

Fully distributed hydrological modelling for catchment-wide hydrological data verification

D. Ocio, T. Beskeen and K. Smart

ABSTRACT

Hydrological data scarcity and uncertainty is a fundamental challenge in hydrology, particularly in places with weak or declining investment in hydrometric networks. It is well established that fully distributed hydrological models can provide robust estimation of flows at ungauged locations, through local calibration and regionalisation using spatial datasets of physical properties. Even in situations where data are abundant, the existence of inconsistent information is not uncommon. The measurement, estimation or interpolation of rainfall, potential evapotranspiration and flow as well as the difficulty in monitoring artificial influences are all sources of potential inconsistency. Less studied but as important, distributed hydrological models, given their capability of capturing both the temporal and spatial dimensions of the water balance and runoff generation, are suitable tools to identify potential deficiencies in, and reliability of, input data. Three heavily modified catchments in the East of England such as the Ely Ouse, the Witham, and the Black Sluice have been considered, all of which have issues of data scarcity and uncertainty. This paper demonstrates not only the benefits of fully distributed modelling in addressing data availability issues but also in its use as a catchment-wide data validation tool that serves to maximise the potential of limited data and contributes to improved basin representation.

Key words | data uncertainty, data validation, distributed hydrological modelling, ungauged catchments, water resource assessment

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INTRODUCTION

The development of hydrological models for the determination of water resource availability is dependent on suitable hydrological data records. In many countries, particularly developing ones, hydrometric networks are extremely limited in spatial coverage and the quality of available records. Worldwide, there has also been a decline in both developed and developing countries in hydrometric data being collected (Rodda 1998; Sene & Farquharson 1998; Lanfear & Hirsch 1999; Hannah *et al.* 2011; Mlynowski *et al.* 2011). Even the UK, which is a well-monitored country with one of the longest and densest meteorological and hydrometric records worldwide (Dixon *et al.* 2013), has inevitable gaps in the hydrometric network and areas that are ungauged. Likewise, the uncertainty in flow estimation

is seldom considered in practical applications prompting calls for improved engagement with the issue (McMillan *et al.* 2012; Coxon *et al.* 2015; Kiang *et al.* 2018). For example, the use of rating curves to stage measurements is by far the most common way to indirectly estimate the existing streamflow. Even in the best conditions, there will always be some uncertainty in the observed discharge. It derives from the accuracy of the instrumentation (especially for low flows), the changing nature of the flow regime (e.g. hysteresis, roughness variation and drowning conditions), the suitability of the mathematical expression being fitted, or the need to extrapolate the curve out of the range of measurements (McMillan *et al.* 2012). This implies that, on many occasions, available hydrometric records in a certain

catchment may be inconsistent. The same is true when calculating the catchment average rainfall based on a certain interpolation technique and a number of rain gauges with potential measurement problems too (Neff 1977; Moulin *et al.* 2009), or when estimating the potential evapotranspiration (PET) based on sparse weather information and uncalibrated techniques (Andréassian *et al.* 2004). Notwithstanding the long-term need to improve meteorological and hydrometric network coverage and hydrological practices, hydrologists are faced with the challenge of estimating flows in ungauged or partially gauged basins or with data of unknown quality.

The challenge of estimating flows in ungauged basins has received significant attention in the last decade among hydrologists (see the Predictions in Ungauged Basins initiative in Sivapalan *et al.* (2003) and Hrachowitz *et al.* (2013)). Current methodologies can be classified into (1) regionalisation approaches (Wagener *et al.* 2004) designed to transfer the parameters of a hydrological model calibrated in gauged basins to ungauged basins by establishing a regression between them and catchment descriptors (He *et al.* 2011) and (2) response signature methods, based on a regression between hydrological signatures and catchment descriptors obtained from gauged basins, and used to condition the predictions generated by a hydrological model within a Bayesian framework (Holmes *et al.* 2002; Young *et al.* 2003; Bulygina *et al.* 2009, 2011; Wagener & Montanari 2011; Almeida *et al.* 2015). Fully distributed hydrological models, which explicitly consider the spatial distribution of physical properties across the catchment, when applied to estimate flows at ungauged locations, can be assigned to the first category, providing that realistic relationships between model parameters and spatial properties are adopted (Refsgaard 1997). This kind of approach has been criticised for its excessive determinism (Beven 2001), but when model parameters are obtained from physical properties through multiple linear regressions, the uncertainty can be significantly reduced (Blöschl 2005). While this technique has successfully been applied to many cases (Reed *et al.* 2004), the widespread use of distributed models in the industry is limited due to their relative complexity, something which this paper seeks to challenge.

However, distributed models can also offer an effective tool to identify potential problems in both input data and

the observed flows used to validate a hydrological model. While the initial emphasis as regards hydrological uncertainty was placed on parameter equifinality (Beven & Binley 1992; Freer *et al.* 1996; Vrugt *et al.* 2003), the relevant role input and output uncertainty can play in the total runoff estimation error has recently received significant attention, usually involving a Bayesian approach (Vrugt *et al.* 2009; Renard *et al.* 2011; Le Coz *et al.* 2014; Coxon *et al.* 2015). Nevertheless, in applied hydrology, the uncertainty in input and output data is often not considered, being in best cases limited to a sensitivity test of assumptions. As flow series are often used in subsequent modelling exercises to optimise the operation of the current infrastructure or to select the most suitable new infrastructure, dealing with hydrological uncertainty can be cumbersome. Therefore, if practitioners assume that existing measurements are true representations of the variable of interest, there is an increased chance of introducing a bias in the analysis. In this context, distributed models can provide consistency in evaluating the goodness of observations. Assuming that the model is capable of sufficiently representing the physical processes involved in the flow generation when model parameters are derived across the basin based on similar spatial information, and with the same degree of accuracy and quality, deviations between modelled and observed flows can be attributed to deficiencies in data. Likewise, when data have been verified, deviations can be due to the existence of a particular mechanism not adequately captured by the model. This use of models as scientific tools to test data or hypotheses is far less frequent than the most widely used application for scenarios simulation (Silberstein 2006).

Conversely, lumped models, with a poor connection to physical properties, are likely to ignore these deficiencies and therefore risk being able to reasonably simulate observed flows despite problems in the source information. Parameters may then be biased and their application to other periods, historical or future, can be imperfect (Wilby 2005; Oudin *et al.* 2006; McMillan *et al.* 2010). In heavily modified basins, where the extent of artificial influences is large, the existence of uncontrolled or poorly monitored abstractions/returns in certain parts of the basin will go unnoticed in lumped models but can be inferred from a distributed analysis (Nalbantis *et al.* 2011). Notwithstanding

this, lumped models are still predominant in hydrological practice given the quickness and easiness of its application and, therefore, their related lower costs.

In addition to the primary purpose of the work to assess water resource yields, this paper aims to demonstrate the use of fully distributed modelling as a catchment-wide data validation tool in three catchments in the East of England with data coverage and quality issues. Specific objectives were to overcome the limitations in the hydrometric station coverage and critically review the quality and assumptions behind the input data. In particular, artificial influence information is known to be incomplete across the three catchments, as in addition to significant licenced abstractions there are unmonitored transfers, not requiring a licence, to lowland internal drainage board (IDB) areas (National Rivers Authority 1993). A previous hydrological modelling study within the part of the basin (Mott MacDonald 2007) adopted a semi-distributed model. Although consideration was given to adopting a semi-distributed model in this study, this was not considered a viable option because of the gaps in gauging station coverage and quality and the resulting significant scaling for ungauged areas. As such, it was considered that a distributed modelling approach would provide improved basin representation.

In the case of the Ely Ouse, since groundwater interactions are important, consideration was given to adopting the Environment Agency's North East Anglia Chalk (NEAC) model (Black *et al.* 2012). However, the purpose of the model is primarily to understand the impacts of groundwater abstraction, and as a tool to regulate groundwater abstraction licenses, and as such, this model was not readily applicable to surface water applications.

In the specific context of these catchments, accuracy was required for the derivation of flow estimates, as the results were used directly to facilitate a water company water resources assessment of the East of England. The wider importance of this cannot be underestimated, as all water companies are responsible for maintaining public water supply and analysing options to ensure this supply remains secure in the face of growing demand and increasing environmental pressures. This implies a need to establish reliable baseline flow series across catchments to allow the understanding of current and future water availability and to inform the development and appraisal of

possible future water supply options. A small deviation in simulated flows might modify the feasibility of certain proposed infrastructure to a point where another alternative would be preferred, with potential monetary consequences for the final consumer. This issue is not only relevant in the UK but in any part of the world regardless of the temporal and spatial coverage of meteorological and hydro-metric information. Having a clear understanding of the reliability of input data and deriving a good basin representation are essential when attempting to quantify available flow for potential abstraction for any water supply project (such as domestic, agricultural, industrial or hydropower).

Study area

With approximately 600 mm of annual rainfall and less than 200 mm of effective annual rainfall, the East of England is the driest region of the UK, which, with the population and agricultural demand, results in the existence of serious water stress (Environment Agency and National Resources Wales 2013). This situation is expected to worsen given the ongoing demographic expansion and the impact of climate change (Christerson *et al.* 2012; von Lany *et al.* 2013). In addition, new sources of cheap and abundant water are scarce, and securing the future supply requires a difficult exercise of finding an optimal solution. An accurate assessment of water availability is therefore critical. The three catchments under specific consideration as part of this study are the Ely Ouse, Witham and Black Sluice (see Figure 1).

The Ely Ouse catchment drains an area of 3,581 km² upstream of the Denver Complex, including the major tributaries of the Rivers Cam, Lark, Little Ouse and Wissey. The tributaries drain the uplands of the Great Ouse Chalk outcrop and have a heavily modified hydrological regime. There are no major reservoirs in the studied area. However, there are numerous abstractions (including the diversion of water to South Essex through the Ely Ouse to Essex Transfer Scheme) and effluent discharges that, due to their magnitude, substantially alter the natural flow regime. The River Witham catchment drains an area of 2,066 km², including tributaries of the Rivers Brant, Bain, Sleas and Barlings Eau which drain the Lincolnshire Limestone and Spilsby Sandstone outcrops. Similarly, this catchment also has numerous abstractions and also the

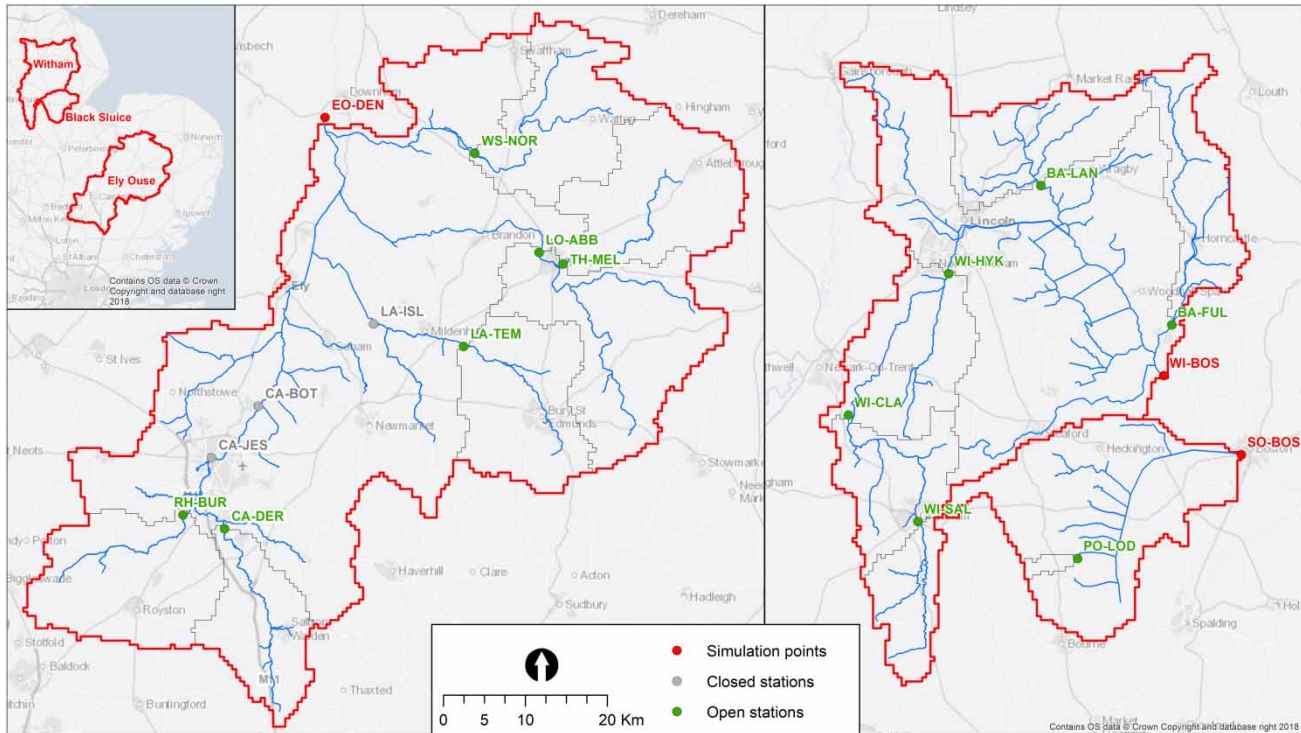


Figure 1 | Location of gauging stations used in the study.

Trent-Witham-Ancholme Transfer Scheme, which serves to supplement flows in the River Witham (Environment Agency 2013b). The Black Sluice catchment, which is drained by the South Forty Foot Drain, has an area of 520 km² covering high-grade agricultural parts of the low-lying Lincolnshire Fens.

All three catchments under consideration are predominantly rural and drain towards the Wash, and have lower sections that have been extensively drained and managed by a system of drains and dykes, allowing the high-grade low-lying agricultural peatland to be farmed (Environment Agency 2013a). The Denver Complex, comprising several sluices and gates, helps to control and manage water in the Ely Ouse catchment, allowing the protection of low-lying fenland from tidal flooding and the drawing of river flows into low-lying drains via slackers for crop irrigation (Environment Agency 2013a). The Grand Sluice and Boston Lock serve similar functions for the River Witham and South Forty Foot Drain, respectively.

The Ely Ouse and Witham catchments are seemingly well instrumented with numerous gauging stations as summarised in Table 1 and shown in Figure 1 (considering

drainage areas greater than 200 km² for the Ely Ouse and greater than 100 km² for the Witham and any gauging station for the Black Sluice catchment). In the case of the Ely Ouse, there has been a decline in the station coverage in downstream areas in recent years.

However, the River Witham lacks a main gauging station on its lower section, and the one covering the largest drainage area (North Hykeham, which was put in 1998) was thought by the operator (Environment Agency) to underestimate flows, and there is not yet consensus about its validity (Dan Burbidge, personal communication, 20 July 2017). This is due to an apparent much lower runoff than at the upstream gauging station at Claypole Mill and the lack of a proper control structure to measure low flows. Likewise, the most downstream station for the Ely Ouse, at Denver Complex, contains major gaps and inconsistencies (National River Flow Archive 2017) as it is a composition of the flows through five sets of sluices whose value is obtained from hydraulic calculations. A review and improvement of flow derivation methods at the Denver Complex (Environment Agency 2012) increased the accuracy of flow records from 2009 onwards, although there are still some concerns with

Table 1 | Gauging stations used in the study

Basin	Official code	Model code	Name	Catchment area (km ²)	Period of record	Mean flow (m ³ /s)	Q95 flow (m ³ /s)
Ely Ouse	33035	EO-DEN	Ely Ouse at Denver Complex	3580.7	1958–2015	15.79	1.80
	33003	CA-BOT	Cam at Bottisham	807.3	1936–1987	3.66	0.91
	33016	CA-JES	Cam at Jesus Lock	769.1	1959–1983	2.81	0.71
	33021	RH-BUR	Rhee at Burnt Mill	306.1	1962–2015	1.18	0.26
	33024	CA-DER	Cam at Dernford	199.6	1949–2015	0.92	0.27
	33004	LA-ISL	Lark at Isleham	464.4	1936–1986	1.80	0.44
	33014	LA-TEM	Lark at Temple	274.1	1960–2015	1.29	0.46
	33034	LO-ABB	Little Ouse at Abbey Heath	707.7	1968–2015	3.83	1.16
	33019	TH-MEL	Thet at Melford Bridge	311.4	1960–2015	1.89	0.46
	33006	WS-NOR	Wissey at Northwold Total	259.4	1956–2015	1.88	0.47
Witham	30001	WI-CLA	Witham at Claypole Mill	297.9	1959–2015	1.88	1.26
	30005	WI-SAL	Witham at Saltersford Total	126.1	1988–2015	0.82	1.17
	N/A	WI-HYK	Witham at North Hykeham	550.2	1998–2015	2.89	1.02
	30002	BA-LAN	Barlings Eau at Langworth Bridge	210.1	1960–2015	1.45	0.22
	30003	BA-FUL	Bain at Fulsby Lock	197.1	1962–2015	1.27	0.59
Black Sluice	30014	PO-LOD	Pointon Lode at Pointon	11.9	1972–2015	0.07	0.00

Source: National River Flow Archive (2017) and Environment Agency (2017).

the data quality. For these reasons, direct calibration against this data was not undertaken, and it was only used for model comparison purposes. The upstream parts of both catchments have gauged catchments with known differences in terms of meteorology, land use, soils and geology, which would prevent a reliable transposition downstream using traditional lumped models. For the Black Sluice catchment, the only available gauging station is located on the small Pointon Lode stream, covering only 12 km². Overall, the Ely Ouse, River Witham and Black Sluice catchments have, respectively, 49%, 46% and 2% of their areas effectively monitored by currently operational long-term gauging stations.

METHODOLOGY

Selected model and input data

The TETIS model, developed by the Research Group of Hydrological and Environmental Modelling (GIMHA) of the Technical University of Valencia in Spain, has been adopted to simulate the hydrological response of the catchments, making it the first application in the UK. For a detailed description of the TETIS model, including a

conceptual schematic, see [Francés *et al.* \(2007\)](#) and [UPV-GIMHA \(2014\)](#). The TETIS model is a fully distributed rainfall-runoff algorithm, in which the catchment is divided into a number of cells whose physical properties are assumed homogeneous and characterised by a series of tanks linked vertically and representing different hydrological processes (discussed further below). In each cell, these hydrological processes are represented by linearised approximations of the non-linear differential equations that govern the movement of water. In this sense, TETIS can be classified as a conceptual model, but with parameters that are assigned to physical properties. All cells drain downstream according to their elevation until the flow reaches the river channel, where the flow is routed to the model outfall. Two model domains were set up: one for the Ely Ouse catchment and one covering both the Witham and Black Sluice catchments. A 500 m cell size grid was adopted as a compromise between computation requirements and the ability to sufficiently capture the spatial variability.

National 5 km by 5 km gridded rainfall (Met Office) and PET (MORECS v2.0) datasets ([Hough & Jones 1997](#)) were adopted as input data for the two models. Major public water supply abstractions and effluent discharges were introduced at individual locations where possible. Other smaller

abstractions (mainly for agricultural purposes) were included in an aggregated way based on data provided by the Environment Agency and assigned to the cell upstream of the respective gauging station or the point of interest. For the Ely Ouse catchment, groundwater augmentation schemes were also modelled; based on advice from the Environment Agency, a proportion of the augmentation was assumed to be lost due to infiltration. For the Witham, the Trent-Witham-Ancholme Scheme was included introducing an additional inflow at Lincoln. In order to avoid overcounting the stormwater captured by the sewerage network, the monthly Q80 value (i.e. the flow rate exceeded with a probability value of 80% during each month) was estimated as representative of the Dry Weather Flow for effluent discharges.

Model parameters

Water balance and fluxes at each cell are controlled by 11 parameters (numbered below and taking the form of GIS raster layers within the model), which reflect spatial variability across the catchment. These GIS raster layers are derived from physical properties in a uniform way across the catchment to enable the transfer of information attained at gauged stations to ungauged locations (Götzinger & Bárdossy 2007). The parameters are modified by nine global correction factors (two parameters, the interception capacity and the soil optimum water content, are fixed) that are adjusted during calibration and scale the GIS raster layers consistently.

An Ordnance Survey 50 m Digital Elevation Model, resampled to 500 × 500 m cells, and conditioned to reflect the river network, was used to derive flow direction, accumulated drainage area and slope. The latter was used to characterise the overland flow velocity v (1) at each cell (see Figure 2(a)) and for in-channel flow routing. Maximum interception capacity $Imax$ (2) was related to vegetation cover as well as the crop coefficient λ (3) that modifies the PET through the year. Vegetation cover throughout the studied region was defined based on the Corine Land Cover 2006 dataset (European Environment Agency 2007).

Overland flow can occur due to both soil saturation (the Dunnean mechanism) and the exceedance of the infiltration capacity (the Hortonian mechanism). Evapotranspiration

depends on the type of vegetation cover and varies seasonally, being also reduced as the soil approaches the wilting point. Overland flow, interflow and baseflow are modelled with a linear reservoir approach, with constants derived from the expected velocity over the surface or through the soil. Flow is routed through the river channel by a kinematic wave, in which the size and roughness of the channel are a function of the contributing drainage area (Bérod *et al.* 1999).

The static storage capacity H_u (4), which represents the maximum water that can be held in each cell without generating flow, comprises two components: surface detention capacity, which is a function of the vegetation cover and the surface slope, and soil tension capacity, which is the water stored in the soil matrix by capillary forces and only used by plants for their transpiration. The soil tension capacity was estimated as the product of the soil thickness and the difference between the field capacity and the wilting point. The HORIZON Hydraulics version 2 dataset (Hollis *et al.* 2015), developed by the Cranfield University Soil and AgriFood Institute (CSAI), provides an estimation of this information for each soil horizon. In the case of urban areas, it was limited to the surface storage capacity (see Figure 2(b)). The soil optimum water content θ (5), below which the PET is reduced due to water stress, was established as 60% of the tension storage. Likewise, the maximum capacity of the gravitational tank H_g (6) can be defined as a certain percentage of the static storage capacity. When exceeded, water can move to the surface and produce overland flow. A similar process was conducted to characterise both the infiltration capacity k_s (7) and interflow velocity k_{ss} (8), which were associated with the sub-vertical hydraulic conductivity of the topsoil and the weighted averaged horizontal hydraulic conductivity of the whole soil package, respectively (see Figure 2(c) and 2(d)). Further spatial variability was introduced by considering the soil texture. Several studies conducted by the European Soil Data Centre were used to characterise the hydraulic properties of the soil based on the abundance of sand, clay and organic matter (de Brogniez *et al.* 2015; Ballabio *et al.* 2016) and by applying pedotransfer functions fitted to a wide range of soils around the world (Saxton & Rawls 2006).

The percolation capacity k_p (9) into the aquifer and the connected aquifer flow velocity k_{sa} (10) are directly related

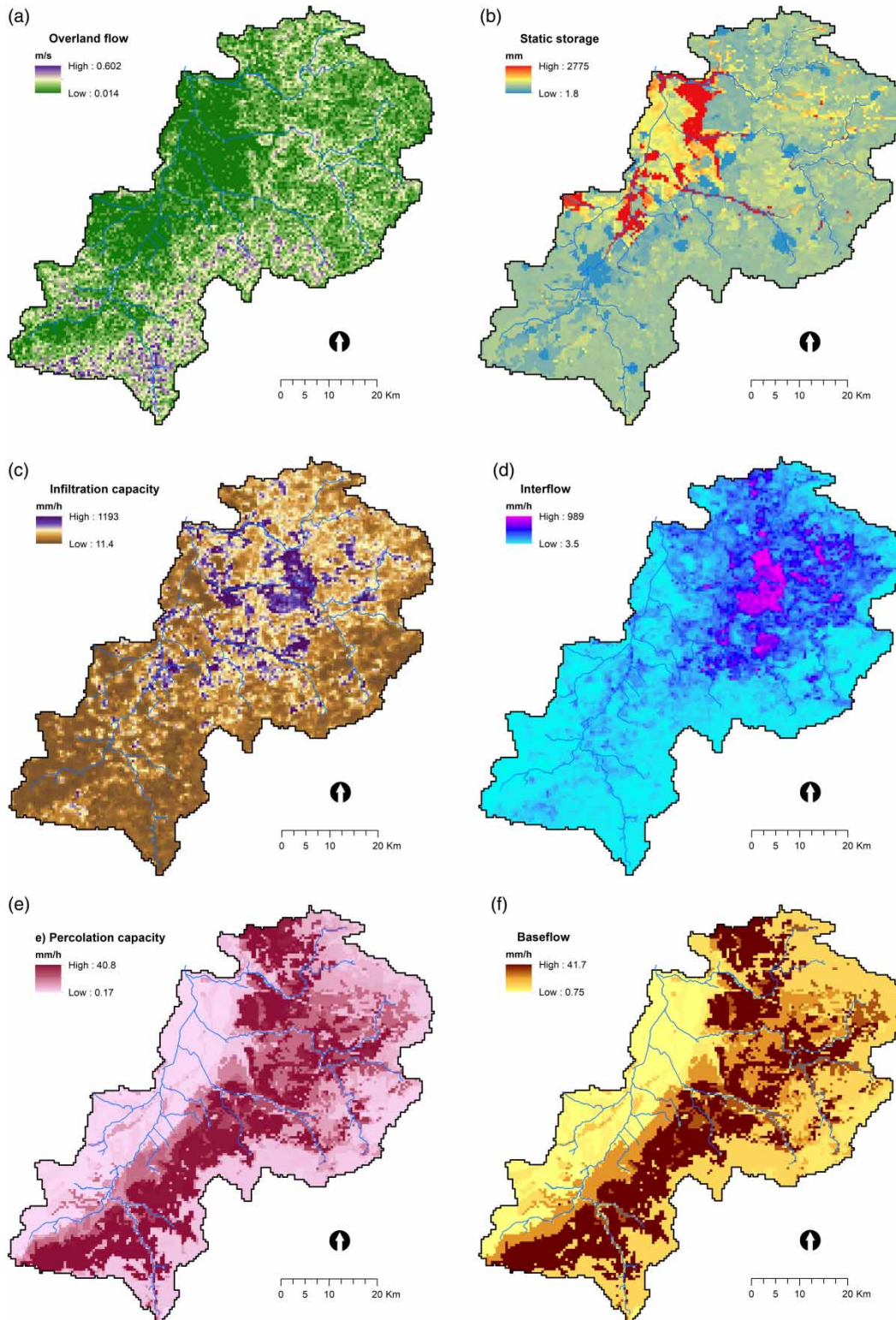


Figure 2 | Spatial distribution of main model parameters for the Ely Ouse: (a) overland flow velocity, (b) static storage capacity, (c) infiltration capacity, (d) interflow velocity, (e) percolation capacity and (f) baseflow velocity.

to the permeability of the bedrock and superficial deposits. Maximum and minimum bedrock and superficial deposit permeability classes obtained from the British Geological Survey 1:50,000 Digital Geological Map of Great Britain (Lewis *et al.* 2006) were used to establish a relative spatial distribution of aquifer properties by assigning a notional hydraulic conductivity to each class using a logarithmic scale (see Figure 2(e)). To account for the additional influence of soil thickness and texture on percolation, the initial aquifer flow velocity estimation was further modified with the Base Flow Index (the ratio of base flow to total flow) estimated for each soil association by the CSAI (see Figure 2(f)).

Finally, the deep aquifer percolation rate k_{ps} (11) refers to losses due to the lack of connection between the deep aquifer and the river network within the studied catchment. It has only been applied in the special case of the Ely Ouse catchment which contains a major aquifer in the Chalk. The Chalk is a thick cretaceous white limestone aquifer with low matrix permeability but a well-developed and interconnected network of fractures and is a major source of water supply in SE England (Allen *et al.* 1997). The behaviour of the Chalk is quite complex and highly variable. This complexity is also reflected in the unsaturated zone, which controls the recharge of the aquifer. Ireson *et al.* (2009) demonstrated that percolation from the surface could last several years during which water would not be available for generating baseflow. Isotopic analyses confirmed this fact, extending the recharge duration to several decades in some areas (Darling & Bath 1988). Given this, and in order to close the water balance, the activation of the deep aquifer percolation parameter is required, assuming a value of 1 for areas where the Chalk outcrop is present.

Calibration and validation

Even within the field of distributed hydrological modelling, parsimony is a desirable principle. Reducing the number of parameters increases the chances of their identifiability, allowing a more reliable temporal and spatial extrapolation (Wagener *et al.* 2002), and reducing parameter equifinality (Beven & Binley 1992). Therefore, model parameters should be calibrated regionally for the whole catchment so that the spatial relationships derived from physical

properties are retained. This requires the use of correction factors that modify model parameters globally and that are calculated by comparing simulated and observed flows at one key gauging station in the catchment (Francés *et al.* 2007). As part of the calibration process, all individual cells for each parameter are scaled by the same equivalent global correction factor. In TETIS, there are nine correction factors that modify the storage capacities and the velocities of the different flow components (correction factors and other model start conditions are summarised in the Supplementary Material).

For the Ely Ouse model, the Little Ouse at Abbey Heath gauging station was selected for calibration for the period 1995–2014 due to it having relatively minor artificial influences, a reasonable gauged record and the most significant drainage area of the available stations. For the Witham and Black Sluice model, the Claypole Mill gauging station was selected for calibration for the period 1995–2014.

A four-step calibration process was adopted which involved an initial manual calibration of the water balance, followed by the application of the SCE-UA optimisation algorithm (Duan *et al.* 1994), after which two sets of further manual calibrations were made to firstly match the hydrograph shapes, followed by a verification of the water balance. The Nash–Sutcliffe coefficient (NSCC) (Nash & Sutcliffe 1970) and the volume error were both adopted as objective functions with the target of achieving a mean flow percentage error of less than 5% and an NSCC greater than 0.7 for calibration. Further details on the calibration strategy are contained in the Supplementary Material. A subsequent validation process was undertaken for other gauging stations in the basin with the aim of verifying the transferability of the calibration (Vélez *et al.* 2009) or to explore a potential inconsistency.

RESULTS

Calibration performance

Figure 3 shows the comparison of calibration flow duration curves (FDCs) achieved for the Little Ouse at Abbey Heath and River Witham at Claypole Mill which shows a good resemblance. Calibration statistics (see Table 2) were

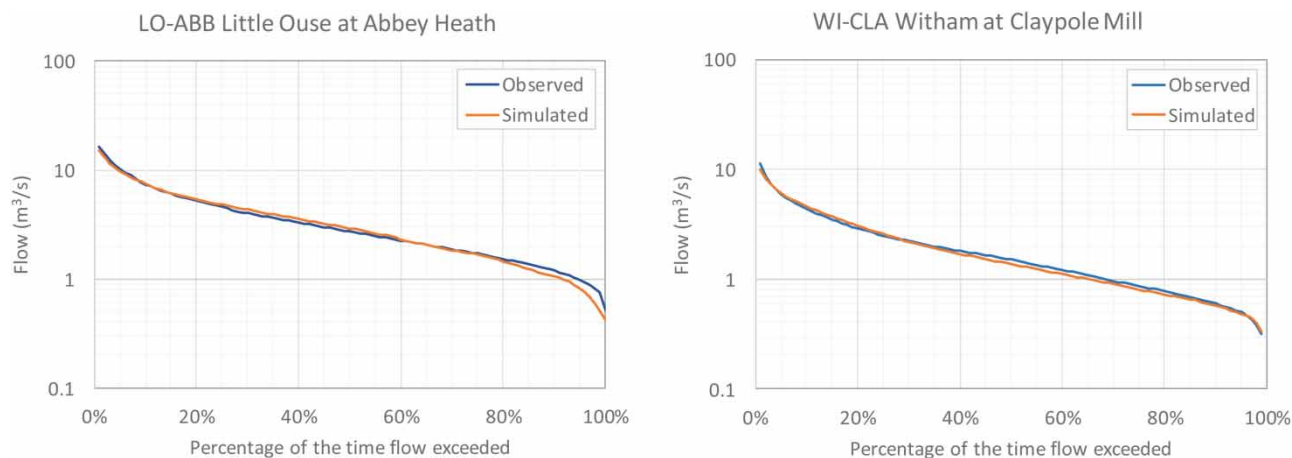


Figure 3 | Little Ouse at Abbey Heath and River Witham at Claypole Mill observed and simulated calibration FDCs (1995–2014).

Table 2 | Statistics of the calibration (bold) and the validation process

Model	Gauging station	Period for statistics	Mean flow percentage error	NSCC	P (mm)	PET (mm)	Runoff observed (mm)	Runoff simulated (mm)
Ely Ouse	Little Ouse at Abbey Heath	1995–2014	–0.4%	0.85	637	648	167	168
	Rhee at Burnt Mill	1995–2014	0.4%	0.81	587	651	115	116
	Cam at Dernford	1995–2014	11.2%	0.70	619	650	135	150
	Lark at Temple	1995–2014	5.0%	0.73	631	644	149	157
	Thet at Melford Bridge	1995–2014	–14.0%	0.82	666	670	204	175
	Wissey at Northwold Total	1995–2014	–22.1%	0.58	700	670	237	184
	Ely Ouse at Denver	1995–2014	–	–	622	656	–	120
		2009–2014	0.4%	0.80	602	728	136	137
Witham and Black Sluice	Witham at Claypole Mill	1995–2014	–1.9%	0.82	637	662	226	223
	Witham at Saltersford Total	1996–2014	5.6%	0.79	686	658	215	228
	Witham at North Hykeham	1999–2014	11.5%	0.71	645	664	180	200
	Barlings Eau at Langworth Bridge	1995–2014	–12.5%	0.65	664	667	248	217
	Bain at Fulsby Lock	1995–2014	–1.4%	0.80	721	664	258	256
	Pointon Lode at Pointon	1995–2014	–9.8%	0.58	648	665	201	183

considered good with both models achieving an NSCC greater than 0.8 and a match to the mean flow within 2%. Comparison of the hydrographs is included in the Supplementary Material.

Validation performance

The correction factors established in the calibration process have been applied to the whole catchment, with flows simulated at the locations of the remaining gauging stations and compared to the observed record as a spatial validation of the model performance. If the calibrated model predicts the observed flows at these gauging stations well, the reliability of simulated flows at ungauged locations is likely

to be high as long as the records for the validation stations are considered accurate. Deviations between modelled and observed flows at validation stations can also be indicative of measurement problems. In this regard, Table 2 also includes the results of the comparison between simulated and observed flows for validation stations. For some stations, the reference period had to be restricted due to the availability of data, particularly for the Ely Ouse at Denver which only had suitable reference data for the period 2009–2014.

Likewise, a comparison of FDCs for the corresponding validation periods listed in Table 2 has been included in the Supplementary Material. As can be seen from Table 2, the distributed modelling approach is, in general, able to

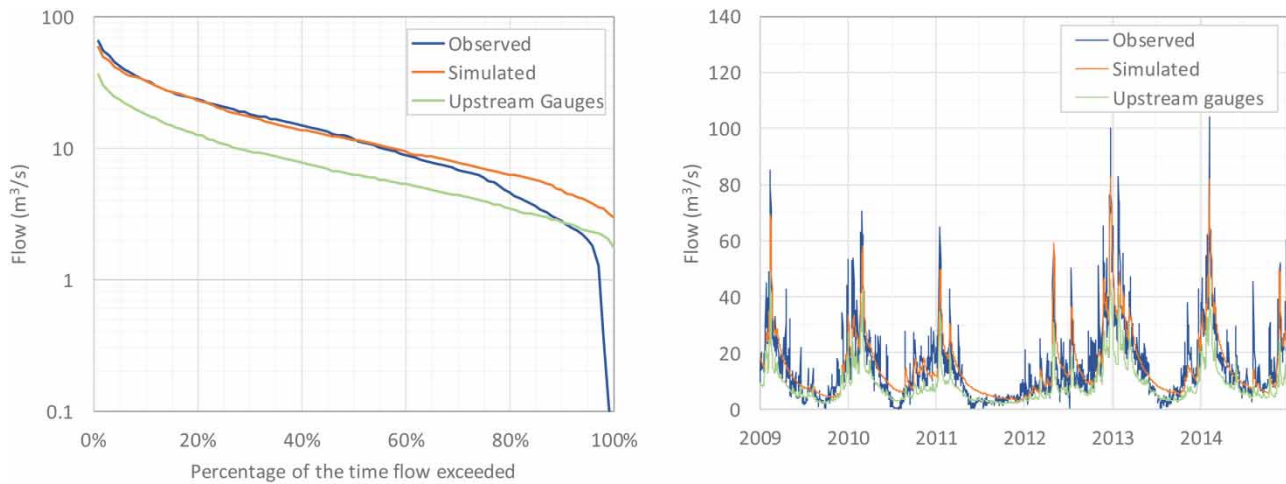


Figure 4 | Ely Ouse at Denver FDC (left) and daily flow series (right) (2009–2014).

provide a good representation of flows at the validation stations, with some achieving comparable statistical performance to the calibration stations.

Verification of meteorological and hydrometric data

Various stations used in the model validation were subject to concerns regarding the quality of the flow record available. Given the availability of a limited validation flow record for the Ely Ouse at Denver for the period 2009–2014, specific mention of this location is warranted.

A comparison of the observed and simulated FDC (Figure 4) shows a good match across the upper half of the flow range, with an increasing deterioration towards the lower end. The daily flow series shows that there are significant fluctuations and sudden drops in flows that are likely to be associated with water management activities in the low-lying parts of the catchment, a feature which is not present when summing the flows from the upstream gauged stations (see Figure 1). The fact that at times, there is less water available at Denver than at the sum of the upstream gauged stations is an indication of unrecorded transfers from the Ely Ouse into low-lying IDB areas via slackers for water-level management purposes. This is a long-standing arrangement that pre-dates licencing, which in the past has been estimated to account for 50% of river flow from the upland area (National Rivers Authority 1993). In drier periods, IDBs actively retain water to maintain higher levels in drains and channels so

that water conveyance is ensured and ecosystems preserved (Hodge & McNally 2000). Part of this water infiltrates back into the soil enhancing evapotranspiration and effectively acting as irrigation. River bed and bank leakage may also be a factor in contributing to channel flow loss. Despite these issues at lower flows, the broad visual fit between the simulated and observed series and a reasonable NSCC gives confidence that the modelling approach delivers improved representation of these ungauged areas.

The model has also highlighted a high volume error and a low NSCC for the Wissey at Northwold. The examination of the daily flow series indicates that while there is a reasonable match against the observed flows during the first half of the period, the model increasingly fails to replicate them in the latter half (see Figure 8 in the Supplementary Material). While uncertainties in input datasets cannot be ruled out, since the station record (National River Flow Archive 2017) cites regular drowning of the weir as an issue and a lack of adjustment in periods of anomalously high flows, an inaccurate record is likely to be contributing to the high volume error. Similarly, the Thet at Melford Bridge weir is subject to drowning due to downstream weed growth (National River Flow Archive 2017), which is likely to explain the relatively high volume error, particularly given that at the calibration station the volume error is minimal.

The reliability of low flow measurements for Pointon Lode in the Black Sluice catchment is also considered uncertain as it is known to drown at high flows and the record displays some anomalous recessions, for example in

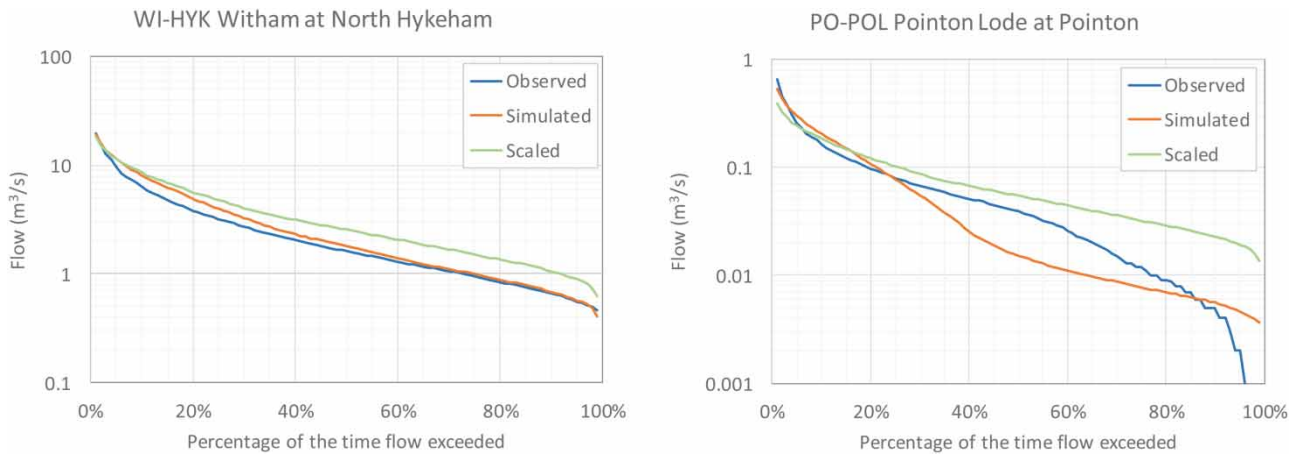


Figure 5 | Witham at North Hykeham FDC (left) and Pointon Lode at Pointon FDC (right) (1995–2014). Green line represents the Claypole Mill FDC scaled as a function of drainage area.

1994, 1998 and 1999, the reason for which is unknown (National River Flow Archive 2017). Under these circumstances, the model would be expected to undersimulate against the record, as can be seen in Figure 5. As an additional verification of the simulation in the Black Sluice catchment, results from the water balance assessment undertaken within the Water Resources East project (Mott MacDonald 2017) to determine the contribution of the Lincolnshire Limestones to the South Forty Foot Drain were compared with the outputs of the TETIS model at 10 simulation points along the springline villages, yielding only a 3% difference. In addition, the estimated average flow passing the downstream pumping station, just west of Boston, was only 1% lower than the value simulated with the calibrated model.

Likewise, flows at North Hykeham in the Witham have historically been thought to be underestimated (Dan Burbidge, personal communication, 20 July 2017). In fact, the available spot flow measurements point towards an underestimation of 5% in low flows (below $1 \text{ m}^3/\text{s}$) and of 10% in the rest of the flow range. After correcting the observed flow series due to this bias, the model was able to provide a very good match to the medium and low flows (see Figure 5), much better than if the FDC at the upstream Claypole Mill gauging station was scaled only as a function of drainage areas to each station, something that would have been done if a lumped model would have been adopted and calibrated at Claypole Mill. This shows that changes in rainfall and physical properties in the intermediate catchment are properly captured by the model, and

reinforces the need for updating the North Hykeham rating curve based on the spot flow measurements.

DISCUSSION

The modelling results have clearly shown an improved representation of ungauged areas when compared to scaling as a function of the drainage area, which would be similar to the procedure if a lumped model would have been adopted. In many applications, this reason alone would be enough to justify the adoption of a distributed modelling approach. However, this application of distributed modelling has highlighted wider benefits associated with the verification of hydrological data and improved catchment understanding.

The flagging of potential bias in meteorological datasets commonly used by the hydrological community, either highlighting a problem in the methodology or in the raw data coming from certain stations, is a key benefit. Without this approach highlighting water balance discrepancies across the area, it may not have been identified that the MORECS v2.0 PET dataset (Hough & Jones 1997) was derived without using any climatological stations within the Ely Ouse basin. The resultant interpolation of climatological variables may therefore not reliably reflect local conditions. MORECS v1.0 (pre-1996) has much lower variation in PET across the catchment, which in addition to the above factor casts some doubt on the validity of the MORECS v2.0 PET dataset for the basin. It should be noted that this issue does not appear to affect the Witham-Black Sluice model as

there is lower variability in PET (Table 2). Highlighting these issues can help in the update and improvement of these meteorological datasets.

Other spatial differences in calibration performance highlighted by using distributed modelling can help point to potential model improvements in the representation of hydrological processes in different areas. A particular issue for the Ely Ouse catchment is groundwater influencing base-flows. Water percolating to the Chalk aquifer, which stretches across the central part of the catchment, can return to the river network either at springs or gradually along lengths of the river (Environment Agency 2013a). The validation gauging stations are all located within the Chalk and will, to varying degrees, be affected by losing to, or gaining from, the aquifer. While deep aquifer losses have been simulated in the model for the Chalk outcrop, the current configuration of TETIS has not allowed simulation of groundwater returns to the channel. This may explain the inability to obtain a precise water balance for the smaller upstream catchments (e.g. the Cam at Dernford).

The issue of unrecorded transfers has been readily identified using distributed modelling. In the case of the Ely Ouse, this is potentially $2 \text{ m}^3/\text{s}$ at Q95. In the Witham catchment, there is also a concern that this may be a contributory factor to the weaker model performance for the Barlings Eau at Langworth, a catchment which is known to be affected by irrigation abstractions. The verification of these issues could allow the water regulator to better understand the scale of these transfers and the overall impact from both licenced and non-quantified permitted abstractions.

As outlined in the results, there are multiple examples where the model has highlighted issues with hydrometric station performance. This can help focus attention on the gauging stations that require improvement. This could lead to the development of an enhanced rating curve based on new spot flow gaugings and a detailed hydraulic model, or alternative methods for the measurement of non-modular flow (if backwater effects or seasonal changes cannot be avoided), or relocation of the station.

A better understanding of all these issues, thanks to the use of a distributed approach, has several benefits. In summary, distributed modelling could help improve the quality of the hydrological information, which is the

basis of any water resources management or flood-risk assessment, leading to the best informed planning processes.

The progressive increase in publicly available spatial datasets characterising the physical properties of the region obtained through remote sensing is now enabling the application of this kind of approach worldwide, even in remote areas. With reducing related costs, GIS efficiencies and model run automation, it is increasingly possible to deliver distributed modelling as a commercially and practically viable option. Distributed modelling can open opportunities to enhance hydrological assessments in the industry, particularly in data scarce and uncertain environments.

CONCLUSIONS

Fully distributed modelling has been applied as part of the overarching purpose of assessing water resource yields but has also served as a valuable catchment-wide data validation tool in three catchments in the East of England with data coverage and quality issues. The approach has successfully shown its capability of considering differences in climate and physical properties when transposing the calibration made at a key gauging station to other points, maximising the potential of limited available flow data within the area and providing improved basin representation compared to traditional lumped modelling approaches.

Moreover, it has been demonstrated how the models can be used to identify potential deficiencies in the reference flow data across all considered catchments. This is a valuable tool to supplement gauging station reviews and has significant potential to help deliver improved modelling results in situations where gauged flow data are of variable quality. This can be particularly relevant when investment decisions (e.g. the size of a reservoir or the location of a river abstraction) are to be made based on the availability of water resources at either an ungauged location or a location where the existing hydrometric data are dubious. It is acknowledged that distributed modelling is more costly than lumped modelling due to its increased complexity. However, if simpler lumped modelling approaches are not adequate to capture the catchment characteristics or resolve issues with data coverage and quality, the additional

costs of the distributed approach can be small in comparison with the investment decisions being made.

The models have also identified potential issues with other input datasets, in this case the MORECS v2.0 PET dataset and transfers for irrigation abstractions. The wider use of distributed modelling within the water resources industry will only help with the identification and feedback of these issues to data custodians and water regulators and help to improve the accuracy and reliability of water resource assessment in the long term. The ease of identification of these issues presents an advantage over lumped or semi-distributed modelling approaches, where potential errors may be masked by the calibration of the input parameters and be more difficult to identify. While input uncertainty and output uncertainty are not explicitly defined, the approach reduces uncertainty as it takes into account spatial consistency, leading to more robust predictions.

The study has also highlighted areas for further work and investigation. Unrecorded transfers (pre-dating licencing requirements) are a specific issue in this area that despite being a known long-term issue still requires further consideration and quantification to improve the model reliability for low flows. The representation of groundwater processes within the TETIS model in complex chalk streams is also an aspect that needs further development. While there are recommendations for further model refinement and improvement, the work has demonstrated the benefits of the application of distributed modelling. In the international context, where often even less reliable hydrological data are available, the potential benefits are even greater. The paper has also demonstrated that, with the progressive increase in publicly available spatial datasets, fully distributed hydrological modelling can be effectively and beneficially implemented in commercial water industry applications, similar to groundwater modelling. As such, a wider consideration of these hydrological approaches within the industry is strongly recommended.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Anglian Water Services and Mott MacDonald in publishing this paper. Thanks are also due to Dan Burbidge (Environment Agency) for his useful advice regarding the gauging

stations and artificial influences present in the catchments. We are also grateful to Peter Ede for his helpful comments on the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at <https://dx.doi.org/10.2166/nh.2019.006>.

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