and (right) validation periods.

calibrated to a CN value of 60. The remainder of the catchment conserved the original CN2 values as given in Neitsch et al. (2005).

Whilst the bed of the Upper Eastern Arm appears impermeable due to a thick clay layer (Holman et al., 2007), there is the potential for significant losses of water through the lake beds of the other Arms due to the thin or negligible sediment cover above the limestone. Such losses of water enter the shallow aquifer and are likely to flow to discharge at sea. The lake levels for the Central Lake–Western Arm, Lower Eastern Arm and Central Arm seepages were calibrated with RES_K (effective saturated hydraulic conductivity of the reservoir bottom) values of 4.0, 1.5 and 1.0 mm/h.

Following calibration, the Nash–Sutcliffe coefficient of efficiency for the simulated lake levels were 0.67 for the Upper Eastern Arm, 0.67 for the Lower Eastern Arm, 0.74 for the Central Arm and 0.71 for the Western Arm–Central Lake (Fig. 7). Values of 0.5–0.65 are described as 'Good' by Henriksen et al. (2003) and 0.65–0.85 as 'Very Good'.

In addition to the calibration of hydrological variables, the simulated annual crop biomass of the principal crops (barley, wheat, maize, potatoes and grass) were satisfactory in comparison to values in Hough (1990). Good crop growth representation is essential for good reproduction of evapotranspiration processes and water balances.

Validation results

The validation period for lake levels covered the earlier years of 1984–1994. The resultant Nash–Sutcliffe coefficient values for the lake levels were 0.56 for the Upper Eastern Arm, 0.74 for Lower Eastern Arm; 0.57 for Central Arm; 0.64 for Western Arm–Central Lake (Fig. 7). According to Henriksen et al. (2003), the model performance is Good or Very Good for all of the water bodies. As a final qualitative element of the validation, the simulated outflows from the Central Lake to the sea were compared with the available spot (or instantaneous) measurements (Fig. 8), which showed a reasonable match in flow rate and timing (given the important differences in temporal scale) demonstrating that this simulated flux is not unreasonable.

Discussion

Prior to this study, the quantified understanding of the hydrology and hydrogeology of the Bosherston Lakes system was poor, due in part to the limited hydrological data which was available for different time periods and with different temporal scales (ranging from instantaneous to monthly averages). However, the diverse nature of the limited data which are available, describing stream discharges, lake levels, and periods of hydraulic connection between the lake arms, groundwater levels and lake outflows has allowed the construction of a plausible calibrated and validated SWAT model of the system.

There have been a limited number of previous applications of the SWAT model in karst systems. Benham et al. (2006) reported that SWAT streamflow results did not meet calibration criteria for a watershed in southwest Missouri, but that visual inspection of the simulated and observed hydrographs indicated that the system was satisfactorily modelled. They suggest that SWAT was not able to capture the conditions of a very dry year in combination with flows sustained by the karst features. In contrast, Afinowicz et al. (2005) had to modify SWAT to more realistically simulate rapid movement of recharge through the shallow aquifer to deep aquifer storage in southwest Texas to allow simulated base flows to matched measured streamflows. Spruill et al. (2000) stress the importance of lowering the Curve Number (CN2) values to account for higher infiltration into karstic terrains; whilst Barfield et al. (2004) corrected the time of concentration to account for the flow through the epikarst and attenuated the peaks of discharge, as karstic terrains show a different response in terms of runoff.

The karstic nature of the limestone aquifer influences the overlying streams and tributaries, as the stream flows are reduced by exfiltration through the stream beds, with surface runoff reduced more than would be expected on similar catchments which do not overlie karstic rocks (White, 2002). Exfiltration into sinkholes of flow in the upper reaches of the Merrion stream was observed by Miller (2007), which is consistent with the calculations of discharge/catchment rainfall ratio (for 1983–1985) which showed that 60–73% of the rainfall appears as runoff in the sandstone catchment of the Stackpole Stream compared to only 36–45% in the Merrion Stream catchment which partly overlies the limestone (Rees and Hinton 1989). In calibrating the streamflows within the Bosherston catchment, very low Curve Numbers were required, particularly in the Merrion Stream subcatchment. The values were significantly lower than the default values given in Conservation Engineering Division (1986), consistent with Spruill et al. (2000).

The SWAT model outputs have enabled a comprehensive water budget for the system to be developed for the first time (Fig. 9). The precipitation inputs to the system have been partitioned into different outflows (actual ET, coastal groundwater discharge, lake evaporation, abstraction and lake outflow to the sea) or stores (lake, soil water and groundwater). Prior to this study, groundwater abstraction was thought to impact on water levels. Although the water budget shows that groundwater abstraction and lake evaporation have little effect on the overall catchment water balance (which is dominated by actual ET, groundwater

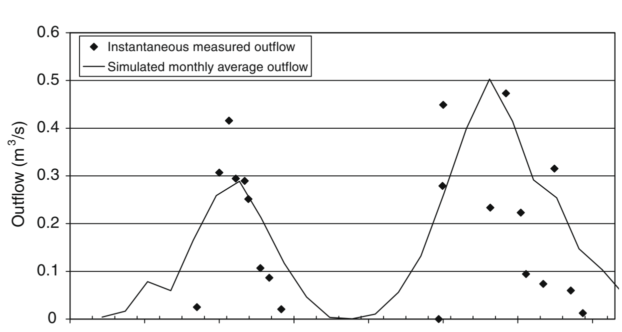

Fig. 8. Modelled monthly average and instantaneous measured lake outflows to the sea during the validation period.

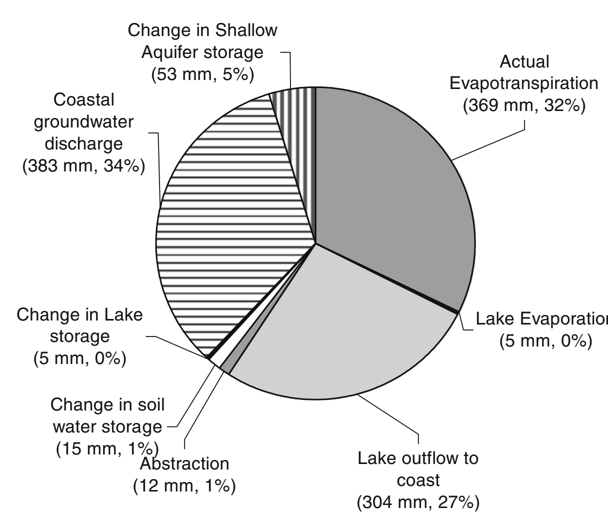

Fig. 9. Water budget for the Bosherston system (years 1984–1994).

flow to the sea and the overflow from the lake to the sea when the lake levels are above the critical height of the overflow sluice), impacts on lake levels of new or increased abstractions, particularly under the drier conditions predicted with climate change cannot be ruled out.

Given that the Bosherston Lakes lie above the highly permeable and karstic Carboniferous limestone, the importance of the coastal groundwater discharge to the water balance is not completely surprising, but the degree of hydraulic connection between the lake and groundwater flow system was poorly understood. The calibration and validation of the fluxes into and out of the different water bodies has made it possible to confirm the parts of the lake system where seepage through the lake bottom is present (Lower Eastern Arm, Central Arm and Western Arm/Central Lake) and others where there is no seepage or it is negligible at the scale of the investigation (Upper Eastern Arm). Given that the lake water levels in the model could not be calibrated against observed levels without the inclusion of seepage through the lake beds, it is confirmed that there is a connectivity between the lake and aquifer in the Western and Central Arms where only unconsolidated lake sediments overly the aquifer and allow the egress of lake water into the aquifer. The good simulation of lake levels suggests that the model assumption that lake leakage is proportional to lake levels, having a winter maximum associated with high water levels and a summer minimum, is realistic. However, it is not possible to ascertain whether the leakage is being entirely driven by head differences or whether there are fissures at different elevations in the lake sides which are contributing to differential leakage (Miller, 2007).

However, the validated model suggests that much of the coastal groundwater discharge is groundwater that bypasses the lake system, rather than originating as leakage from the lakes. Within the SWAT model, calibration of the baseflow component of the stream flows required that a spatially variable proportion of the groundwater recharge entered the Deep Aquifer (which has no connection with the surface water network in the model, and so is lost from the system), rather than the Shallow Aquifer (which can have a connection with the surface water network in the model). The Carboniferous limestone is the principal aquifer in the area, so this ‘loss’ represents larger scale groundwater flow paths within the Carboniferous Limestone which do not interact with the local surface water systems but which discharge directly to sea, rather than a loss of groundwater to a deeper aquifer in the Bosherston catchment. The recharge to the Deep Aquifer (in the Carboniferous limestone areas) in the validated model show a decreasing pattern from the Northern part of the limestone areas – where around 55% of recharge enters the Deep Aquifer, to the central catchment area where about 25% enters, to the areas nearer to the sea where recharge to the Deep Aquifer is about 0–10%. Of the 33% of the water balance outflows which constitute coastal groundwater discharge, 46% is provided by this larger scale groundwater flow and 54% by leakage from the lakes. The model – by means of the specification of the groundwater ‘losses’ – has therefore provided an estimate of the regional flow of water through the karst system out of the catchment to the coast, where significant springs have been observed (Allen et al., 1997). In contrast to Carboniferous Limestone, there are no simulated losses to a Deep Aquifer in the northern Old Red Sandstone areas, indicating that the surface waters are the main groundwater discharge zone for this aquifer, consistent with the higher discharge/rainfall ratios calculated by Rees and Hinton (1989).

However, despite the acceptable model performance, there is still considerable uncertainty in the estimation and apportionment of simulated coastal groundwater discharge due to lake seepage and regional groundwater flow. This arises due to the short period of surface water flows data against which the stream flows and the Deep Aquifer losses have been calibrated, and the limited number of spot observations of lake outflows which have been used to demonstrate the plausibility of the lake levels which partly result from the calibrated lake seepage. This uncertainty could be reduced by improved monitoring of the surface water inflows and lake outflow water balance components.

Woodward et al. (1998) state that the CN procedure “does not work well in karst topography areas ... because a large portion of the flow is subsurface rather than direct runoff”. This would seem to be partially contradicted by the good SWAT model performance in the Bosherston catchment suggesting that the Curve Number concept can be satisfactorily used in such areas providing appropriate model calibration. In addition, the SWAT model gives a satisfactory description of the transfer of all effective precipitation through the groundwater system in those karstic parts of the catchment where the surface hydrography is absent. This is demonstrated by the correct simulation of the behaviour of water levels in the Central Arm, which is fed only by springs and is not influenced by either streams or the water levels in the other arms. The application of the SWAT model to the Bosherston Lakes catchment and the interpretation of the calibrated model parameters governing the groundwater storage and the exchanges between groundwater and surface waters and the model outputs has enabled new understandings of the system behaviour to be developed. The improved quantitative understanding of the hydrological functioning of the lakes and the fluxes through both the surface and groundwater pathways will contribute to the development of a long term management strategy of the site to better manage nutrient and sediment problems under current and future climatic conditions. In addition the high degree of lake–groundwater interaction support the catchment implementation of a proposed Nitrate Vulnerable Zone to reduce groundwater nitrate concentrations and the expected removal of groundwater abstraction licencing exemption. The study has also demonstrated the wider utility of SWAT in improving the understanding of hydrological understanding of karstic systems.

Conclusions

The Soil Water Assessment Tool (SWAT) has been applied to the Bosherston catchment in west Wales, UK. This catchment contains the internationally important set of shallow linked marl lakes, the Bosherston Lakes, whose water levels are controlled by control structures, surfaces water inflows and lake–groundwater interactions. A two-step calibration process was performed, against the limited stream flow data and groundwater levels and the lake levels. Good or very good performance indices (Nash–Sutcliffe coefficient ranging from 0.67–0.74 for the calibration period and from 0.56–0.74 during validation) were obtained for the lake levels, whilst annual crop biomass and lake overflow discharges to the sea were plausible.

A water budget for the system, based on the model simulations, has been developed for the first time. Prior to this study, groundwater abstraction was thought to be significant, but the water budget shows that groundwater abstraction and lake evaporation have a minor effect on the water balance, which is dominated by actual ET, coastal groundwater discharge and the overflow from the lake to the sea when the lake levels are above the critical height of the overflow sluice. A high degree of connectivity between the lake and aquifer in three of the four water bodies is confirmed by the model but, of the 33% of the water balance outflows which constitute coastal groundwater discharge only around 54% originates as leakage from the lakes. The remaining 46% of the coastal groundwater discharge comes from larger scale groundwater flows which bypass the lakes.

The application of the SWAT model to the Bosherston Lakes catchment has enabled new understandings of the system to be developed and has provided an improved basis for the future hydrological management of the catchment and lakes. The high degree of lake–groundwater interaction support implementation of a proposed Nitrate Vulnerable Zone to reduce groundwater nitrate concentrations and the expected removal of groundwater abstraction licencing exemption. However, the lakes face many challenges from climate change and associated sea level rise which need to be incorporated within an adaptive management strategy for lakes (Holman et al., 2009) The study has also demonstrated the wider utility of SWAT in improving the understanding of hydrological understanding of karstic systems.

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