Hydrological Modelling for the Rivers Lavant and Ems

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Executive Summary

The Project "Hydrological Modelling for the Rivers Lavant and Ems" is concerned with conceptual rainfall-runoff modelling of catchments on the Chalk, using the rivers Lavant and Ems in southern England as case studies. Such rivers can exhibit ephemeral streamflow behaviour and be affected by pumped abstractions, external spring flows and underflows beneath the river gauging station. The project aims to assess the utility for real-time flood forecasting of the PDM rainfall-runoff model, in the form extended to represent such behaviour and effects.

This project report first reviews the requirements for flood forecasts in the Lavant and the Ems and the specific objectives of the project. It then outlines the PDM rainfall-runoff model, focussing on its extended formulation that facilitates incorporation of groundwater losses and well level data. Application of the model to the Lavant and Ems catchments is then addressed.

Data required for modelling are first identified and their availability reviewed. The primary data sources considered include time-series of rainfall (from gauges and weather radar), river levels and flows, potential evaporation, pumped abstractions and observation well levels. Their selection and suitability for modelling is discussed. Rainfall data are given particular attention in relation to providing a long time-series of consistent form for modelling purposes. The basic raingauge data are subject to an extensive data quality control check that exposes shortcomings in present processing procedures. Ways of overcoming these are suggested that are relevant to both future work and to wider hydrometric practices. For use in modelling a method is proposed to obtain a consistent and continuous time-series of catchment average rainfall, taking account of data gaps and suspect periods. A comparison between raingauge and radar estimates of rainfall is presented and the future use of radar data operationally is discussed.

The stations for which river level and/or flow are available are reviewed in outline. Closer attention is paid to the main river gauging stations at Graylingwell (Lavant) and Westbourne (Ems) including a review of their ratings. Time-series of potential evaporation data derived from MORECS and MOSES are considered alongside standard profiles in use by the Environment Agency. A strategy for use of MORECS monthly time-series disaggregated in time using linear interpolation and a diurnal profile is formulated for use in modelling. Future operational use of MOSES PE data is envisaged and differences with MORECS discussed.

A strategy for modelling is developed that selects periods of record to be used for model calibration and independent evaluation. Methods to be used for assessing model performance are formulated. The strategy also considers the problem of model conceptualisation for groundwater catchments with ephemeral streamflows affected by pumped abstractions, external springs and underflows, and low-flow augmentation from wells. A need to impose a conceptualisation supported by data and information is recognised due to identifiability problems with the extended PDM formulation. The value of a detailed catchment water balance to identify unaccounted for water transfers is highlighted in this model conceptualisation process. In addition, flow records from a nearby spring-fed stream, Costers Brook at Cocking, are also considered. The modelling work that follows tries to clarify the nature of these transfers with the help of the modelled water balance.

Calibration and assessment of the extended PDM model to the Lavant and Ems demonstrates good model performance that supports future operational deployment. The assessments carried out relate to the quality of model simulation of both river flows and well levels. Sensitivity analyses on the forms of model input to use operationally are used to support recommendations on the combination of raingauges to use, the value of radar rainfall, and the profiles of potential evaporation and abstractions to employ. An emulation of the real-time application of the models in forecast-mode demonstrates their potential to forewarn of the rapid rise in river flow during the onset of major flood events. The model results highlight the benefit the extended PDM could have for flood warning and advance operation of flood alleviation mechanisms.

The report ends with a summary and a review of the recommendations identified as the study progressed. Conclusions are presented that incorporate recommendations on the way forward with regard to operational implementation of the extended PDM model for groundwater catchments.

1 Introduction

1.1 Overview

This report outlines work carried out under the “Hydrological Modelling Components for the Rivers Lavant and Ems Catchments” project. The purpose of the project is to explore the viability for flood forecasting of using the PDM model extended for use in groundwater catchments, as outlined in Moore and Bell (2002). Such catchments can exhibit ephemeral streamflow behaviour and be affected by pumped abstractions, underflows below the gauging station and surface/groundwater catchment boundary differences.

The project aim is to assess the model on the River Lavant to Graylingwell and on the River Ems to Westbourne using historical hydrometric records, including consideration of the use of weather radar. If this assessment reveals that the model, or a development of it, has value for real-time flood forecasting then further work will be proposed as a principal outcome of the project. If appropriate, this may point to further work on other groundwater-dominated catchments, in Southern and possibly other Agency regions.

The study may also recommend adoption of the extended form of the PDM model as a module adapter for real-time use within the NFFS, along with a parallel development of “PDM for PCs” (using the TSCAL environment) for off-line model calibration. This may extend to include similar developments for the PSM model encompassing the TCM used by the Environment Agency. Such possible future model developments relating to the NFFS will require a case for national approval.

The specific requirements for flood forecasts in the case study catchments of the Lavant of the Ems are reviewed in this opening section to highlight the application context. In order to focus on the model and its application from the outset, the section that follows provides an outline of the PDM rainfall-runoff model, highlighting extensions to the model that have been specifically developed for permeable catchments on the Chalk. Against this modelling context, the report then progresses to identify the needs and availability of data to support application of the model to the Lavant and Ems catchments. The tender brief provided valuable background, giving details of the hydrometric network and related records together with a hydrological review of the catchments and their water balances. This background has been supplemented by discussions with Agency staff at meetings in Worthing and email and telephone exchanges.

The report describes the data taken on to support modelling and their quality control. A strategy for model application is developed which identifies the periods to be used for model calibration and independent evaluation. It also addresses the conceptualisation of the modelling problem for the Lavant and Ems catchments, focussing on water balance considerations affected by abstractions and catchment transfers. Any further model development required and/or data needs are also identified.

Calibration and assessment of the PDM rainfall-runoff model to the Lavant and Ems catchments follows this detailed preparatory work. The assessment is complemented by sensitivity analyses aimed at deciding what rainfall, potential evaporation and abstraction data should be used as input to operational forms of the models.

The Report closes with a summary and an inventory of recommendations made during the course of the project. Conclusions are made that lead to recommendations on how the extended PDM model should be progressed as an operational tool for flood forecasting with the Environment Agency's National Flood Forecasting System.

1.2 Forecast requirements for the Lavant and Ems catchments

The principal need relating to the Lavant catchment is for flood forecasts at Graylingwell to support operation of the RLFAS (River Lavant Flood Alleviation Scheme) diversion at Westhampnett immediately downstream, serving to mitigate flooding in the environs of Chichester. The diversion scheme is partially activated at a flow of 2.5 m^3s^{-1} and fully activated at 3.5 m^3s^{-1}. The modelling challenge is to be able to represent the short-term response to rainfall on a saturated catchment together with the longer-term baseflow response to infiltration and changes in groundwater storage. There are clear threshold effects in the observed river flows, with flashier responses being evident above circa 1.5 m^3s^{-1}.

On the River Ems there is a need for flood forecasts at Westbourne gauging station, used as an alarm trigger-level site for flood warning purposes. Whilst the modelling requirement is similar to the Lavant, the rapid response component is more important because the alarm thresholds can be crossed when baseflows (and well levels) are relatively low. The alarm trigger levels are given below.

Table 1.1 Alarm trigger levels for the Ems at Westbourne

	Trigger Level		
	Stage		Flow
	m	mAOD	m^3s^{-1}
H1	-	-	-
H2	0.786	10.40	3.43
H3	0.826	10.44	3.91
H4	0.866	10.48	4.41

Both catchments are subject to significant groundwater pumping. This leads to ephemeral streamflow for the Lavant but a low flow groundwater augmentation scheme prevents this from occurring on the Ems. Whether or not combining the effects of augmentation and abstraction requires further development of the extended PDM will be considered in the model application to the Ems.

A catchment water balance for the Lavant to Graylingwell over the 8 water years 1995 to 2003 indicates 26% is unaccounted for and may relate to groundwater flow out of the catchment. A similar balance analysis for the Ems to Westbourne, for the 10 water years 1995 to 2005, reveals a smaller 13% unaccounted for residual: these could be accounted for by abstractions in part, but also by groundwater outflows. One aim of the PDM modelling work will be to try and clarify the amount of water going to groundwater outflow using the modelled water balance.

1.3 Specific objectives of the project

The main task of the project is to calibrate the extended PDM for the Lavant and Ems catchments and evaluate its performance on an independent record not used for calibration. The assessment should consider the quality of the flow simulation in relation to the processes operating, paying attention to the water balance and the occurrence of ephemeral flows as well as the form of the flood hydrographs. To help in this assessment it is proposed to consider both simulation of river flows and also water table variations in relation to the modelled groundwater storage.

One specific objective is to determine whether the model can run operationally in continuous simulation mode. As with the PDM used in the NFFS, this is already the case (although a module adapter form of the code for real-time use has yet to be implemented). One uncertain area is precisely how abstraction data will be made available to the NFFS to support real-time application. This will be considered and reported on here.

This report first aims to provide the background and develop the strategy for addressing these specific objectives. As issues arise and recommendations on the way forward made, these are highlighted in grey boxes as “Recommendations”. The report then progresses to the calibration and assessment of the models over the Lavant and Ems, treating these as case study catchments from which more general recommendations may be made. A major consideration is the future operational use of the extended PDM within the Environment Agency, both in Southern Region and for other regions experiencing flooding on permeable catchments.

2 The extended PDM model for groundwater catchments

2.1 Introduction

The main purpose of the project is to apply the extended PDM rainfall-runoff model to the Lavant and Ems catchments in order to assess its potential use in real-time flood forecasting for groundwater-dominated rivers. As background, this section aims to provide an overview of the PDM model extended to allow for ephemeral streamflow behaviour and to accommodate losses via underflows, external springs and pumped groundwater abstractions.

The standard PDM model structure is first outlined. Then the extended PDM is introduced and it is shown how the basic representation of groundwater storage is developed to allow for ephemeral flow and groundwater losses. Finally, it is considered how data on well levels may be related to modelled groundwater storage and used in model assessment, calibration and real-time state updating.

2.2 The standard PDM

The Probability-Distributed Model, or PDM, is a fairly general conceptual rainfall-runoff model which transforms rainfall and potential evaporation data to flow at the catchment outlet (CEH Wallingford, 2005; Moore, 2006). Figure 2.1 illustrates the general form of the model. The PDM has been designed more as a toolkit of model components than a fixed model construct. A number of options are available in the overall model formulation which allows a broad range of hydrological behaviours to be represented. Figure 2.1 presents the standard form of the PDM commonly used.

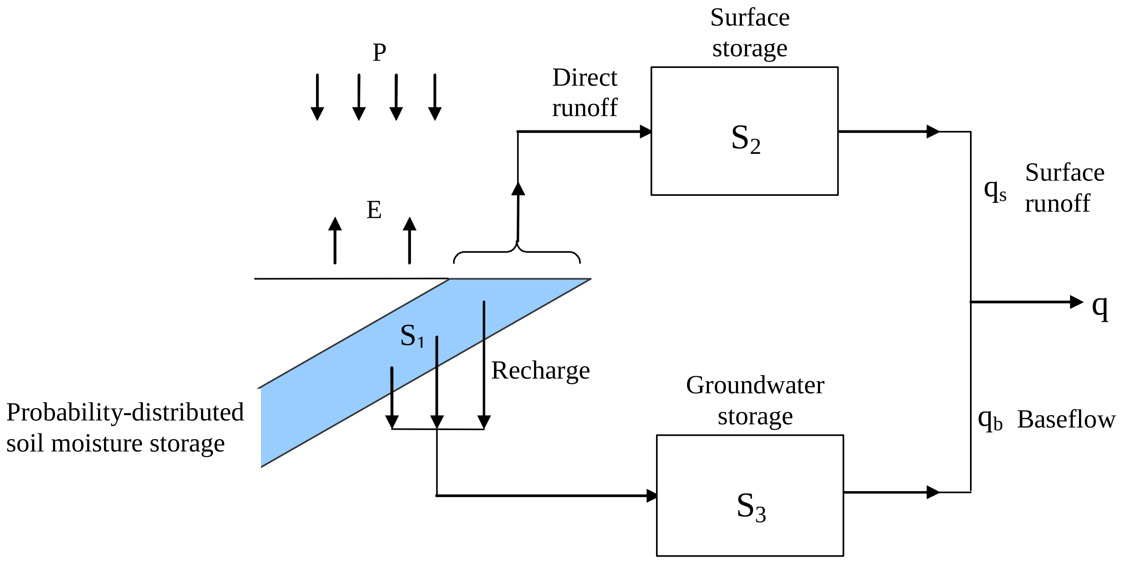

Figure 2.1 The PDM rainfall-runoff model.

Runoff production at a point in the catchment is controlled by the absorption capacity of the soil to take up water: this can be conceptualised as a simple store with a given storage capacity. By considering that different points in a catchment have differing storage capacities and that the spatial variation of capacity can be described by a probability distribution, it is possible to formulate a simple runoff production model which integrates the point runoffs to yield the catchment surface runoff into surface storage. The standard form of PDM employs a Pareto distribution of store capacities, with the shape parameter b controlling the form of variation between minimum and maximum values $c_{\min}$ and $c_{\max}$ respectively.

Probability-distributed moisture stores with depths below a given critical capacity will be full and spilling during rainfall, contributing “direct runoff” to the surface storage. This surface storage represents the fast pathways (such as river channels) to the basin outlet. This is usually modelled by a cascade of two linear reservoirs expressed as an equivalent transfer function model (O’Connor, 1982).

Water draining from the probability-distributed moisture store passes into subsurface (groundwater) storage as recharge. The rate of drainage is in proportion to the water in store in excess of a tension water storage threshold. The subsurface storage, representing translation along slow pathways to the basin outlet, is often taken to be of cubic form, with outflow proportional to the cube of the water in store.

The outflow from surface and subsurface storages, together with any fixed flow representing, say, compensation releases from reservoirs or constant abstractions from the river, forms the model output. The parameters involved in the standard form of PDM model are summarised in Table 2.1.

2.3 The extended PDM

2.3.1 Introduction

Specifically for groundwater-dominated catchments, such as those on the Chalk, the *subsurface storage component* can be extended to accommodate pumped abstractions from groundwater; losses to underflow and external springs. This extended formulation allows ephemeral streamflow behaviour to be represented through keeping track of the groundwater storage depletion during dry river periods. It also allows explicit inclusion of pumped abstraction time-series data and the use of well level records to support model assessment and calibration.

The extended PDM was first reported on and trialled within the Environment Agency’s “Comparison of Rainfall-Runoff Models for Flood Forecasting” R&D project (Moore and Bell, 2001;Bell *et al.*, 2001). This work was later published, using the River Lavant as a case study, by Moore and Bell (2002). This extended formulation does not yet feature in the CEH software product codes available to the Environment Agency through the NFFS, either in the form supplied for off-line model calibration (CEH Wallingford, 2005a) or for real-time use as an NFFS module adapter (CEH Wallingford, 2005b). It is the extended PDM research code that is used in the present study.

Table 2.1 Parameters of the standard PDM model

Parameter name	Unit	Description
f_c	none	rainfall factor
τ_d	h	time delay
Probability-distributed store		
$c_{\min}$	mm	minimum store capacity
$c_{\max}$	mm	maximum store capacity
b	none	exponent of Pareto distribution controlling spatial variability of store capacity
Evaporation function		
b_e	none	exponent in actual evaporation function
Recharge function		
k_g	h mm^{b_g-1}	groundwater recharge time constant
b_g	none	exponent of recharge function
S_t	mm	soil tension storage capacity
Surface routing		
k_s	h	time constant of cascade of two equal linear reservoirs ($k_s = k_1 = k_2$)
Groundwater storage routing		
k_b	h $\text{mm}^{m\text{-}1}$	baseflow time constant
m	none	exponent of baseflow nonlinear storage
q_c	m^3 s^{-1}	constant flow representing returns/abstractions

The subsurface groundwater component of the PDM is outlined in detail in the following sub-sections, first in its standard form and then in its extended form. Incorporation of well level data to support model assessment, calibration and real-time state updating is considered at the end.

2.3.2 The basic form of groundwater storage

First we will review the groundwater storage component used in the standard PDM, as this forms the basis of the extended formulation. Recall that the probability-distributed store of the PDM partitions rainfall into direct runoff, groundwater recharge and soil moisture storage. Direct runoff is routed through surface storage: a "fast response system" representing channel and other fast translation flow paths. Groundwater recharge from soil water drainage is routed through subsurface storage: a "slow response system" representing groundwater and other slow flow paths.

The routing of recharge through the groundwater system can be represented by a variety of types of nonlinear storage. For notational convenience, *S(t)* is used here to denote the volume of water stored in the nonlinear groundwater storage, expressed as a depth over the basin (specifically the suffix b for quantities relating to “baseflow” storage is omitted for clarity). The rate of outflow per unit area from a nonlinear storage, $q \equiv q(t)$, is considered to be proportional to some power, m, of the volume of water held in the storage per unit area, $S \equiv S(t)$, so that

$$q = k\,S^m, \qquad k>0\ ,\ m>0 \tag{2.1}$$

where k is a rate constant. The storage here can be conceptualised as a reservoir with a bottom outlet representing aquifer storage and the release of water from it as the baseflow component of catchment flow. Combining the nonlinear storage equation above with the equation of continuity

$$\frac{dS}{dt} = u - q, \tag{2.2}$$

where $u \equiv u(t)$ is the input to the store, gives

$$\frac{dq}{dt} = a(u - q)q^b, \qquad q>0, -\infty<b<1, \tag{2.3}$$

where $a=mk^{1/m}$ and $b=(m-1)/m$ are two parameters. The input here is the groundwater recharge and is the rate of drainage from the soil per unit area. This ordinary differential equation is sometimes called the Horton-Izzard model (Dooge, 1973) and can be solved exactly for any rational value of m (Gill, 1976, 1977).

Horton (1945) considered nonlinear storage models as descriptors of the overland flow process. He found that the exponent m for fully turbulent flow is 5/3, and for fully laminar flow is 3. This allowed Horton to define an “index of turbulence, $I=¾(3-m)$, ranging from 1 for turbulent flow to 0 for laminar flow. Horton (1938) found a solution in terms of tanh (the hyperbolic tangent) when m=2 (the quadratic storage function), corresponding to I=0.75, which he referred to as the “75% turbulent flow” case. It is given a conceptual interpretation as an “unconfined or non-artesian” storage element by Ding (1967) based on Werner and Sundquist’s (1951) theoretical analysis of flow from a deep non-artesian aquifer based on Darcy’s law and Dupuit’s assumption (they also show that m=1 is appropriate for confined or artesian aquifers). Todd (1959) provides an accessible introduction to the groundwater theory involved. The quadratic storage function was used by Mandeville (1975) as the basis of the Isolated Event Model (IEM) used in the UK Flood Study (NERC, 1975) and later adapted for real-time flood forecasting by Brunsdon and Sargent (1982). It is also used in the Thames Catchment Model (TCM) to represent release from groundwater storage (Greenfield, 1984).

The choice of nonlinear storage to use in the PDM includes the linear, quadratic, exponential, cubic and general nonlinear forms. The theoretical work of Werner and Sundquist (1951) and Ding (1967) suggests the use of linear and quadratic forms for confined (artesian) and unconfined aquifers respectively. However a cubic form, corresponding to the laminar flow case (I=0, m=3), has been found useful in practical applications of the PDM where the hydrograph recession is initially steep but subsequently is sustained and slowly decreasing. In this case where $q=kS^3$ an approximate solution utilising a method due to Smith (1977) yields the following recursive equation for storage, given a constant input u over the interval $(t, t+\Delta t)$:

$$S(t+\Delta t) = S(t) - \frac{1}{3kS^2(t)}\left\{\exp\left(-3kS^2(t)\Delta t\right) - 1\right\}\left(u - kS^3(t)\right). \qquad (2.4)$$

Discharge may then be obtained simply using the nonlinear relation

$$q(t+\Delta t) = k\, S^3(t+\Delta t). \qquad (2.5)$$

Solutions for the other nonlinear forms are presented in Appendix A of Moore and Bell (2002). When used to represent groundwater storage, the input u will be the drainage rate per unit area, d_i, from the probability-distributed moisture storage, and the output $q(t)$ will be the "baseflow" component of flow per unit area $q_b(t)$. The parameterisation $k_b=k^{-1}$ with units h mm^{m-1} is also used.

The above provides a review of the groundwater storage formulation used in the standard PDM. Explicit allowance for ephemeral flow and groundwater abstractions is incorporated in the extension of the PDM. The theoretical basis of this extension is outlined next.

2.3.3 The extended form of groundwater storage

Water held in groundwater storage can be lost to the surface catchment by artificial pumped abstractions, by underflow below the gauged catchment outlet or by spring flow external to the surface catchment. Losses via underflow and spring flow will be considered later. In the case of abstractions, A, the nonlinear storage theory introduced in the previous section requires extension to consider the case of negative net input to storage, u, and the possibility of storage being drawn down below a level at which flow at the catchment outlet ceases. This extension allows for the modelling of ephemeral streams typical of catchments on the English Chalk.

Formally, we can define the input to the nonlinear storage, u, as recharge d, less abstractions, A, dropping the time suffix for notational simplicity. With $u = d - A$, the prospect arises of negative inputs to storage leading to the cessation of flow. Consider the time interval $(t, t+\Delta t)$ within which cessation of flow occurs after a time T'. Using the cubic storage, $q = kS^3$, for the purposes of illustration, then equation (2.4) gives the time to flow cessation, T', by solving

$$0 = S(t) - \frac{1}{3kS^2(t)}\left\{\exp\left(-3kS^2(t)T'\right) - 1\right\}\left(u - kS^3(t)\right)$$

which gives

$$T' = -\frac{1}{3kS^2(t)}\ln\left\{1 + \frac{3kS^3(t)}{u - kS^3(t)}\right\}. \qquad (2.6)$$

Now consider an extended form of storage is conceptualised which, instead of emptying at zero flow, allows for further withdrawal of water for abstraction. A storage of this kind is depicted schematically in Figure 2.2. Then the "negative storage" at the end of

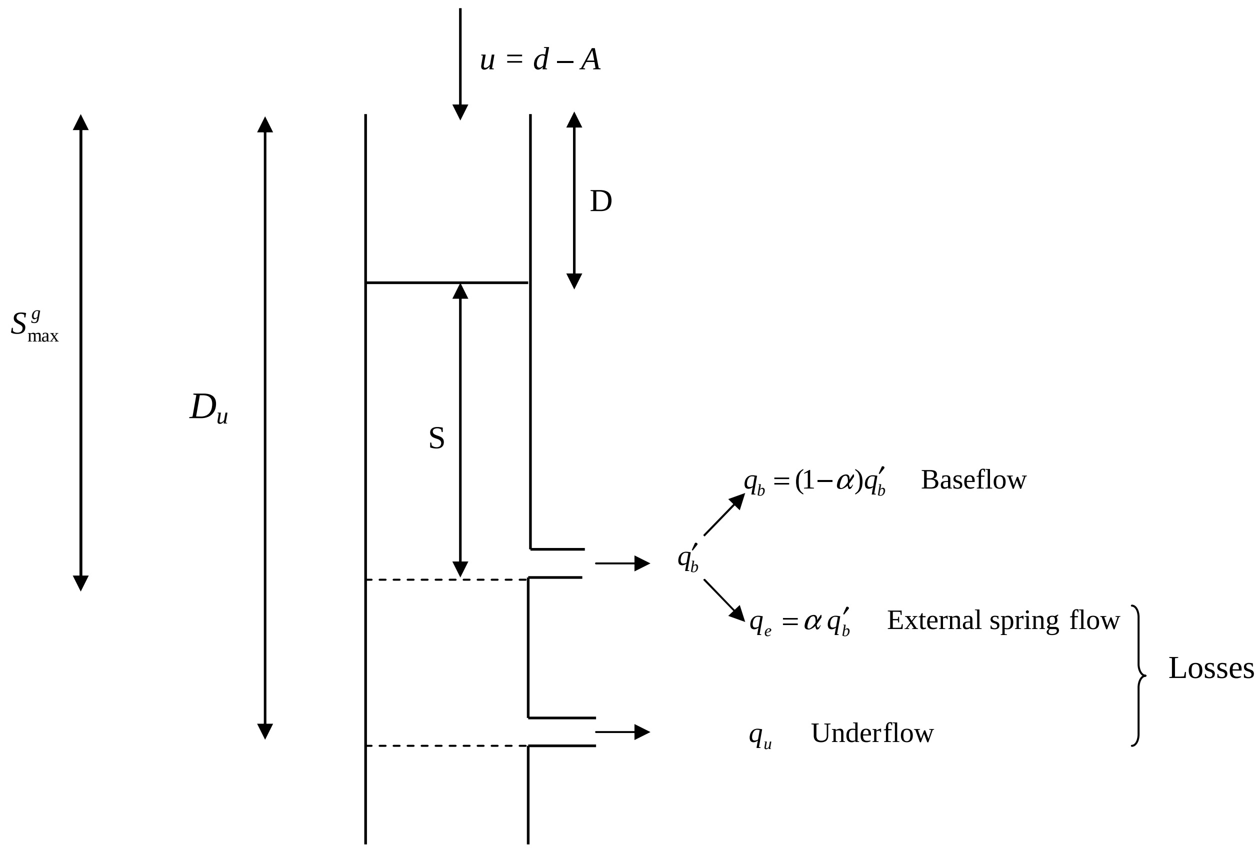

Figure 2.2 Conceptualisation of extended nonlinear storage.

the interval during which storage changes from positive to negative can be calculated as

$$\begin{aligned} S(t+\Delta t) &= u(\Delta T - T') \\ &= u\Delta t\left\{1+\frac{1}{3kS^2(t)\Delta t}\ln\left\{1+\frac{3kS^3(t)}{u-kS^3(t)}\right\}\right\} \qquad (2.7) \\ &= u\Delta t\left\{1+\frac{1}{a\Delta t q^{2/3}(t)}\ln\left\{1+\frac{3q(t)}{u-q(t)}\right\}\right\} \end{aligned}$$

where $a = 3k^{1/3}$.

With further abstractions from storage the negative storage can be calculated by simple continuity. When recharge exceeds abstractions the storage is replenished and at some time flow is initiated once more. The time interval within the model interval Δt that this occurs is calculated by simple continuity and the residual time interval used in equation (2.4) in place of Δt (with $S(t) = 0$). The normal calculations apply whilst the storage is in surplus. Expressions for the time to flow cessation, T', and the initial negative storage, *S(t+Δt)*, for other types of nonlinear store are given in Appendix B of Moore and Bell (2002). As previously indicated, in practice the parameterisation $k_b = k^{-1}$ with units h mm$^{m\text{-}1}$ is used.

By introducing a maximum groundwater storage, $S^g_{\max}$, then the groundwater storage deficit can be calculated as

$$D = S^g_{\max} - S \qquad (2.8)$$

for both positive and negative values of S. This deficit will be used later when relating model storage to well level data and is also used in the parameterisation of losses to underflow.

To cater for situations where information on all abstractions affecting the catchment water balance does not exist, an abstraction model which scales and adds to known abstractions is included in the overall model formulation; thus

$$A = c_A + f_A A_r . \qquad (2.9)$$

where A_r is the recorded total abstraction for a time interval and c_A and f_A are parameters. No limit is imposed on the modelled or recorded abstraction in relation to the available groundwater in storage. In practice there will be a minimum well level for pumping that will be reflected in the abstraction record. Care needs to be exercised in setting the parameters of the abstraction model to avoid unrealistic pumped abstractions being used at low groundwater storage levels.

2.3.4 Incorporation of losses to underflow and external springs

Having extended the theory of nonlinear storage models to accommodate pumped abstractions, it is now appropriate to consider the conceptualisation of losses to underflow and external spring flow. Flow emerging from the catchment beneath the ground surface of the gauging station is referred to here as *underflow*. It is reasonable to suppose that underflow is controlled by the hydraulic head and thus the water in storage, and that this relation is linear. Then the rate of underflow can be defined as

$$q_u = k_u^{-1}(D_u - D) = k_u^{-1} S_u , \qquad (2.10)$$

where k_u is the underflow time constant (units of time) and parameter D_u is the maximum deficit for underflow to occur with $D_u \geq S^g_{\max}$; also $S_u = S + D_u - S^g_{\max}$. This is depicted in Figure 2.2 as an additional lower "underflow" outlet to the nonlinear storage. Note that this conceptualisation of underflow excludes any local phenomenon more strongly linked to local river flow than to the groundwater system, such as bypassing of flood flows around the gauging weir or flows or flows through floodplain alluvium deposits. Here, the notation D_u replaces $D_{\max}$ used by Moore and Bell (2002) to clarify that the water in store can fall below the level of the "underflow" outlet.

Note that underflow across the topographic catchment boundary is only considered as a loss of water out of the catchment. Underflow gains, if known, could be incorporated via the abstraction time-series (or by introducing a separate time-series for this purpose). It would be possible to use the forecast underflows from one catchment model in quantifying this for an adjacent catchment it exports to. A more detailed coupled representation might be achieved using a spatially distributed model.

The normal outflow from the nonlinear storage arising from positive values of storage, S, has been assumed to be the baseflow component of the flow at the catchment outlet. An extension allows a fraction, α, to contribute as springs external to the catchment with flow, q_e, whilst the remaining fraction, $1-\alpha$, contributes as the baseflow, q_b, at the catchment outlet (Figure 2.2). Note that with this simple formulation, cessation and commencement of external spring flow and catchment flows will be coincident.

2.3.5 Incorporation of well level data

If well measurements of groundwater level are available it is possible to relate the model storage, $S \equiv S(t)$, to the well level, $W^o \equiv W^o(t)$. Well measurements normally record the depth of the water table from the ground surface. The storage deficit D can be used to calculate the depth to the water table as

$$W = Y_s D \,. \qquad (2.11)$$

Here, Y_s is the specific yield of the groundwater reservoir, defined as the volume of water produced per unit aquifer area per unit decline in hydraulic head. This dimensionless parameter takes values typically in the range 0.01 to 0.3 (Freeze and Cherry, 1979).

An additional datum correction corresponding to the height of the ground surface at the well, h_w, is required to relate W to observed well levels, W^o, when these are referenced to Ordnance Datum; then the modelled depth W is comparable with the observed depth $h_w - W^o$.

The above provides the basis of incorporating well level measurements into both the model calibration process and the model state updating procedure. Wells are best chosen that reflect the bulk water storage changes in the aquifer, rather than more localised redistributions of groundwater.

2.3.6 Additional parameters of the extended PDM

Finally, the additional parameters introduced into the extended form of the PDM model are summarised in Table 2.2.

Table 2.2 Additional parameters of the extended PDM model

Parameter name	Unit	Description
Underflow		
k_u	h	underflow time constant
D_u	mm	maximum deficit for underflow *t*
External springs		
α	none	fraction of groundwater outflow contributing to external springs
Abstraction		
c_A	mm h^{-1}	constant abstraction
f_A	none	factor on recorded abstractions
Well level		
$S^g_{\max}$	mm	maximum groundwater storage
Y_s	none	specific yield of aquifer
h_w	m	well level datum

3 Data requirements and availability for modelling

3.1 Introduction

This section aims to review the data requirements for modelling and the availability of suitable records. This serves to identify the data to be taken on to support the modelling. Quality control of these data is also reported on and shortcomings identified. As issues arise, the way forward is considered and recommendations made. These recommendations are highlighted in grey boxes and serve as a record of actions and decisions made during the course of the project.

The PDM rainfall-runoff model in its basic form employs rainfall and potential evaporation data as input and the output is simulated river flow. The time-step of the model and input/output data is usually 15 minutes for real-time forecasting applications. In simulation-mode, observed river flow data are only used to assess model performance and for initialising the model at the start of the period to be simulated. In real-time mode, river flows are used to sequentially update the model's water contents (the "states") at every time-step up to 'time-now'; they are also used to assess model forecast performance at time-steps beyond time-now for different forecast lead-times.

In the extended PDM developed for permeable catchments, pumped abstraction data can be used as model input. Also, well level data can be used to assess model simulations of groundwater levels. These data can potentially be used in real-time (or near real-time) mode to adjust the modelled groundwater storage: this is outside the scope of the present investigation.

Thus, the time-series data potentially useful for PDM rainfall-runoff model applications encompass the following:

- Rainfall
- River levels/flows
- Potential evaporation
- Abstractions and returns
- Well levels

Spring flow records, within and just outside the catchment, may also help support model conceptualisation and configuration. These time-series data and their use in modelling are reviewed in turn, in the sub-sections that follow, in relation to the rivers Lavant and Ems applications. By way of general background to this section, Figure 3.1 provides overview maps of the network of hydrometric stations.

3.2 Rainfall

This section considers the sources of rainfall information available to support PDM modelling for the Lavant and Ems catchments. Tipping-bucket and daily storage-gauge records from the raingauge network are first reviewed, including gauges in the vicinity of the catchments. The weather radar coverage over the catchments is then looked at along with the historical records available. Only raingauge data will be considered for calibration and evaluation of the PDM as weather radar data do not exist for the entire

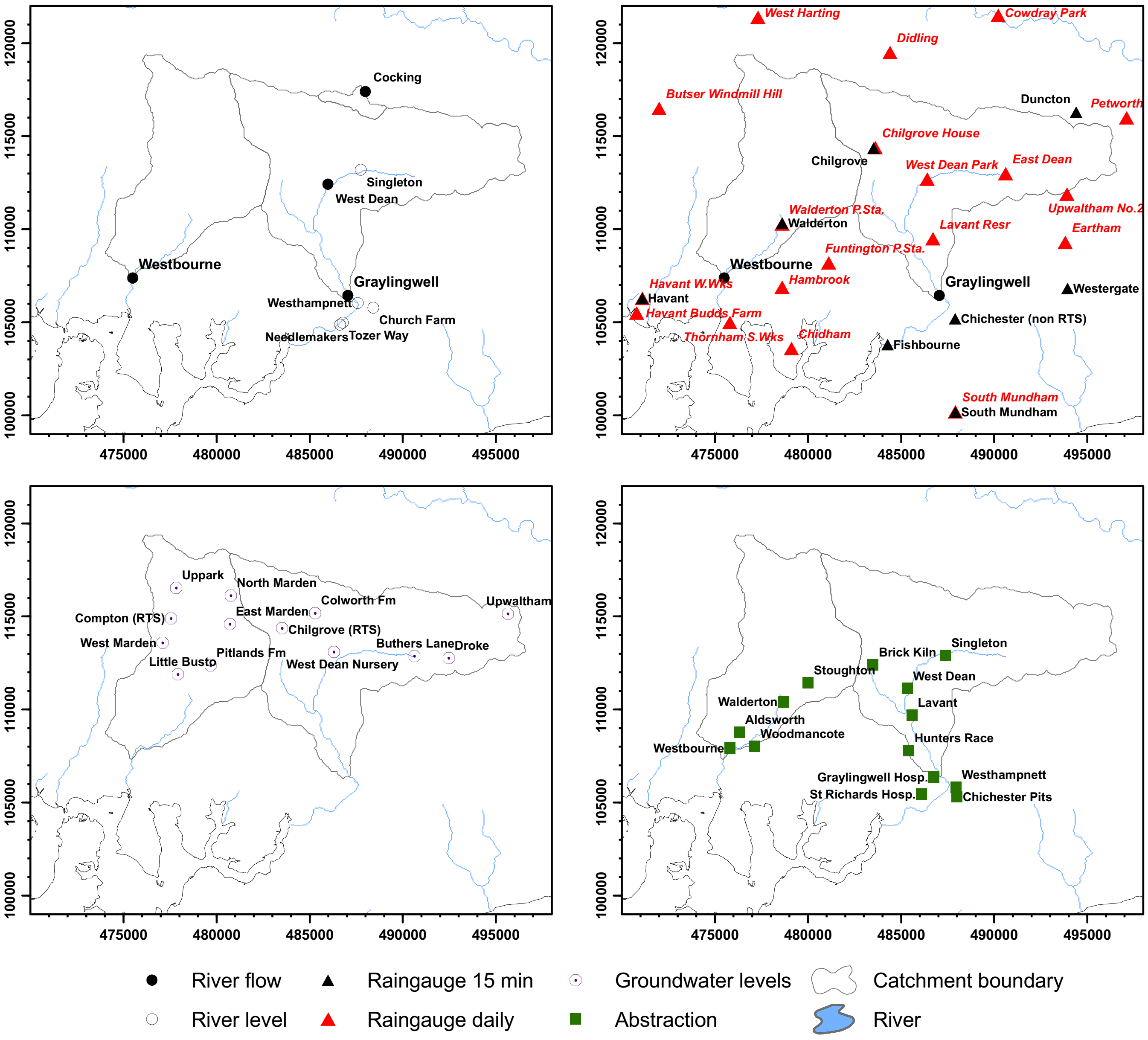

Figure 3.1 Hydrometric network in the vicinity of the Graylingwell (River Lavant) and Westbourne (River Ems) catchments. Note only groundwater level sites with long and complete records are shown.

period being studied (1991 to 2006). However, radar data will be considered in a model sensitivity context. Using this review as background, recommendations are made on the rainfall data to be used for modelling and real-time flood forecasting following the quality control analysis in Section 4.1.

3.2.1 Raingauge data

Tipping-bucket raingauge data for eight locations in the vicinity of the Lavant and Ems catchments were provided by the Environment Agency and details of the data files received are given in Table B.1. Table 3.1 gives information for the raingauges on their location, height, SAAR (Standard Average Annual Rainfall) and availability on telemetry.

Table 3.1 Tipping-bucket raingauges in the vicinity of the Lavant and Ems catchments. Height and SAAR (Standard Average Annual Rainfall) are taken from CEH datasets.

Raingauge	Grid Reference	Height (m)	SAAR 1961-90 (mm)	On Telemetry?
Chilgrove	483526 114367	79.1	907	Y
Fishbourne	484282 103812	5.9	721	Y
Chichester	487900 105200	15.1	753	N
Walderton	478618 110340	33.8	818	Y
Duncton	494400 116300	77.9	1034	Y
South Mundham	487920 100190	7.1	702	Y
Havant	471100 106300	7.2	730	Y
Westergate	493940 106830	19.4	780	Y

Table 3.2 provides information on the Met Office daily rainfall records available at CEH and their relation to the set identified by the Environment Agency. These have been used as part of the data quality control process outlined in Section 4. The location of the daily and tipping-bucket raingauges relative to the Lavant and Ems catchments is presented in Figure 3.2. Also shown is the 1 km grid of SAAR (1961-90).

3.2.2 Weather radar data

The British Isles is covered by a network of weather radars which provide estimates of instantaneous rain-rate. The two main types of radar product available to the Environment Agency for flood forecasting purposes are the single-site radar products and the national Nimrod QC (Quality-Controlled) 1/2/5 km composite weather radar product. CEH's Hyrad system employed by the Environment Agency can be used to process the radar rain-rates to derive catchment average rainfall as 15 minute totals for use in rainfall-runoff modelling.

The single-site radar products are available at resolutions of 1, 2 and 5 km. The time interval is 5 minutes for all resolutions except for the 5 km resolution prior to November 2003 which had a 15 minute interval. Currently the highest resolution 1 km data are available out to a range of 50 km, 2 km data to 100 km range and 5 km data to 250 km range, although these ranges have increased over time. With increasing range the volume of atmosphere sampled by the "radar returns" grows leading to loss of resolution; attenuation effects especially in intense rain can also lead to underestimation of rainfall amounts. The height of the radar beam above the ground increases with range due to the effects of beam inclination and earth curvature. This can result in the beam overtopping areas of precipitation formation and underestimating precipitation on the ground, or intercepting the freezing layer and giving anomalous high returns from melting snowflakes (seen as giant raindrops by the radar). The proximity of the weather radar locations to the Lavant and Ems catchments is indicated in Figure 3.3. No radar is

Table 3.2 Met Office daily raingauge records (available at CEH).

Raingauge	Met Office No.	NGR	Start	End
West Harting	318022	477300 121400	1973	2007
Didling	318304	484400 119500	1969	1987
Cowdray Park	318440	490200 121500	1973	2007
Petworth, Barlavington	318939	497100 116000	1941	2007
Upwaltham No.2	320074	493900 111900	1971	2007
Eartham	320188	493800 109300	1963	2001
South Mundham	320401	487900 100200	1969	2007
East Dean	320836	490600 113000	1969	2007
West Dean Park	320922	486400 112700	1834	2007
Chilgrove House	320994	483600 114400	1834	2007
Lavant Resr	321064	486700 109500	1961	2002
Funtington P.Sta.	321220	481100 108200	1948	2007
Chidham	321311	479100 103600	1935	2007
Hambrook	321324	478600 106900	1975	2007
Thornham S.Wks	321362	475800 105000	1982	1993
Walderton P.Sta.	321551	478600 110300	1969	2004
Butser, Windmill Hill	322179	472000 116500	1990	2006
Havant, Budds Farm	322333	470800 105500	1977	1999
Havant W.Wks	322335	471100 106300	1886	2007

within 50 km range so the best resolution data currently available is 2 km from Chenies and Dean Hill. In general, Dean Hill radar being closest to the catchments would be the preferred choice of radar. However this radar has only been operating since November 2005. Before this, Chenies 2 km radar exists from September 2002 (prior to this the 2 km resolution range did not cover the Lavant and Ems).

The Nimrod QC (Quality-Controlled) 1/2/5 km composite radar product provides estimates of instantaneous rain-rate using the UK network of radars. Prior to November 2007 this radar composite was formed using the 1, 2 and 5 km single-site radar products. Since November 2007 the compositing process has been refined to use the single-site radar data in its polar form (rather than Cartesian) and produces a product with a 1 km resolution. The time-interval of this product was 15 minutes prior to November 2003 and 5 minutes afterwards.

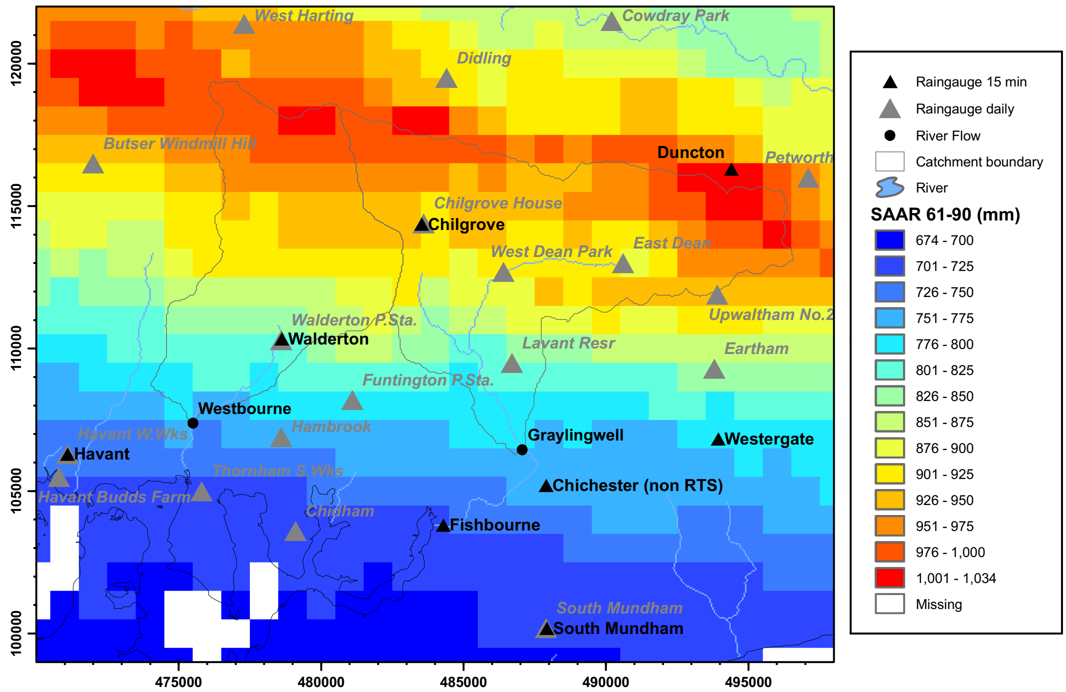

Figure 3.2 Raingauge (15 minute and daily), river flow and groundwater well level stations in the vicinity of the Lavant (to Graylingwell) and Ems (to Westbourne) catchments, superimposed on the SAAR-grid of average annual rainfall.

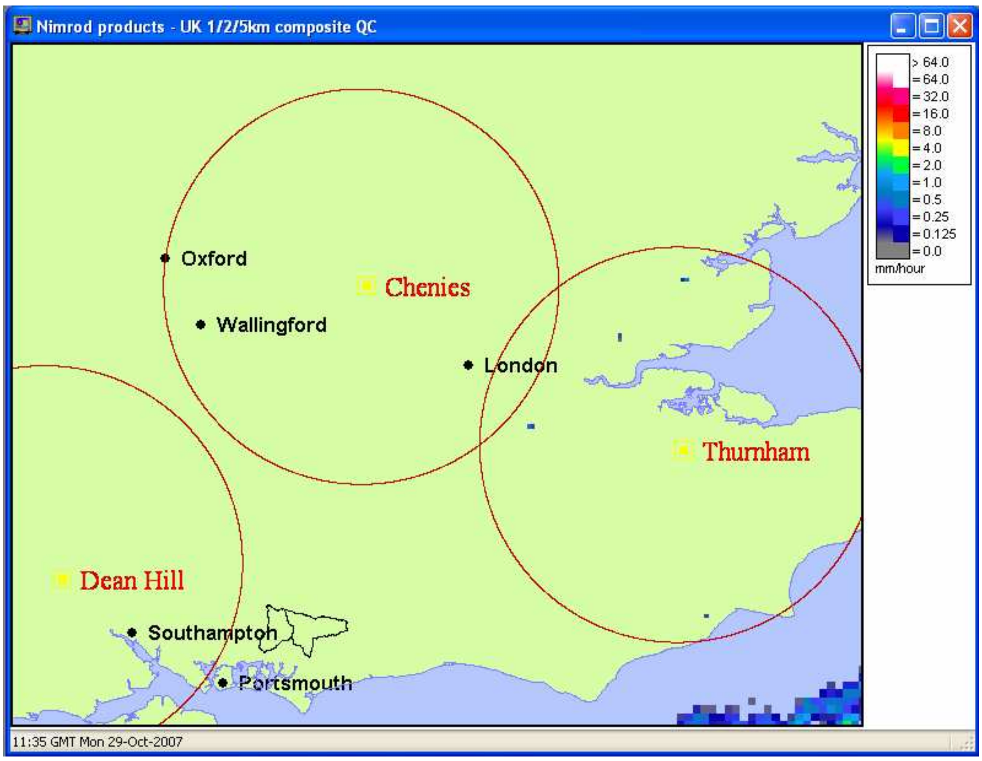

Figure 3.3 Weather radars in the vicinity of the Lavant and Ems catchments: 50 km range circles are indicated.

For hydrological modelling purposes it is desirable to use the finest temporal and spatial resolution of radar data available as this is deemed to be the most accurate estimate of rainfall. Therefore the 5 minute interval Nimrod UK composite is the preferred choice as this has the finest time interval and should also use the most appropriate radar (subject to the data being available in time for the compositing process) thus avoiding the need to infill the single-site data for missing images. Table 3.3 provides details of the best radar products available for the Lavant and Ems as a function of time. A preliminary comparison with the raingauge data is provided in the following section.

Table 3.3 Details of the best radar data available over the catchments.

Period	Best radar data available
21 November 2003 to date	UK only Nimrod QC rainfall actual rate 1/2/5km composite 5 minute resolution (note that the compositing process changed during November 2007 to give a 1 km resolution everywhere)
27 September 2002 to 21 Nov 2003	2 km Chenies Nimrod QC 5 minute resolution
prior to 27 September 2002	5 km resolution data (Chenies or Nimrod composite) available over the Lavant and Ems catchments

3.2.3 Preliminary comparison of raingauge and radar data

Accumulation maps of Nimrod composite radar rainfall are presented in Figure 3.4 along with the tipping-bucket raingauge network in the vicinity of the Lavant and Ems catchments. These show that, over the raingauge network and catchments, the radar data do not appear to be affected by any permanent anomalies. For example, blockages of the beam due to buildings and masts would lead to radial spikes of rainfall underestimation beyond them in long-period rainfall accumulation maps: such anomalous signatures are absent. The maps also show the change in processing of the radar data that occurred in November 2007 and is referred to in Table 3.3.

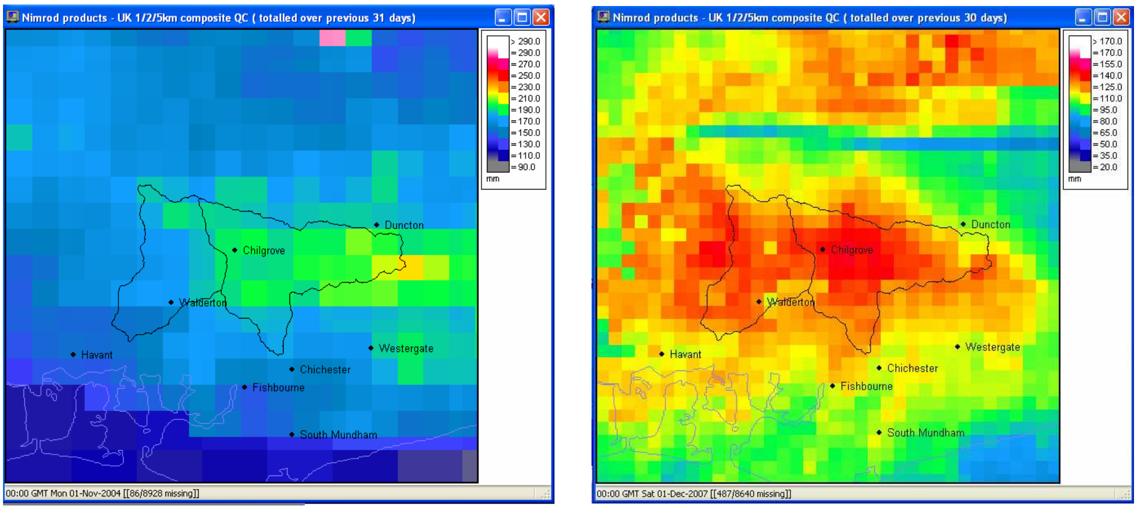

Figure 3.4 Maps of accumulated Nimrod composite radar rainfall for November 2004 (left) and December 2007 (right). Locations of tipping-bucket raingauges are also shown.

Another informative method of comparing raingauge and radar data is to look at the ratio bias of the radar data. For the i'th raingauge the ratio bias, B_i, is defined to be the long-term arithmetic mean ratio of gauge and radar rainfall estimates calculated over n 15 minute time intervals:

$$B_i = \frac{1}{n}\sum \frac{R_g^i}{R_r^i} \tag{3.1}$$

where R_r^i is the radar estimate of rainfall for the grid-square coincident with the i'th raingauge providing an estimate R_g^i. In practice, the ratio is only calculated if both R_r^i and R_g^i are greater than 1 mm h^{-1}. This minimises discretisation errors and the influence of anomalous propagation. Averaging this over the N raingauges gives the ratio bias, B, of the radar as

$$B = \frac{1}{N}\sum B_i \; . \tag{3.2}$$

The long-term ratio biases for the five raingauges nearest the Lavant and Ems catchment are given in Table 3.4 and are all greater than 1. This implies a general underestimation of rainfall by the radar. Plots of yearly and long-term monthly ratio biases are given in Figures 3.5 and 3.6 respectively. These show that the results are similar for all raingauges with the exception of Duncton where the underestimation of the radar appears to be more significant. The Duncton raingauge is situated tight into the foot of the scarp slope of the South Downs and its catch may be affected by local orographic influences. Note its relatively high elevation (Table 3.1) and locally high SAAR (Figure 3.2).

Table 3.4 Long-term ratio biases using Nimrod composite radar data over the period 21 November 2003 to 30 September 2008.

Raingauge	Ratio Bias	No. of observations
Chilgrove	1.306	3374
Fishbourne	1.250	1705
Chichester	1.327	1903
Walderton	1.240	2284
Duncton	1.607	3214
Mean Ratio Bias	1.346	

The overall mean ratio bias of the radar in the vicinity of the Ems and Lavant catchments is 1.346 for the period studied. This general underestimation by the radar has obvious implications for rainfall-runoff modelling. Options for PDM sensitivity analysis using radar data are (i) to simply use catchment average radar data as input to a PDM model calibrated using raingauge data, (ii) use merged radar and raingauge data (e.g. the HyradK NFFS module adapter supplied by CEH Wallingford (2007) as part of EA R&D project FDK(06)03), (iii) consider model calibration using radar or merged

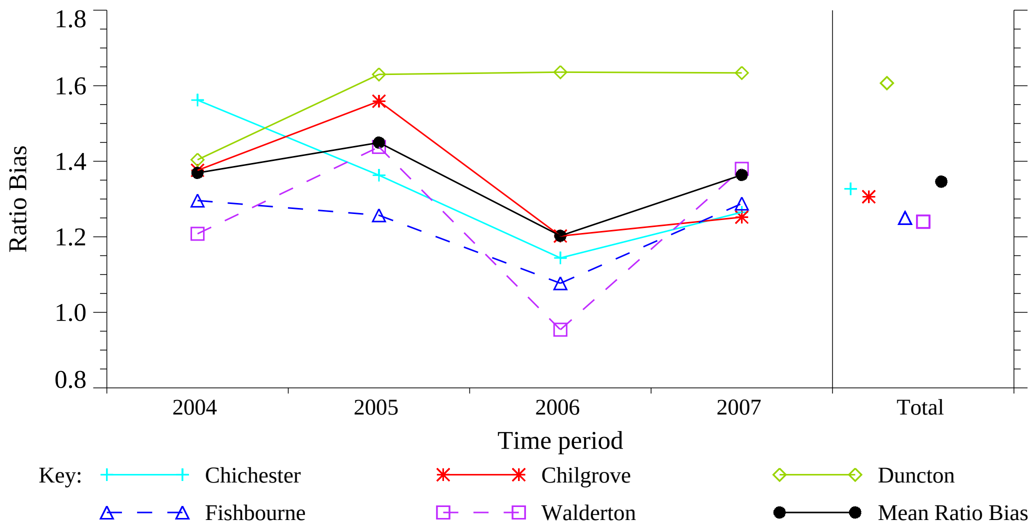

Figure 3.5 Yearly ratio biases using Nimrod composite radar data for the years 2004 to 2007 inclusive.

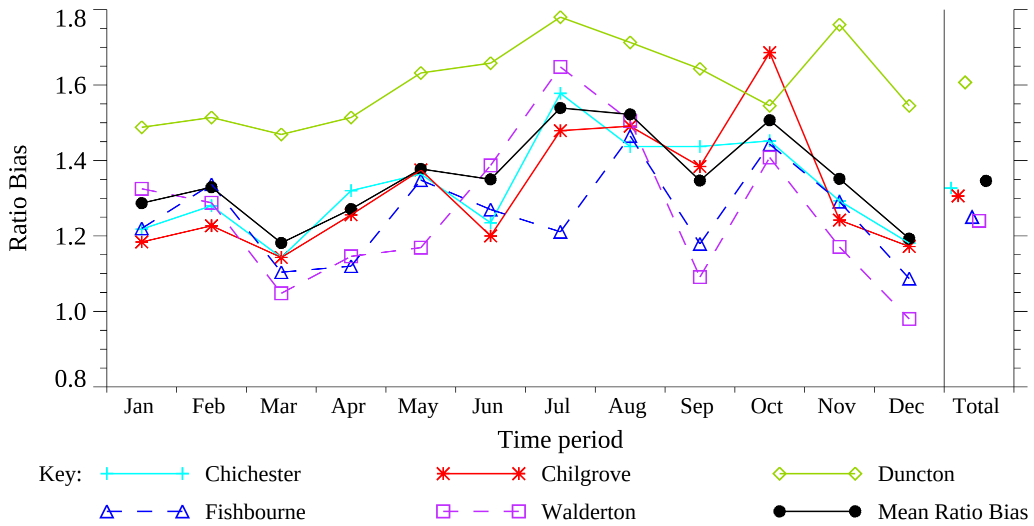

Figure 3.6 Long-term monthly ratio biases using Nimrod composite radar data pooled over the period 21 November 2003 to 30 September 2008.

radar and raingauge data. From previous modelling experience, it would only be worthwhile to perform a rainfall-runoff model sensitivity analysis using the latest Nimrod composite data. Since these data are only available from November 2003 onwards (see Table 3.3) there is not a long enough record with sufficient flood peaks to warrant a more complete sensitivity analysis beyond option (i). In time, when a longer record of Nimrod composite data is available, a fuller sensitivity analysis would be appropriate.

Recommendation

- **Radar data sensitivity analysis.** The model sensitivity analysis comparing raingauge and radar data will be restricted to using catchment average rainfall data using Nimrod composite radar data. This is due to the relatively short record of Nimrod composite radar data and the lack of significant flood events since 2003.

3.3 River levels/flows

The primary objective of this study is to develop PDM rainfall-runoff models for the catchments of the Lavant to Graylingwell and the Ems to Westbourne for the purposes of flood forecasting. Both these catchments have river gauging stations at their outlets and have flow records that can be used for model calibration and assessment. This section reviews these river gauging stations in terms of quality (of stage-discharge curve, flow range, etc.) and availability of data records for modelling purposes. Descriptions of the main features of the catchments are also provided. Other river level/flow stations in the vicinity are also considered in terms of their relevance to this modelling study. For example, the station on the Costers Brook at Cocking is at the foot of the South Downs and, although north of the Lavant catchment, may give some indication of exports from the Lavant due to external springs.

Table 3.5 summarises the river level/flow stations in the vicinity by way of broad background and these are mapped in Figure 3.1 Of primary concern are the river gauging stations at Graylingwell (Lavant) and Westbourne (Ems) and these are reviewed in turn next.

Table 3.5 River level/flow stations in the Lavant and Ems catchments

(a) Lavant

Location	Grid Reference	Notes
Graylingwell Weir	487062 106450	Flow, Level
Tozer Way	486785 104985	Level
Needlemakers	486630 104879	Level
Westhampnett Mill	487587 106052	Level u/s & d/s
Church Farm Pit	488422 105800	Level R. Lavant Flood Relief Channel
Singleton	487743 113210	Level, not RTS
West Dean	485980 112430	Flow (Starflow), not RTS
Cocking (Costers Brook)	488000 117400	Flow, Level

(b) Ems

Location	Grid Reference	Notes
Westbourne	475505 107388	RTS

3.3.1 Lavant at Graylingwell Gauging Station

The groundwater-dominated catchment of the River Lavant in southern England drains an area of 87.2 km^2 to its gauging station at Graylingwell. It is an ephemeral stream on the dip-slope of the South Downs with an elevation range from 20.7 to 255 mAOD. This rural Chalk catchment is highly permeable with little drift cover except for sand and gravel river deposits along its lower valley. Land use is largely arable (37%) plus significant woodland (31%) and grassland (27%) with only a little urban development (2%) close to Graylingwell. Significant groundwater abstractions from wells at Brick

Kiln and Lavant reduce river flows. The gauging structure is a flat-V weir with a weir capacity of 6 $m^3 s^{-1}$. Severe weed growth can cause the structure to drown. The bankfull stage is 1.04 m (8.466 $m^3 s^{-1}$ using the upper rating equation) but bank overtopping occurs upstream at lower stages than this.

Significant bypassing can occur during extreme events leading to uncertainty in peak flow estimation. For example, the flood peak in January 1994 is estimated to be on the 10th at 8.1 $m^3 s^{-1}$ (Taylor, 1995) whilst the flood peak held on Wiski occurs on the 12th at 7.11 $m^3 s^{-1}$ (at stage of 0.922 m, based on the original rating and not accounting for bypassed flows). The peak in December 2000 estimated at ~8 $m^3 s^{-1}$.is held on Wiski as 7.85 $m^3 s^{-1}$. on the 14^{th} (but for a stage of 0.908 m that is lower than in 1994).

Binnies (Chichester Flood Alleviation Scheme Report, April 2000) estimated the 100 year return flow to be 7.88 $m^3 s^{-1}$; this has been revised upwards following the 2000 floods to ~8.5 $m^3 s^{-1}$

The stage-discharge relationship (rating) for the Lavant at Graylingwell was reviewed for the Agency by Mott Macdonald (2003). The rating has the form $Q = \alpha(h + d)^{\beta}$ with range limits $h_l \le h \le h_u$; here, Q is the flow ($m^3 s^{-1}$), h is river stage (m), and α, d and β are parameters. The original rating is in 3 parts defined by the rating parameters and range limits $(\alpha, d, \beta, h_l, h_d)$ as

(9.8777, -0.017, 2.10696, 0.000, 0.264),
(10.5645, -0.105, 1.60956, 0.264, 0.634) and
(11.4934, -0.303, 1.00186, 0.634, 1.0).

The rating curves held on WISKI were provided and identify the above original rating as 'Graylingwell (1012 migrated v1)'. There is also a second version labelled 'Graylingwell (1012 migrated v2)' which has different ranges and is defined as

(9.8777, -0.017, 2.10696, 0.000, **0.238**),
(10.5645, -0.105, 1.60956, **0.238, 0.601**) and
(11.4934, -0.303, 1.00186, **0.601**, 1.0).

The differences with v1 are highlighted in bold. It may be related to a datum shift but the changes were not constant in stage (e.g. 0.264-0.238=0.026 whereas 0.634-0.601=0.033). This second version is also what is held on HiFlows-UK.

The original rating (v1) was derived by fitting a 3-segment power law relationship to selected points from a rating table based on the theoretical equation for a Crump profile flat-V crested weir. This rating was checked against 41-45 valid spot gaugings up to 0.89 m and found to underestimate flow above about 5 $m^3 s^{-1}$ (presented here in Figure 3.7), becoming more pronounced at its upper end.

A full dynamic hydraulic model based on the ISIS software was developed to derive a model-based extended rating: this represented the gauging structure as three broad-crested weirs with stepped crest levels and widths to approximate the actual Crump profile flat-V crest form. Based on a comparison of the ISIS and original ratings with the spot gaugings, Mott Macdonald (2003) recommend the original rating be used up to 0.25 $m^3 s^{-1}$ and the ISIS-model rating above this. The final rating recommended by Mott

Macdonald, and contained on WISKI and HiFlows-UK, is:

(80.583, 0.005, 3.709, 0,0.27)
(9.694,0.030,2.230,0.27,0.74)
(12.162,-0.170,1.443,0.74,1.10)
(19.653,-0.356,1.991,1.10,1.33) and
(48.246,-0.960,0.956,1.33,1.52)

According to WISKI and Hi-Flows UK, this rating is recommended for use from 23 August 1994 onwards with the original Environment Agency rating being used prior to this date. Figure 3.7 shows the Mott Macdonald and original (v1) Environment Agency rating along with the spot gauges.

River flow data (not level) were provided by the Environment Agency and compared to that previously supplied to CEH in 1998 as part of the Moore and Bell (2002) study. Both sources agree to within 0.1 m^3 s^{-1} for the period in common apart from around 7 days in February 1995 for which the differences are a little larger.

The previous data supplied in 1998 covers January 1990 to March 1998 and uses the original EA rating curve (as it predates the Mott Macdonald review). Since the previous and new data agree, it suggests that the latest Environment Agency data are based on the original rating curve (and not the Mott Macdonald rating) for the period 23 August 1994 to 31 March 1998 and possibly beyond. It has been agreed with the Environment Agency that it will be most consistent to use the Mott Macdonald rating throughout the Graylingwell level record for the modelling. This also has obvious implications for any water balance calculations that will be performed.

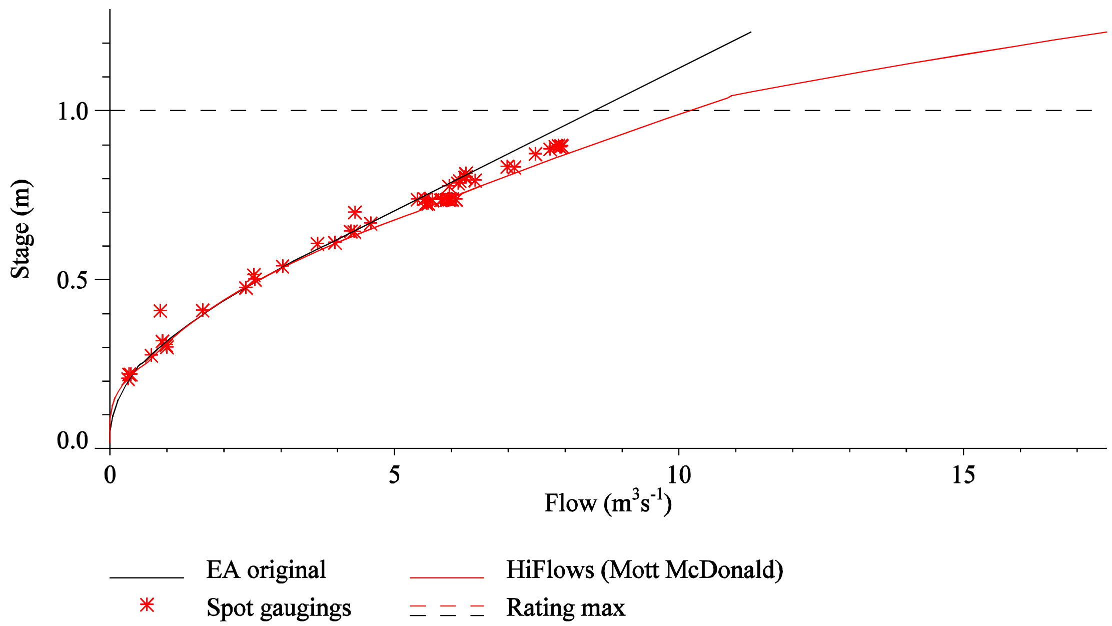

Figure 3.7 Stage-discharge curves and spot gaugings for the Lavant at Graylingwell.

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Recommendations

- **River Lavant at Graylingwell rating curve.** The Mott McDonald rating should be used consistently throughout the Graylingwell stage record for this project.

- **River Lavant at Graylingwell river flow data.** The River Lavant stage time-series will be processed at CEH using the Mott McDonald rating to obtain a consistent river flow time-series for use in rainfall-runoff modelling. Done.

- **River Lavant at Graylingwell river level data.** The river stage time-series for Graylingwell will be supplied to CEH. Done.

3.3.2 Ems at Westbourne

The groundwater-dominated catchment of the River Ems in southern England drains an area of 58.3 km^2 to its gauging station at Westbourne. It is an ephemeral stream on the dip-slope of the South Downs with an elevation range from 9.6 to 242 mAOD. This rural Chalk catchment is highly permeable with minimal drift cover. Land use is largely arable (42%) plus significant woodland (28%) and grassland (26%) with only a little scattered urban development (2%). The gauging structure is an asymmetrical compound Crump profile weir that is modular throughout its flow range and has a theoretical rating. Whilst all flows are contained the structure limit is 5.08 $m^3 s^{-1}$, a flow that was exceeded for long periods during the 2000 event. Significant export of water from the catchment via groundwater abstractions is in part compensated for by borehole augmentation of low flows.

The theoretical rating is approximated by a three-part rating of standard power law form with the rating parameters and range limits $(\alpha, d, \beta, h_l, h_d)$ as

(1.434, -0.000, 1.576, 0.00, 0.19),
(1.468, 0.151, 2.475, 0.19, 0.39) and
(10.664, -0.258, 1.759, 0.39, 0.91).

This rating curve is shown in Figure 3.8 along with the available spot gaugings which serve to broadly confirm the validity of the relation.

River flows have been provided by the Environment Agency for use in this modelling investigation.

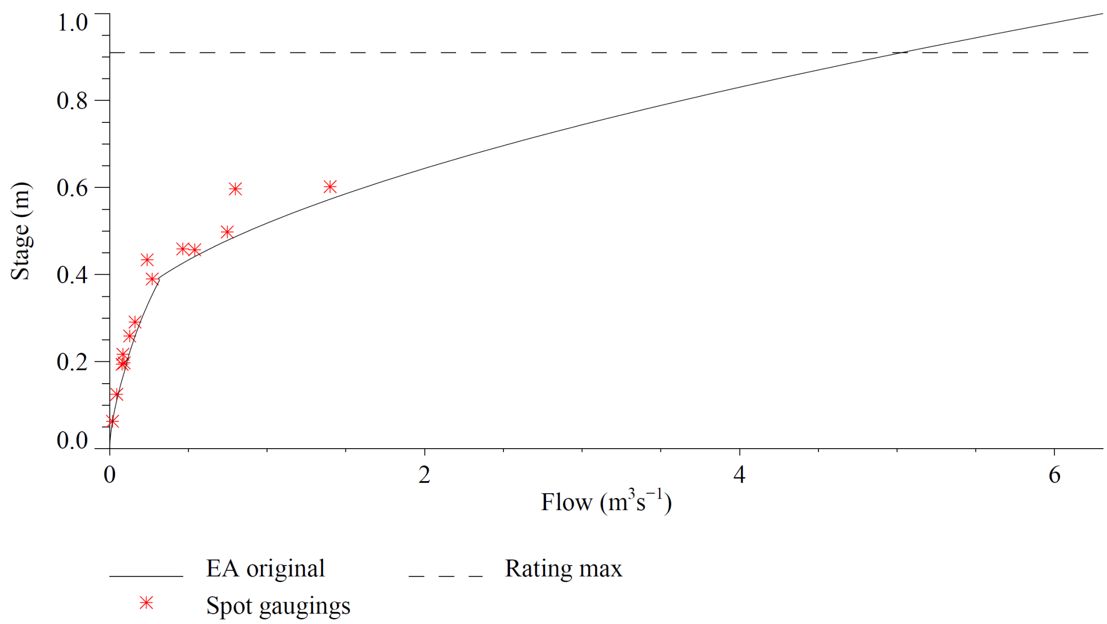

Figure 3.8 Stage-discharge curve and spot gaugings for the Ems at Westbourne.

3.4 Potential evaporation

The application of the extended PDM to the River Lavant by Moore and Bell (2002) used a very simple estimate of potential evaporation (PE). This took the form of a sine curve of daily values over the year with a mean value of 1.4 mm day^{-1}; 15 minute values were obtained by assuming a constant value within a day. Potential evaporation has a cumulative effect on the model water balance. Thus using an average profile over the year and ignoring the diurnal variation can provide a simple approximation in this context. A sensitivity of the calibrated model to the use of MORECS PE monthly estimates has since been carried out by CEH. Use of these time-series data in place of the sine curve PE estimates did not resolve problems observed in the modelled well levels in 1994. Note that the acronym MORECS stands for 'Met Office Rainfall and Evaporation Calculation System' and provides weekly and monthly PE estimates on a 40km grid over Britain based on daily synoptic weather data (Hough and Jones, 1997; Hough *et al.*, 1997).

The Environment Agency in Southern Region employs a standard daily PE profile over the year. A standard diurnal profile is used to apportion daily PE into 15 minute values, with zero values at night. The daily profile is based on average MORECS values for each month. The standard profile is scaled to take into account the MORECS square(s) over the catchment being modelled. It is believed that the base profile was developed for Midland Region and yields an annual PE total of 523 mm. A higher value is generally more appropriate for Southern Region so is scaled up for a MORECS grid-square of interest using the long-term annual average PE. For square 183 over the Lavant and Ems this average is 617 mm (for the water years 1971-2007), giving a scaling factor of 1.180. The long-term monthly average PE amounts for square 183 over the 1971-2007 water years are listed in Table 3.6. Note that the annual MORECS PE values derived from data held at CEH differ slightly from those provided by the EA in Table B1.3 of Hall (2008) for the years 1995, 2003 and 2006. A summary of the annual differences are summarised in Table 3.7.

Table 3.6 Long-term monthly average MORECS PE amounts for square 183 over the 1971-2007 water years (using MORECS records held at CEH).

Month	MORECS PE	MORECS AE
January	14.9	14.9
February	18.1	18.1
March	36.1	36
April	59.5	59
May	86.5	83.6
June	88.3	77
July	96.5	70.9
August	88.1	60.9
September	59	46.1
October	37.1	33.1
November	19.3	19
December	13.6	13.6
1971-2007 Water Year Average	616.9	532.1

Table 3.7 Differences between the annual MORECS PE/AE totals derived from data held by the Environment Agency and CEH for MORECS square 183 and the period 1971-2007.

Period	MORECS PE		MORECS AE	
	EA	CEH	EA	CEH
1995 Calendar Year	733	739.8	434	473.3
1994/95 Water Year	743	730.9	442	463.4
1995/96 Water Year	652	671.1	526	544.9
2003 Calendar Year	639	662.1	456	472.2
2003/04 Water Year	625	648.2	576	592.6
2006 Calendar Year	576	580.7	467	471.2
2005/06 Water Year	579	583.7	467	471.6
2006/07 Water Year*	630	579.2	618	568.5
1971-2007 Calendar Year Average	614	615.4	530	531.9
1971-2007 Water Year Average	617	616.9	532	532.1

* Note that the EA values listed for the 2006/07 Water Year relate to Table B1.3 of Hall (2008). These values have since been updated (ref email from John Hall 21/11/2008) and now agree with the CEH values.

Since identifying this disagreement between the EA and CEH MORECS records, the monthly data have been provided by the EA for detailed comparison with the monthly data held by CEH. A summary of the monthly differences between the two sources is given for potential evaporation (PE), actual evaporation (AE), rainfall and soil moisture deficit (SMD) in Table 3.8

Table 3.8 Differences between the monthly MORECS PE, AE, rainfall and SMD data held by the Environment Agency and CEH for MORECS square 183 and the period 1961-2007. Shading indicates values which are different.

Year	Month	PE		AE		Rainfall		SMD	
		EA	CEH	EA	CEH	EA	CEH	EA	CEH
1995	6	104.2	98.7	32.8	46	12.6	13	143.6	141.1
1995	7	117.2	108.8	34.2	32.8	34.1	29.8	143.6	143.6
1995	8	134.1	129.6	5	10.6	5	7.2	143.6	143.6
1995	9	58.2	64.1	54.6	58.2	148.9	148.3	49.2	53.4
1995	10	37.8	50.2	37.7	49.9	24.9	42.5	61.8	55.8
1995	11	15.4	21.9	15.4	21.7	89.2	96.8	0.9	1.1
1995	12	12.1	12.4	12.1	12.4	100	118.4	0	0
1996	3	31.6	31.6	31.6	31.6	46	46	9.9	7.9
1996	4	55.3	55.3	55.2	55.2	37.3	37.3	23.5	25.7
1996	5	84.5	84.5	83.8	83.8	64.8	64.8	50	44.6
1998	5	104.2	104.2	103	103.4	22.8	22.8	89.7	89.7
2003	10	22	45.6	10.6	27	54.9	71.3	98.7	98.7
2004	12	7.6	7.6	7.3	7.6	83.9	83.9	0.5	0.5
2006	5	64.1	68.6	63.9	68.5	18.4	102.1	64.6	12.3

Initial discussions with Met Office colleagues at the Joint Centre for Hydro-Meteorological Research (JCHMR) suggest that the differences in the EA and CEH MORECS data holdings could be due to Met Office quality control processes. There are two forms of MORECS data issued and both are received by the Environment Agency: (i) a pseudo real-time product calculated weekly using the driving data available at the time and (ii) a quality controlled product which uses the quality controlled driving data which is produced at a later date (this does not always result in altered MORECS values). The quality controlled monthly MORECS data were used in Hall (2008) and passed to CEH for the detailed comparison. There is ongoing work at CEH to verify with the Met Office the source of CEH data holdings. Within this report the CEH MORECS data will be used unless specifically stated otherwise.

The long-term monthly average PE data contained in Table 3.6 are represented in Figure 3.9 by black crosses at the mid-point of each month. These have been interpolated in two ways to generate a daily time-series. The black line is standard linear interpolation and, whilst this has a ‘smooth’ appearance and preserves the annual long-term PE, it does not preserve the monthly values and slightly underestimates PE during the summer and overestimates during winter. The blue line represents an alternative linear interpolation method which preserves the long-term monthly and annual PE

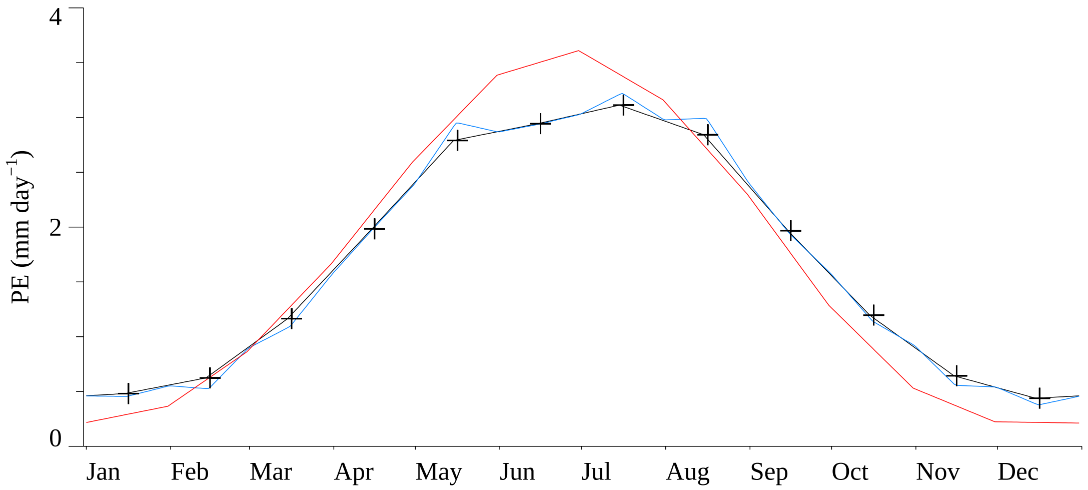

Figure 3.9 MORECS annual profiles. Black crosses (+) denote the long-term average PE amounts for square 183 (see Table 3.6). The black line is simple interpolation between the monthly values. The blue line is interpolation that preserves the monthly average PE. The red line is the EA Southern Region profile scaled by 1.180 (gives annual PE of 617 mm).

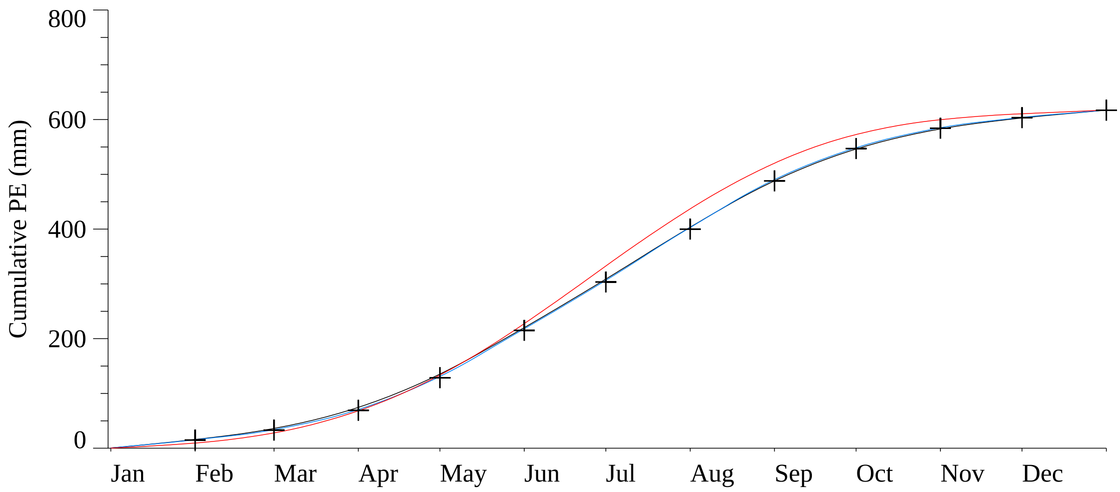

Figure 3.10 MORECS cumulative profiles. Black crosses (+) denote the long-term average PE amounts for square 183 (see Table 3.6). The black line is simple interpolation between the monthly values. The blue line is interpolation that preserves the monthly average PE. The red line is the EA Southern Region profile scaled by 1.180 (gives annual PE of 617 mm).

totals. It does this by fitting to the bi-monthly average values at the end of each month (i.e. the January and February average for the end of January) and then introducing another fitting point at the middle of the month whose value ensures the long-term monthly PE is preserved. The red line is the scaled EA profile that gives a yearly PE value of 617 mm. The plot suggests that the profile was created by fitting to points at the start/end of the month and clearly, in comparison to the profile for square 183, significantly over-estimates during summer and underestimates during winter. Comparing the different profiles, through the cumulative PE plots in Figure 3.10, highlights that the scaled EA profile (red line) does have rather different properties whilst the difference between the two interpolation methods is rather more subtle.

Recommendations

- **Standard daily PE profile.** The current standard daily profile used by Southern Region overestimates during the summer and underestimates during the winter compared to the long-term monthly values of MORECS square 183. It is recommended that, if a daily profile is needed, the linear interpolation method which preserves the long-term monthly and annual MORECS PE totals be used for the Lavant and Ems catchments.

- **MORECS PE profile for use in modelling.** It is recommended that the historical daily PE profile is derived using the linear interpolation method which preserves the monthly totals. The 15 minute totals will be derived using the standard EA diurnal profile.

In addition, the Environment Agency receives hourly MOSES PE estimates on a 5 km grid, via the Hyrad system. The acronym MOSES stands for ‘Met Office Surface Exchange Scheme’. There is interest in using these PE estimates for flood forecasting application, particularly on account of their near real-time availability. However, there is concern over the difference with MORECS PE estimates and their possible impact on rainfall-runoff model calibrations. The Environment Agency and Met Office jointly funded a comparison project which was reported on by Hough (2003). This study used the MORECS daily weather archive to generate a pseudo-hourly driving dataset for the MOSES output and therefore differs from the driving datasets used operationally. The comparison was restricted to two periods of 2-years duration (the drought of 1975-76 and floods of 2000-01) and four contrasting MORECS squares. Both schemes employ Penman-Monteith estimates of PE but differ in the detail. Hough (2003) reported that hot, sunny and low humidity days with high PE causes the crop canopy resistance to moisture flow to increase in MOSES, moderating PE values. This effect is not included for grass in MORECS causing its PE estimates to be higher than MOSES for such conditions.

Here the operational MOSES feed received by the Environment Agency is used for comparison with MORECS. The MOSES data in the Hyrad back-up archive at CEH Wallingford starts on 26 July 2005 and has some small gaps. Monthly totals have been calculated from the hourly 5 km MOSES grass (C3) PE for the 40 km MORECS square 183. A major difference from the Hough (2003) study is the use of hourly Nimrod analyses of precipitation, cloud cover and near-surface atmospheric variables as input to the operational MOSES product (Smith *et al.*, 2006). This also contrasts with MORECS which employs quality-controlled synoptic station data including rainfall data from the daily raingauge network (supplemented by radar data depending on gauge coverage).

The difference in rainfall data between MOSES and MORECS will affect data-quality of some products and will vary with location and the genesis of the rain. However, using radar rainfall in MOSES will impact on the AE and SMD products but not on PE: this is the potential atmospheric demand for evaporation assuming soil water is not limited. Consequently the radar rainfall underestimation bias identified in Section 3.2.3 has no bearing on the quality of the MOSES PE estimates. The monthly MOSES and MORECS grass PE totals are listed in Table A.1 along with the amount of missing MOSES data for each month. These are compared graphically in Figures 3.11 and 3.12 which show, in contrast to Hough (2003) which used MORECS-based input data for MOSES, that the operational MOSES scheme consistently estimates more PE than MORECS.

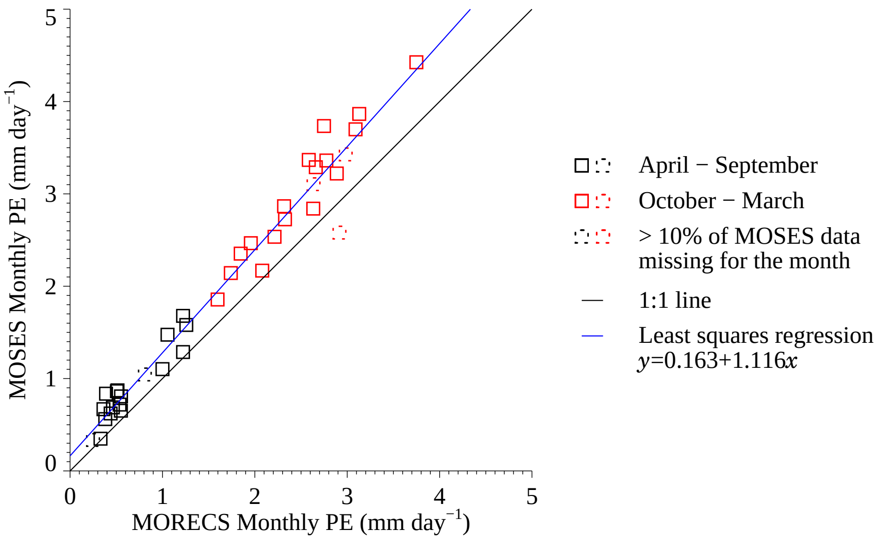

Figure 3.11 Comparison of monthly MOSES and MORECS PE values for the period July 2005 to August 2008 inclusive.

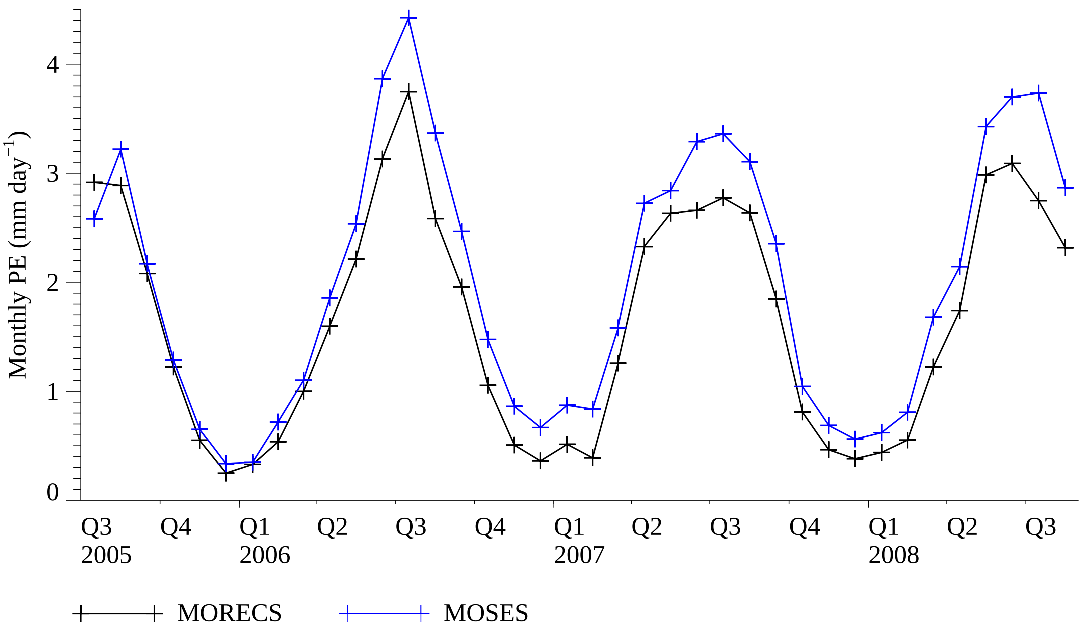

Figure 3.12 Time-series of monthly MOSES and MORECS PE values for the period July 2005 to August 2008 inclusive.

The least square regression line in Figure 3.11 also shows that the relative difference increases with increasing PE. This implies that if a PDM model has been calibrated using MORECS PE then simply swapping the PE source to MOSES *may* cause a reduction in modelled river flow due to the increased evaporation. Since MOSES is only available from July 2005 onwards there is not a long enough record with sufficient flood peaks to warrant a more complete sensitivity analysis of MORECS versus MOSES beyond the data comparisons performed here. In time, when a longer record of MOSES data is available, a fuller sensitivity analysis would be appropriate. If switching from MORECS to MOSES does cause degradation in PDM performance it would be sensible to consider recalibrating the evaporation (b_e) and recharge parameters (k_g, b_g and S_t) of the PDM. With a view to real-time application, a sensitivity analysis is recommended between using MORECS and profiles based on the long-term MORECS PE and in the form of a sine curve.

Recommendations

- **MOSES PE data sensitivity analysis.** A full model sensitivity analysis comparing MOSES and MORECS PE data is not warranted at this time. This is due to the relatively short record of MOSES data and the lack of significant flood events since 2005.

- **MORECS PE data sensitivity analysis.** A model sensitivity analysis should be performed within the project comparing the use of historical MORECS PE estimates with using a sine curve formulation and the long-term MORECS PE profile. This is carried out in Section 6.2.3.

3.5 Well levels

Well level records provide a potentially useful source of information for the PDM rainfall-runoff model extended for groundwater catchments. Depending on location, observation wells can provide a useful indication of the volume of water held in groundwater storage. In turn, the PDM employs a conceptual groundwater reservoir whose water content is updated through the addition of recharge from soil drainage and subtraction of pumped abstractions and water released to form baseflow at the catchment outlet. The PDM groundwater store water content can be related to well level measurements by converting the content to a storage deficit and scaling it by the specific yield of the groundwater reservoir to obtain a modelled depth to the water table, taking account of any datum adjustment needed. In this way, well level records can be used to support model calibration and assessment. Real-time updating of the model using well level records presents a further possible use that might be considered.

Table 3.9 presents an inventory of well level stations in the vicinity of the Lavant and Ems catchments. Figure 3.1 map their location. Records for some locations are held by CEH Wallingford as part of the British Geological Survey's contribution to the National River Flow Archive. The Environment Agency initially provided data for some of the locations. In addition, plots of well level data were provided by John Hall for a selection of locations within each catchment.

In the study of Moore and Bell (2002) for the Lavant catchment it was found that the well level site at West Dean Nursery had variations in level that corresponded best with the modelled groundwater levels. This probably reflects the close proximity of this station to the river and good hydraulic connectivity to it. The modelling work has investigated the usefulness of these well records further and in particular those sites currently on telemetry, namely Chilgrove and Compton. To achieve this, additional well level data were obtained at an interim review stage of the project, as outlined in the recommendations that follow. A summary of the well level data supplied is given in Table 3.10.

Recommendations

- **Chilgrove data.** The time-series '245221099.WL.ir.P' to be obtained. Done.
- **Compton data.** The time-series 'Compton.WL.Telemetry.60.P' and '245121511.WL.60.P' to be obtained. Done.
- **Chilgrove and Compton data.** Definitions of the various different time-series supplied are to be obtained. Done.
- **West Dean Nursery.** The time-series 'WestDeanN.WL.ir.P' to be obtained. Done.

Table 3.9 Groundwater well level stations in the Lavant and Ems catchments

(a) Lavant

Location	Grid Reference	Notes
Chilgrove House	483526 114367	RTS, goes artesian: flat tops. Hourly data from 1 Jun 1999 – 12 Aug 2001. 15 minute data from 1 Jan 2004.
Compton	477551 114895	In Ems
East Dean Butchers Lane	490624 112875	not RTS
East Dean Droke	492469 112763	not RTS
Upwaltham Dog Kennel	495648 115149	not RTS
West Dean Colworth Fm.	485292 115178	not RTS
West Dean Nursery	486300 113100	not RTS, used in study of Moore and Bell (2002), large periods of no dips (~1977-1991 and 1997-2001)

(a) Ems

Location	Grid Reference	Notes
Compton	477551 114895	RTS, WISKI Hourly data from 5 Jan 2001
Uppark Deerkeepers Cottage	477825 116540	not RTS
North Marden Meredon Farm	480765 116132	not RTS
East Marden Well	480713 114597	not RTS
West Marden Farm	477107 113592	not RTS
Walderton Pitlands Farm	479680 112375	not RTS 15 min data available from 10 Apr 2007
Walderton Little Busto	477929 111899	not RTS

Table 3.10 Well level data supplied by the Environment Agency.

Time-series name	Time Period	Comments
CHILGROVE RTS mAOD.WL.15.P	01/11/2000 - 24/09/2008	Hourly data from 01/11/2000 to 01/01/2001. Then 15 min data from 01/01/2004 to 24/09/2008.
ChilgrveGW.WL.ir.P	03/01/1990 - 26/08/2008	Periodic data. Data almost exclusively time-stamped at 12:00 until 31/07/2002 then recorded to the nearest 1 or 5 minutes. Surveyed 01/11/02. New datum is 77.74mAOD to top of new standpipe (installed to prevent well over-topping). This is 56cm higher than historical datum of 77.18m which was 30cm too high. (New standpipe is 86cm high).
245221099.WL.ir.P (Chilgrove)	01/06/1999 - 12/08/2001	Hourly telemetry data. Some small periods of 15 minute data.
COMPTON RTS.WL.60.O	16/11/2004 - 24/09/2008	Hourly data.
Compton.WL.ir.P	03/01/1990 - 26/08/2008	Periodic data. Data exclusively time-stamped at 12:00 until 31/07/2002 then recorded to the nearest 1 or 5 minutes.
Compton.WL.Telemetry.60.P	15/03/2000 - 08/02/2007	Hourly telemetry data. Larger period of missing data 12/05/2000 – 12/02/2002.
245121511.WL.60.P (Compton)	05/01/2001 - 14/08/2002	Hourly logger data.
LtleBusto.WL.ir.P	24/01/1990 - 26/08/2008	Periodic data. Data almost exclusively time-stamped at 12:00 until 29/10/2002 then recorded to the nearest 1 or 5 minutes. Well becomes dry every year so not ideal for modelling.
PitlandsFm.WL.15.P	10/04/2007 - 26/08/2008	15 minute data.
PitlandsFm.WL.ir.P	24/01/1990 - 26/08/2008	Periodic data. Data almost exclusively time-stamped at 12:00 until 29/11/2002 then recorded to the nearest 1 or 5 minutes.
WestDeanN.WL.ir.P	21/01/1976 - 10/02/2009	Periodic data. Data almost exclusively time-stamped at 12:00 until 31/12/2002 then recorded to the nearest 1 or 5 minutes. Missing 21/04/1997 to 12/05/2000. Suspect dip of 21.9m on 12/09/1995 removed by CEH.
WMardenFm.WL.ir.P	24/01/1990 - 26/08/2008	Periodic data. Data almost exclusively time-stamped at 12:00 until 29/11/2002 then recorded to the nearest 1 or 5 minutes.

3.6 Groundwater abstractions and flow augmentation

The PDM rainfall-runoff model, extended to model groundwater catchments, is able to utilise time-series records of pumped abstractions. Abstractions are included when maintaining the water balance of the conceptual groundwater reservoir from time-step to time-step. A simple abstraction model is provided in the PDM that allows the recorded abstractions to be scaled and a constant value added to accommodate the effects of unrecorded abstractions. The application to the Lavant involved the addition of Brick Kiln and Lavant recorded daily abstractions: it was judged that unrecorded abstractions were not significant and so no scaling or addition was invoked.

Table 3.11 presents a list of groundwater abstraction sites in the Lavant and Ems catchments. Figure 3.1 map their location. For the Lavant, the abstractions that are

Table 3.11 Groundwater abstraction sites in the Lavant and Ems catchments

(a) Lavant

Licence no.	Location	NGR	Purpose	Source	Period	Licensed quantity			
						Max. daily		Max. annual	
						m^3	Ml/d	m^3	Ml/d
10/41/521601	Hunters Race Lane gravel pit (2 boreholes)	SU 8541 0779	Mineral washing	Chalk/UGS	All year	1309	1.309	472784	1.295
10/41/522002	Lavant PS (3 boreholes)	SU 8545 0978 SU 8548 0975 SU 8566 0960	Public water supply	Chalk/UGS Chalk/UGS Chalk/UGS	All year All year All year	} 32000	32.00	9950000	27.260
	Brickkiln PS (2 boreholes)	SU 8359 1245 SU 8360 1238		Chalk/UGS Chalk/UGS	All year All year	} 7500	7.500		
10/41/522206	Boiler House, West Dean (2 boreholes)	SU 8646 1272 SU 8640 1275	Private Water Undertaking	Chalk/UGS	All year	} 200	0.200	10000	0.027
27/178	St. Richards Hospital, Chichester	SU 8610 0545	Hospitals	Chalk/UGS	All year	255	0.255	61000	0.167
27/179	Graylingwell Hospital, Chichester	SU 8675 0637	Hospitals	Chalk/UGS	All year	300	0.300	43000	0.118
10/41/522204	Weald & Downland Museum, Singleton	SU 8739 1292	Private non-industrial	Chalk/UGS	All year	150	0.150	15000	0.041
10/41/522205	Preston Farm, West Dean	SU 8533 1113	Spray irrigation - direct	Chalk/UGS	May - Sep.	581.9	0.582	34095	0.093
27/173	Westhampnett Gravel Pit	SU 8795 0582	Mineral process water	Valley gravels	All year	64	0.064	17600	0.048
10/41/531310	Chichester Gravel Pits (7 abstraction points)	SU 8807 0534 SU 8786 0526	Mineral washing	Valley gravels	All year	} 27273	27.27	7727273	21.171

(b) Ems

Licence no.	Location	NGR	Purpose	Source	Period	Licensed quantity			
						Max. daily		Max. annual	
						m^3	Ml/d	m^3	Ml/d
10/41/511005	Westbourne	SU 7581 0792	Watercress/Fish Farm			45.5	0.046	3,409	0.009
10/41/511202	Aldsworth	SU 7632 0878	Spray irrigation			818	0.818	45,455	0.125
10/41/520101	Woodmancote (2 boreholes)	SU 7713 0802	Public water supply		All year	4545	4.545	1,363,636	3.736
10/41/511002	Walderton (3 boreholes)	SU 7863 1035 SU 7869 1041 SU 7873 1032	Public water supply			9092	9.092	} 9,954,426	27.272
10/41/511007	Walderton	SU 7869 1041	Public water supply			36368	36.368	}	
10/41/512301	Stoughton	SU 8000 1144	Agriculture			22.7	0.023	8,182	0.022

considered significant for the modelling study are those for the pumping stations at Lavant and Brick Kiln Farm. For the Ems, the abstractions significant to this modelling study are at Walderton and Woodmancote. Their impact is offset by a low flow augmentation scheme at Walderton.

Records of daily abstractions for these four locations and the flow augmentation releases at Walderton have been provided by the Environment Agency for the years 1989 to 2006 inclusive and details of the station and licence numbers are provided in Table 3.12. As part of the Moore and Bell (2002) study, daily abstraction data were provided for the Brick Kiln and Lavant sites for the period January 1990 to May 1998. Comparison with the recently supplied daily abstraction data reveal they are identical in total amounts for the periods in common, although there is a time difference between the two sources of 4 days for Brick Kiln during February 1993 and 1 day for Lavant during October 1996. These are only small differences which would have a minimal impact on the modelling so have only been reported here for completeness. The more recently provided data will be used to support the modelling work.

Table 3.12 Details of the daily abstraction and flow augmentation data provided by the Environment Agency.

Location	EA Station Number	Licence numbers
Brick Kiln	1051	10/41/522002
Lavant	2051	10/41/522002
Woodmancote	3071	10/41/520101
Walderton	3011	10/41/511002 and 10/41/511007
River Ems (Walderton flow augmentation releases)	2081	10/41/511002 and 10/41/511007

The magnitude of the flow augmentation releases to the Ems at Walderton are summarised in Table 3.13 as annual totals alongside the abstractions at Walderton and Woodmancote. On average, it can be seen that the augmentation flow is little more than 2% of the combined abstractions from Walderton and Woodmancote. This indicates that the augmentation is only a minor component of the overall water balance of the Ems and may not need to be considered explicitly within a model for flood forecasting. The impact of the flow augmentation on modelling flood flows will be considered further in the model application to the Ems in Section 6.

Table 3.13 Water year abstractions and flow augmentation for the Ems.

Water Year	Walderton Abstraction Ml	Woodmancote Abstraction Ml	Woodmancote Augmentation Ml
1989/90	7.5198	0.4120	0.1042
1990/91	6.3790	0.1611	0.1975
1991/92	5.9021	0.0003	0.3639
1992/93	4.6391	0.0471	0.0925
1993/94	4.2728	0.0015	0.0068
1994/95	5.1836	0.2430	0.0673
1995/96	6.2158	0.5144	0.4382
1996/97	5.6132	0.3265	0.2553
1997/98	4.5300	0.4848	0.0814
1998/99	4.0107	0.3586	0.0938
1999/00	3.9033	0.3129	0.0342
2000/01	5.2565	0.2923	0.0000
2001/02	4.4612	0.0650	0.0000
2002/03	4.4836	0.3119	0.0512
2003/04	4.5485	0.1840	0.1170
2004/05	4.3317	0.3253	0.0865
2005/06	5.9835	0.3377	0.0631
Water year mean	5.1314	0.2575	0.1208

3.6.1 Real-time use of abstraction data

Currently there is a delay of approximately 2 months before the daily abstraction data are available in WISKI. This is partly due to the time taken for the operating agency to submit abstraction data and partly due to the time taken for the Environment Agency to process these data. The effect of this delay on the modelling results needs to be considered within this project. Options for mitigating the impact of the delay are the use of a default abstraction profile or a persistence assumption. These options have been considered and are discussed under the model sensitivity analyses in Section 6.2.4 If the impact of the delay is found to be significant, a project recommendation could be for the data to become available for modelling sooner.

Recommendations

- **Real-time use of abstraction data.** The impact on the modelling of the 2 month delay in abstraction data being available in WISKI needs to be considered as part of the model investigation. Mitigating options such as a default abstraction profile or a persistence assumption also need to be considered. This is addressed under the model sensitivity analyses of Section 6.2.4.

4 Data quality control

4.1 Raingauge data

A main focus of the data quality control concerned the raingauge dataset. Areal rainfall estimation is often a major source of uncertainty when considering the water balance of a catchment and has significant implications for any subsequent rainfall-runoff modelling. As an outcome of the quality control process, a method is proposed for constructing a consistent time-series of 15 minute rainfall totals that is required for the PDM modelling.

As outlined in Section 3.2.1 and Appendix B, up to three types of rainfall data were provided for eight raingauges. The South Mundham gauge is not well located in relation to the study catchments. Because of this, and the time taken to quality control the data, a detailed analysis of its record has not been done. Westergate raingauge data were also not analysed as judged not to be critical to this modelling investigation.

4.1.1 Consistency check between time-of-tip and the 15 minute and daily totals

The three types of rainfall data received were time-of-tip data, 15 minute totals and daily totals. The first stage of the analysis checked for consistency based on the assumption that the 15 minute and daily totals have been formed from the time-of-tip record. To do this, 15 minute and daily rainfall totals using the time-of-tip record were calculated and compared to those provided by the EA. This initial analysis has raised several questions about the data provided. A summary of the assumptions used in the analysis and the findings is given below.

Time-of-tip records

1. It is assumed that the start of a missing period in the tipping-bucket record is identified by a value field of --- and a quality flag of M. The tipping-bucket raingauge data, and any totals formed from them, should then be treated as missing until the next ‘good’ tip is recorded. Looking at the data either side of the missing flag we are confident this is the correct interpretation.

2. The temporal resolution of the time-of-tip records vary over time from recording at minute intervals to recording by the second (see Table B.1 for more details).

3. There were occasional zero values in the time-of-tip records which were flagged as good. Therefore these values have simply been included as zero in forming the 15 minute and daily totals.

4. Occasionally there are instances where the time-of-tip data have recorded values that are a large multiple of the 0.2 mm tip size and look like they may be daily totals.

Daily totals

5. The CEH and EA daily totals agree for the entire record, including missing days, for all raingauges tested. (Note: South Mundham was not tested as it was not used in the

subsequent modelling and Westergate was not tested as WISKI daily data were not supplied.)

15 minute totals

6. There are inconsistencies between the EA 15 minute totals and the time-of-tip records when the time-of-tip record is flagged as missing. The 15 minute totals provided by the EA appear to assume that the missing flag in the time-of-tip data indicates the **end** of the missing period rather than the **start**. This results in the EA data having long periods of zero rainfall which should actually be set to missing. The periods which are affected by this are listed in Table B.2 for reference.

7. There are a few instances where the 15 minute totals do not agree with the time-of-tip records. The difference on these occasions is normally one tip either way. These periods are also listed in Table B.2.

Recommendations

- **15 minute raingauge totals.** The 15 minute totals generated by CEH from the time-of-tip data should be used as opposed to the EA generated 15 minute totals.

- **WISKI.** The method used to store and extract 15 minute totals within WISKI should be reviewed in relation to the handling of missing time-of-tip data.

4.1.2 Quality control of the tipping-bucket raingauge data

The quality control process has involved three principle steps:

- Visual comparison of cumulative hyetographs for all raingauges to identify suspect periods (periods which aren't recording, blockages, large totals, etc.) and cross-reference with EA quality control flags.
- Cross-reference suspect periods against daily raingauge data (see Table 3.2 for daily gauges used). Particularly useful for checking magnitudes.
- Cross-reference against weather radar data using Hyrad. Particularly useful for identifying periods of rain/no-rain, high spatial variations (e.g. convective events) and detecting blockages.

The periods that are deemed suspect following the above quality control process are detailed in Table B.3. There were many reasons for why periods were deemed suspect but the most common and most significant are summarised below along with some examples of the cumulative hyetographs which illustrate the issues.

1. There are periods where the tipping-bucket records only exist during a small window of time (typically 00 – 02 hours) each day that doesn't tie in with radar but the daily totals appear to be correct. This can affect more than one station at the time: for example Chichester, Walderton and Fishbourne all suffer from this problem from November 2007 to June 2008. Figure 4.1 illustrates the problem during April 2008.
2. Blocked raingauges causing a slow trickle of tips. Cumulative totals may appear satisfactory over long periods but hyetographs immediately reveal the problem: see Figure 4.2 for an example showing blockages at Chichester and Fishbourne.

3. Dry periods when a raingauge is incorrectly recording rain. An example is given for Duncton during April 2003 in Figure 4.3.
4. Periods where the raingauge data should be flagged as missing (rather than assuming no rain). An example is given in Figure 4.4 for Chichester during October 2001.
5. The Walderton and Chichester records are identical (or almost identical) for the period 4/11/1996 to 4/07/1997.
6. On the 15/09/2000 Chichester recorded 70-80mm less than at Walderton and Chilgrove which appears to be an underestimation.

Recommendations

- **Tipping bucket raingauge data.** The two serious issues identified with the tipping-bucket records (points 1 and 5) should be investigated by the Environment Agency and an explanation for their occurrence sought. This has been reported to FMD and an investigation is ongoing.

- **Chichester raingauge.** Check with Environment Agency regarding Chichester totals on 15 September 2000 (point 6). This check has been done and the totals have since been removed from the record at CEH.

- **WISKI quality flags.** The quality control analysis summarised in Table B.3 should be considered for inclusion within the WISKI quality flag information where appropriate.

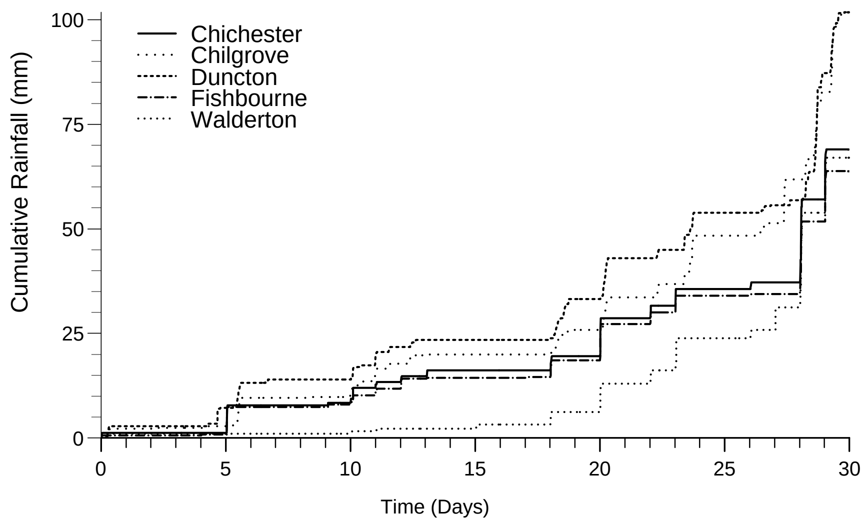

Figure 4.1 Cumulative hyetographs for April 2008 highlighting recording problems at Chichester, Walderton and Fishbourne.

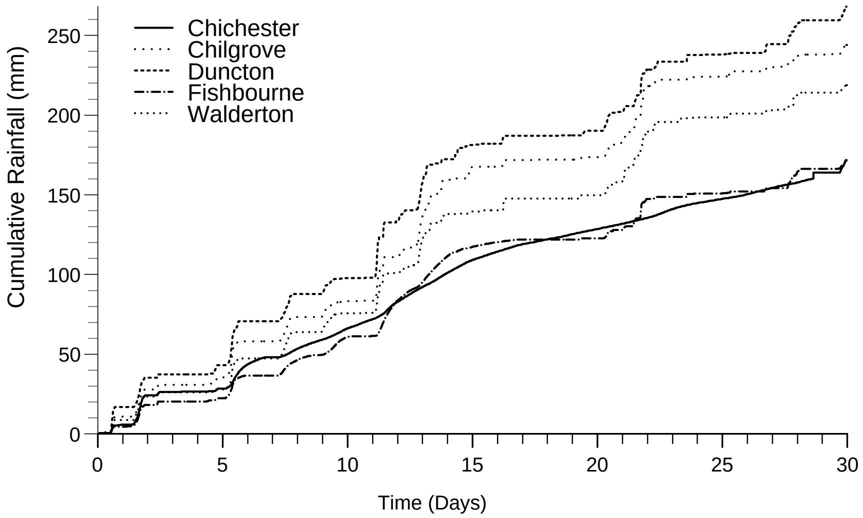

Figure 4.2 Cumulative hyetographs for November 2002 highlighting blockages at Chichester and Fishbourne.

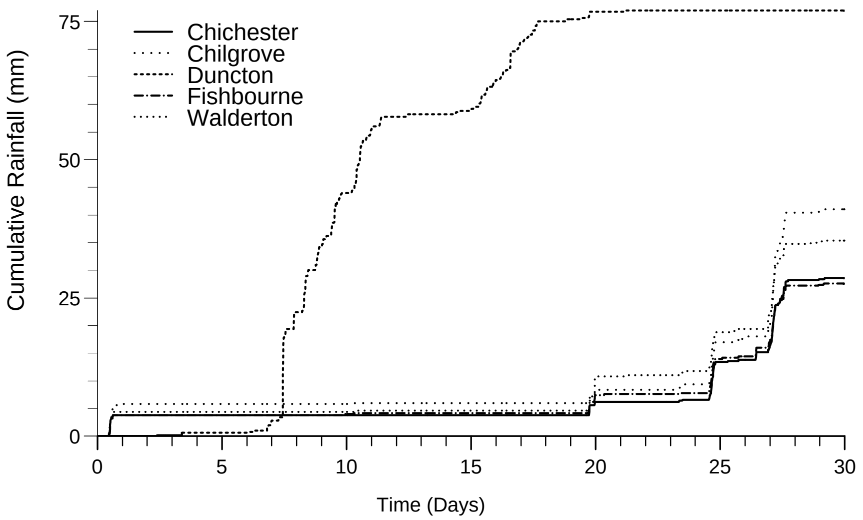

Figure 4.3 Cumulative hyetographs for April 2003 highlighting erroneous recordings at Duncton.

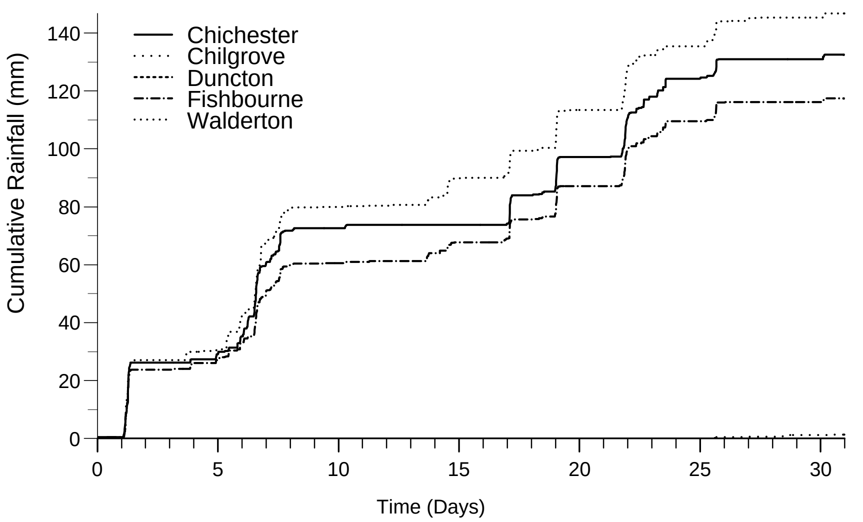

Figure 4.4 Cumulative hyetographs for October 2001 highlighting that Chichester should have recorded some rain between 11 and 17 October.

4.1.3 Proposed method for generating rainfall time-series for rainfall-runoff modelling

Here the aim is to generate a consistent time-series across the entire modelling period to allow like-for-like comparison of modelling results from calibration and evaluation periods. It is anticipated that these modelling periods will encompass the significant flood peaks of January 1994 and December 2000. Therefore the raingauges used must be available from at least 1994 onwards. Table 4.1 lists the start date of the data provided for each raingauge and reveals that only Chichester, Walderton and Havant should be considered for model calibration and evaluation. Since these raingauges have relatively low SAAR (see Table 3.1), we anticipate an underestimation of catchment average rainfall that will have to be accounted for in the modelling work.

Table 4.1 Tipping-bucket raingauges in the vicinity of the Lavant and Ems catchments: start dates of data provided.

Raingauge	Start date of data provided
Chilgrove	2 October 1999
Fishbourne	22 January 2001
Chichester	8 October 1990
Walderton	20 February 1991
Duncton	11 June 2002
South Mundham	1 January 2000
Havant	1 January 1990
Westergate	1 November 1999

For the PDM modelling, the topographic catchment average rainfall is calculated by applying a set of linear weights to the appropriate set of raingauges. Here the weights have been derived using the 'integrated multiquadric method' (Moore *et al.*, 2006; Cole and Moore, 2008). This method shows that sets of linear raingauge weights can be derived which are equivalent to fitting a multiquadric surface to the point raingauge values and then integrating over the catchment. As these linear sets of raingauge weights are independent of the point raingauge values, this method captures the benefit of surface fitting without incurring the cost of calculating catchment average rainfalls from surfaces fitted at each time-step. The raingauge weights to be used for modelling are given in Table 4.2. The expected SAAR (1961-90) of each network is included, formed by weighted averages of the values from Table 3.1, along with the catchment SAAR from the on-line National River Flow Archive gauging station summary sheets.

To mitigate the possible impact on the PDM modelling of periods that are missing or identified as suspect through quality control (subject to the issues raised under Section 4.1.2 being resolved), it is proposed to infill the Chichester, Walderton and Havant raingauge records according to the following hierarchy of priority:

1. A SAAR-scaled version of a nearby tipping-bucket record
2. If no nearby tipping-bucket record is present then a SAAR-scaled version of the nearest available daily raingauge will be used. The sub-daily breakdown will be determined using radar data or a more distant tipping-bucket raingauge if available.

Table 4.2 Sets of linear raingauge weights for the Lavant and Ems catchments derived using the integrated multiquadric method.

Catchment / use of raingauge weights	Raingauge							
	Chichester	**Walderton**	**Havant**	**Chilgrove**	**Duncton**	**Westergate**	**Fishbourne**	**SAAR 1961-90 (mm)**
Lavant at Graylingwell								922
Modelling period	0.55	0.45	-	N/A	N/A	N/A	N/A	782
Sensitivity analysis (including Chichester)	0.12	0.05	-	0.46	0.29	0.08	-	911
Sensitivity analysis (excluding Chichester)	N/A	0.04	-	0.47	0.29	0.12	0.08	911
Ems at Westbourne								897
Modelling period	0.08	0.80	0.12	N/A	N/A	N/A	N/A	802
Sensitivity analysis	-	0.51	0.13	0.36	-	-	-	839

Recommendation

- **Rainfall input for rainfall-runoff modelling.** A consistent time-series of raingauge rainfall data will be used for rainfall-runoff modelling. Gaps and suspect periods in the Chichester, Walderton and Havant raingauge records will be infilled using the approach recommended here.

4.1.4 Rainfall time-series for real-time flood forecasting

Over the modelling period studied, the raingauge and radar network has improved. As discussed earlier, a sensitivity analysis using radar data will be undertaken. A sensitivity analysis of model performance using the improved raingauge network will also be undertaken. Particular consideration will be paid to the Chilgrove raingauge for the Ems catchment and the Chilgrove, Duncton, Fishbourne and Westergate raingauges for the Lavant catchment as these gauges, due to their proximity to the catchments, provide the most obvious potential for improving the catchment average rainfall estimates.

Raingauge weights have been derived using the current raingauge network for the Lavant and Ems catchments in Table 4.2. For the Lavant sets of raingauge weightings have been derived, one set including Chichester and one set excluding Chichester. This is because Chichester is not currently on the telemetry system and so the sensitivity analysis may assess whether it is beneficial to add Chichester to the telemetry network.

Note that, since different raingauges experience different amounts of rainfall on average (due to orographic enhancement for example), a recalibration of PDM parameters, particularly f_c, may be necessary when substituting one network for another.

Recommendation

Raingauge network sensitivity analysis. Use of the improved raingauge network will be considered as part of the model sensitivity analysis.

4.2 Well level data

The primary methods used for checking the well level data were to visually inspect the data files and the well level hydrographs.

In the time-series 'ChilgrveGW.WL.ir.P' there is the following comment at time 28/11/2002 12:41:00:

> *'Surveyed 01/11/02. New datum is 77.74mAOD to top of new standpipe. This is 56cm higher than historical datum of 77.18m which was 30cm too high. (Standpipe is 86cm high).'*

The implication is that the well levels (m AOD) prior to 01/11/02 should be based on a datum 30cm lower at 76.88m AOD and therefore the well level readings should also be 30cm lower.

Recommendation

- **Time-series ChilgrveGW.WL.ir.P:** Well level data (m AOD) prior to 01/11/02 should be reprocessed with the correct datum of 76.88m AOD (this is 30cm lower than the historical datum used). CEH has reprocessed the data internally to support the modelling work.

Visual comparison of the well level/dip hydrographs for the various time-series available at Chilgrove and Compton were provided by John Hall as part of the Lavant data availability document and are reproduced here in Figures 4.5 and 4.6 respectively. Inspection of the Chilgrove data immediately identifies a problem with the RTS data (blue line) from 21 September 2007 onwards where the dip and well level data columns have been switched in the file provided. This also coincides with the installation of a new sensor during October 2007. The data file confirms that previously the dip and well level data column switching had been corrected for manually.

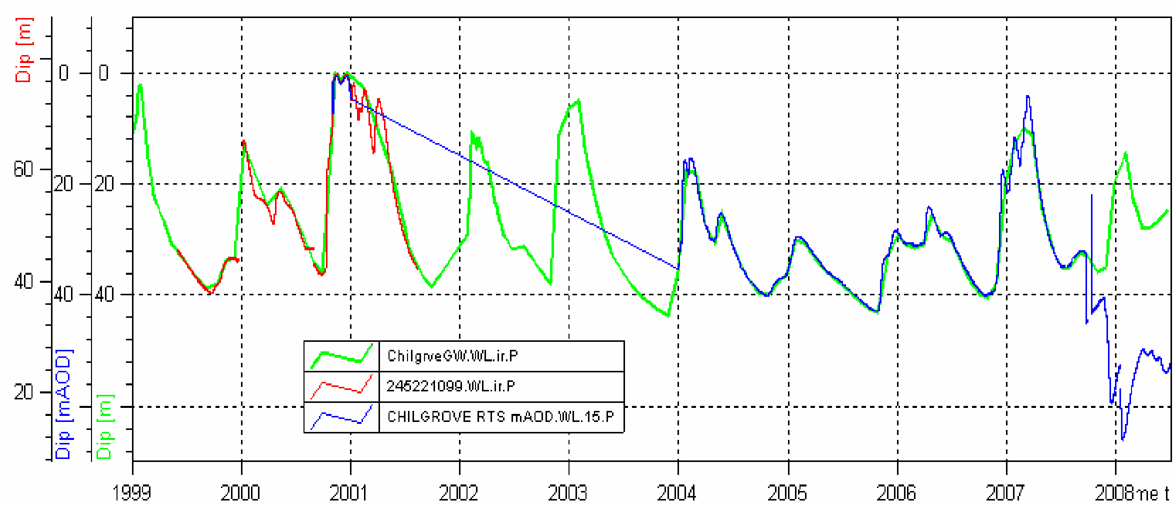

Figure 4.5 Well level hydrographs for the different Chilgrove time -series (courtesy of John Hall).

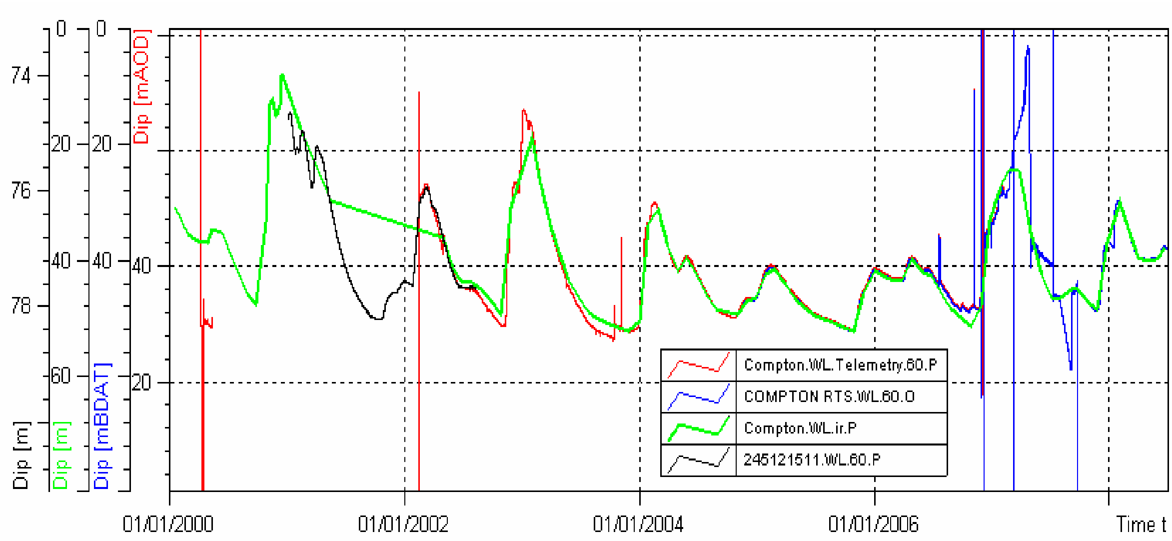

Figure 4.6 Well level hydrographs for the different Compton time-series (courtesy of John Hall).

Analysis of the Compton well level data presented in Figure 4.6 reveals two issues with the sub-daily data. Firstly there are a few instances of spurious spikes in the data that should be removed (e.g. 20-26 July 2007, 11:00 9 November 2006). Secondly the recent RTS data (blue line) appears to be very circumspect between 1 December 2006 and 25 September 2007. During this period negative or spuriously large dip values are recorded and there is little agreement with the monthly dip values.

Recommendations

- **Chilgrove RTS data.** The EA time-series 'CHILGROVE RTS mAOD.WL.15.P' stored in WISKI should be reprocessed from 21 September 2007 onwards to switch the 'Dip' and 'Well Level' data columns. (Note this doesn't affect the proposed calibration and evaluation periods for the PDM modelling). Note that this has now been done.

- **Compton RTS data.** The EA time-series 'COMPTON RTS.WL.60.O' stored in WISKI should have spurious spikes manually removed (e.g. 20-26 July 2007). The period 14:00 01/12/2006 to 13:00 25/09/2007 (inclusive) should be treated as suspect. Note that whilst spikes are present in the original series (marked 'O'), these have been removed in the production series (marked 'P') so no action is required.

- **Compton RTS data.** The EA time-series 'Compton.WL.Telemetry.60.P' should have spurious spikes manually removed (e.g. 20-26 July 2007). The Environment Agency has addressed this.

Note that, due to the good agreement of other well level records with the flow records, and since the Chilgrove and Compton RTS data are not available over the full modelling period, use of these does not feature in the modelling work that follows. This is an area that might be investigated in the future.

4.3 River level/flow data

The ratings for the Lavant at Graylingwell and Ems at Westbourne gauging stations have been discussed in Section 3.3. The main method used to assess the river level or flow data was to view hydrographs and examine the data flags and comments within the data files.

4.3.1 Lavant at Graylingwell

A flow hydrograph for Graylingwell, produced by applying the Mott MacDonald (2003) rating to the river level data, is presented in Figure 4.7. This covers the proposed modelling period and immediately highlights the ambiguity between how missing and zero level/flows are recorded for this ephemeral river. A summary of some of different periods of zero recording is given below.

1. From 1 January 1991 to 12 October 1995 zero levels are recorded and there are no missing levels
2. From 13 October 1995 to 31 December 1995 zero levels are recorded at 23:45 each day and the remainder are set to missing. These should probably all be zero.
3. For the period 1 January 1996 until 23 December 1997 all values are missing except 00:00 1 January 1996 and 00:00 1 January 1997. Again, these should all probably be zero.

In general this ambiguity only causes a problem in years where there are missing data for periods longer than a year (e.g. 13 October 1995 to 23 December 1997) as it is then not clear whether the stream was actually dry or if there was a genuine period of missing data. For the period 13 October 1995 to 23 December 1997 it is believed that the stream was dry. A knock-on effect of this ambiguity in zero and missing data is that it has a small effect on the calculated performance measure statistics.

By examining the recent data for Graylingwell it appears that zero flow are currently been recorded correctly. It is recommended that the missing data in the Graylingwell level and flow records are reviewed and replaced with zero where the stream is known to have been dry.

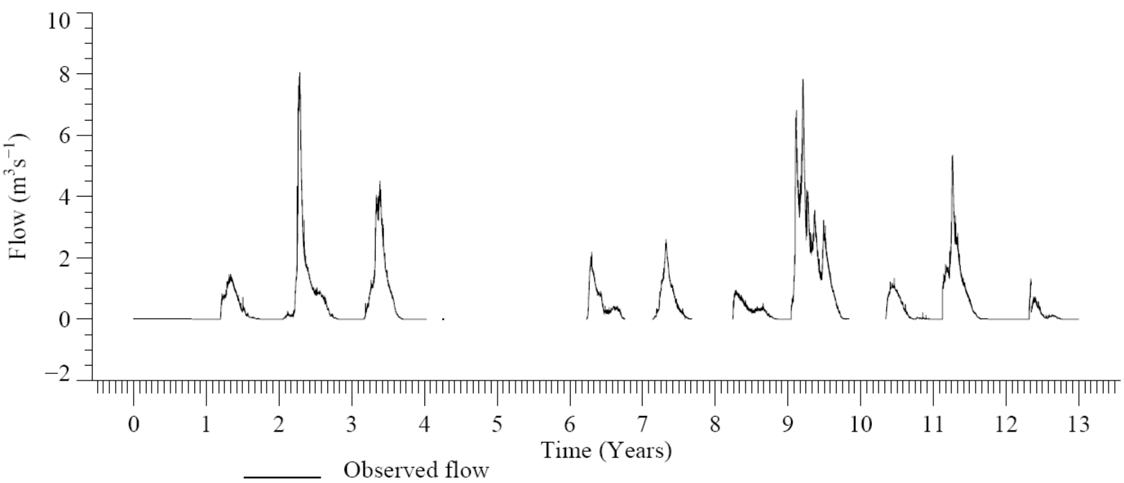

Figure 4.7 Flow hydrograph for the Lavant at Graylingwell over the water years 1991/2 to 2003/4. Flows have been derived using the Mott MacDonald (2003) rating.

There are two periods of suspect level data during the 2000/2001 and 2002/03 water years. Figure 4.7 shows a large upward jump at the initiation of observed streamflow during these water years. The relevant sections of the Graylingwell stage record are repeated here:

16/10/2000	12:00:00	0.000	G
16/10/2000	12:15:00	0.219	G

17/11/2002	14:00:00	0.000	G
17/11/2002	14:15:00	0.341	G

Prior to these two records, the stage is recorded as 0.000 since 16:00 27 August 2000 and 15:30 27 October 2002 respectively. This sudden jump at initiation of flow does not occur at other initiation events, although several of these are preceded by periods of missing data. It is considered appropriate to treat the records as missing for some period leading up to the above records.

There is another period of suspect level data during the 2003/04 water year. Figure 4.7 shows a large downward jump just after the initiation of observed streamflow during the 2003/04 water year. The relevant section of the Graylingwell stage record is repeated here:

05/02/2004	10:45:00	0.355	G
05/02/2004	11:00:00	---	M
05/02/2004	11:15:00	0.200	G

This shows the sudden downward jump in level interspersed by a single missing value. However, as this water year does not have a particularly large flow peak and occurs during the evaluation period rather than the calibration period, it does not have a serious effect on this study.

It is recommended that the Environment Agency review these periods of record and take the appropriate action (e.g. add comments to WISKI).

Recommendation

- **Lavant at Graylingwell.** The Environment Agency should review the problem records on 16 October 2000, 17 November 2002 and 5 February 2004 and take appropriate action (e.g. add comments to WISKI). The missing data in the level and flow records should also be reviewed and replaced with zero where the stream is known to have been dry.

4.3.2 Ems at Westbourne

A flow hydrograph for Westbourne is presented in Figure 4.8 and covers the proposed modelling period. In contrast to the Lavant at Graylingwell (Figure 4.7), Westbourne is not ephemeral which is partly due to the low flow augmentation scheme in operation. It also has a more significant fast-response element in addition to the strong seasonal baseflow signature.

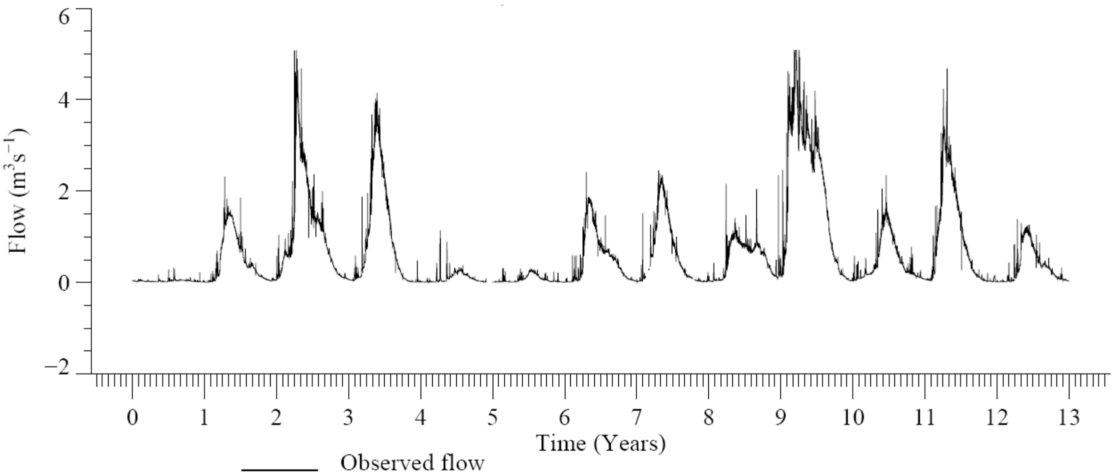

Figure 4.8 Flow hydrograph for the Ems at Westbourne over the water years 1991/2 to 2003/4.

Analysing the record reveals that flows are being capped to the upper limit of the rating curve which corresponds to flow of approximately 5.08 m^3s^{-1}. This only happens in a few instances and those during the modelling study period are listed in Table 4.3.

Table 4.3 Periods when the flow of the Ems at Westbourne is above the upper limit of the rating curve.

Start date	End date	Length
30/12/1993 16:30	30/12/1993 17:00	30 minutes
09/01/1994 23:45	09/01/1994 23:45	1 reading
07/12/2000 19:15	08/12/2000 00:15	15 hours
11/12/2000 18:15	12/12/2000 02:15	8 hours
12/12/2000 14:00	18/12/2000 22:00	6 days, 8 hours
31/12/2000 22:30	01/01/2001 02:30	4 hours

The most significant period is during the 2000 floods where several peak flows are beyond the upper limit, as illustrated in Figure 4.9. It is recommended that these periods in the Westbourne where the flow is ‘capped’ should either be set to missing or, preferably, estimated using the extrapolated rating curve. Note that the capped flows have not been corrected in this study.

Recommendation

- **Ems at Westbourne.** The Environment Agency should review their practice of capping the flow to that at the upper limit of the rating curve and allow the extrapolated rating curve to be used to estimate flows (with the knowledge that they are out of range).

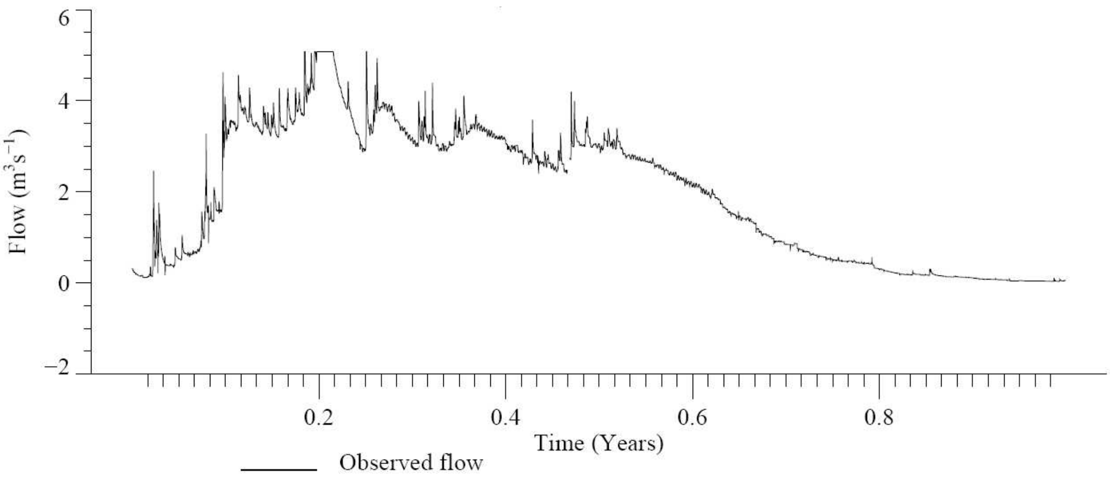

Figure 4.9 Flow hydrograph for the Ems at Westbourne over the water year 2000/1.

5 Strategy for modelling

5.1 Introduction

The aim of this section is to develop a strategy for PDM modelling to be used in the project. It addresses how model performance will be assessed and what information will be used to underpin the conceptual form the PDM model will take. The latter aims to identify any further model development required and any further data or information needed.

5.2 Strategy for model assessment

5.2.1 Selection of periods for assessment

The strategy for model assessment first aimed to identify separate periods of record to be used for calibration and independent evaluation of the PDM rainfall-runoff model applied to the Lavant and Ems catchments. This would provide a form of rigorous "split-sample testing" of model performance for these catchments. Selection of the periods would be with reference to periods of high flow in the record, be done in consultation with the Agency and would take account of any problems with non-natural flows.

The tender brief suggested that a 5 year record be given to CEH for calibration in the first instance. In CEH's response to the brief, we advised that the full historical records be provided at inception: this has efficiencies for data take-on and quality control, and would allow the appropriate calibration and evaluation datasets to be chosen in discussion and agreement with the Agency before modelling commenced. It was subsequently clarified at the Project Inception Meeting that the 5 years originated from a belief that the PDM software was restricted to around 5¼ years; in practice the current product version of the PDM has no limit imposed on the length of time-series it can handle.

The Project Inception Meeting discussed the problem of selecting calibration and evaluation periods due to the small number of high flow events and some dry years. It was agreed, based on an inspection of the Lavant record, that the five water years 1991/92 to 1995/96 be used for calibration and the eight water years 1996/97 to 2003/4 for evaluation. Subsequent inspection of the Ems record confirmed the suitability of these periods for both study catchments.

Recommendation

- **Model calibration and evaluation periods.** A split-sample strategy for model assessment will be used, employing the five water years 1991/92 to 1995/96 for calibration and the eight water years 1996/97 to 2003/4 for independent evaluation.

5.2.2 Methods for evaluating model performance

The form of assessment needs to consider ways of evaluating model performance in relation to its end use for real-time flood forecasting and warning. This means that a number of formal and informal measures of performance need to be decided upon for use in the model assessment. An invaluable overall impression of performance is provided by a simple visual comparison of observed and modelled river flow using hydrograph plots. This provides an immediate impression of how the PDM transforms rainfall to river flow, taking into account losses via abstractions and evaporation.

Such plots can be complemented by formal *portmanteau performance measures* such as the root mean square error (*rmse*) and R^2 Efficiency (Nash-Sutcliffe Efficiency). The latter provides a dimensionless measure of the proportion of variance in the observations accounted for by the model simulations: a value of unity indicates a perfect model whilst a value less than zero arises when the model is less good than a model based on the (assumed unknown) mean of the river flow over the period used for assessment. Other assessments could focus on particular features of the hydrograph: percentage error of peak flow magnitude and timing errors in peak flow, flow initiation and cessation (the last two being relevant to ephemeral streams). These can be judged informally through inspection of the modelled and observed hydrographs.

The availability of well level records is exploited by using these in the assessment of the PDM's modelling of water held in groundwater storage, providing an "internal check" on model behaviour. Similar plots and performance measures to those outlined above are used.

The above discussion has focussed on assessment of the PDM as a deterministic process model of the catchment in question. Input data (rainfall, potential evaporation and abstractions) are transformed to modelled runoff at the catchment outlet without reference to observed river flow (except for initialising the model and assessment of its performance). Such modelled runoff is referred to as a *simulation-mode forecast*. In real-time running of the model there is the opportunity to use observations of river flow to sequentially improve model forecasts. Such *updated forecasts* or *real-time forecasts* can be assessed in similar ways to the simulation-mode forecasts but with respect to the lead-time they relate to. Visual assessment of selected *fixed lead-time forecasts* made for all forecast origins (every ¼ hour) can be made through comparison with river flow observations. Such forecasts are called *fixed lead-time variable time-origin forecasts*. A more insightful visual assessment is to take forecast origins, chosen at points on the hydrograph as a flood develops, and plot the forecast hydrographs from these origins along with the observed hydrograph. These are called *fixed-origin variable lead-time* forecasts. This form of forecast emulates the situation that the forecaster must manage in practice, but with reference to the "future observation" against which performance can be assessed in hindsight. Use of the formal performance measures (*rmse* and R^2) can be made by calculating these over all possible forecast origins (every ¼ hour) for each lead-time (say 0.25, 0.5, 0.75, .., 24 hours) and constructing a plot of the performance measure value against lead time. This is useful in seeing how the forecast performance degrades with increasing lead-time.

Further performance measures can be introduced more closely aligned to end-user requirement. Flood warnings may be issued based on the *crossing of critical flow (or level) thresholds*. Thus performance statistics that measure the success of forecasting the crossing of flow thresholds can be really informative. *Categorical Skill Scores* can be formed based on an *event* (in this case a crossing of a flow threshold) occurring or not and whether or not the event is forecast. There are clearly four possible outcomes which can be summarised in a *two-way contingency table*, and from which a skill score can be calculated. Commonly used skill scores are the Critical Success Index (*CSI*), the Probability of Detection (*POD*) and the False Alarm Rate (*FAR*). These scores can be calculated for selected thresholds of interest. However, a single pooled Skill Score can be formed by calculating the score over *all possible thresholds* without the need to focus on a specific threshold, or set of thresholds. Selected Skill Scores could be used for assessment of the real-time forecasts: but these would add little insight beyond that gained from visual assessment of the fixed-origin variable lead-time forecasts focussed on the rising limbs of flood hydrographs. The Skill Scores have therefore been considered out of scope for the present project.

For this study, a limited set of measures and hydrograph plots will be used, targeted at what will be useful in assessing and summarising model performance.

Recommendations

- **Model assessment.** Model assessment will be carried out in simulation-mode and updating-mode.

- **Model assessment.** Visual assessment of modelled and observed hydrographs could be complemented by performance measures of continuous variable (*rmse*, R^2 Efficiency) and, where appropriate, categorical form (CSI, POD, FAR). The latter focus on the success of forecasting the crossing of critical flow/level thresholds; the relatively small number of threshold crossings for groundwater-dominated rivers can limit the usefulness of these statistics for typical record lengths. A limited set of measures will be used in this study tailored to what is judged useful for model assessment purposes. The ones chosen are R^2 Efficiency and *rmse* along with visual assessment.

5.3 Strategy for model conceptualisation

The PDM rainfall-runoff model, adapted and extended to accommodate features that can be important in groundwater catchments, requires careful application. The formulation allows for losses from pumped abstractions, external springs and underflows, and the possibility of ephemeral streamflow behaviour. The catchment area can be changed to accommodate any mismatch between surface and subsurface drained areas.

This flexibility of model conceptualisation comes at a price. Unless there are observations supporting the application of these additional conceptual components there will be an inevitable lack of identifiability. This brings with it the possibility of obtaining unrealistic model simulations, or realistic ones for the wrong reasons. The modeller may need to impose their view on how a given catchment behaves hydrologically, drawing on information sources that may only help in an informal way. A study of catchment water balance can be of great help in supporting model conceptualisation. Trying to quantify the components of water balance is key. This must go beyond consideration of rainfall, evaporation and catchment river flow. It must try to identify and quantify abstractions/returns and water imports/exports across the catchment boundary (e.g. external springs, underflows below the gauging station). Discrepancies when closing the water balance can be used to infer missing components and possibly be used to stimulate further investigation.

Hall (2008), in the Model Specification document used for the Tender Brief, carried out detailed water balances for the Lavant and the Ems: these feature as Appendices B and C of the Brief. The catchment water balance for the Lavant to Graylingwell over the 8 water years 1995 to 2003 indicates 26% is unaccounted for and may relate to groundwater flow out of the catchment. A similar balance analysis for the Ems to Westbourne, for the 10 water years 1995 to 2005, reveals a smaller 13% unaccounted for residual: these could be accounted for by abstractions in part, but also by groundwater outflows. One aim of the PDM modelling work will be to try and clarify the amount of water going to groundwater outflow using the modelled water balance.

A useful insight into possible groundwater outflows is given by the flow record for Costers Brook at Cocking. This is a spring fed stream issuing from the north-facing scarp slope of the South Downs and is located immediately north of the Lavant catchment (see Figure 3.1). The National River Flow Archive station summary for Cocking states that the topographic drainage area is 2.7 km^2, the mean flow is 0.06 m^3/s (700.8 mm) and the 1961-90 SAAR is 969 mm. The MORECS average annual actual evaporation for the Costers Brook catchment over the period 1971-2007 is 532.1 mm (see Table 3.6). Forming an indicative water balance using these values indicates an annual average import of water equivalent to 264 mm or 0.7 Mm^3 and suggests that the groundwater catchment area is larger than the topographic area of 2.7 km^2.

Due to the proximity of the Costers Brook catchment to the Lavant catchment, it is reasonable to assume that the import to Costers Brook is an export from the Lavant. An average annual export of 0.7 Mm^3 equates to 8 mm over the Lavant. This is significant as it is approximately 13% of the annual average abstractions (given as 5.414 Mm^3 by Hall (2008)) and would account for around 2.5% of the average water balance residual (given as 315 mm by Hall (2008)). Of course only a small proportion of the Lavant catchment export will be captured by the Cocking record. However, the Cocking record can give some useful insight into when export may be occurring from the Lavant catchment (particularly to the north) and under what conditions.

An approach for investigating the water balance further is to visually plot the various components, in terms of mm water over the catchment, as both daily time-series and cumulative amounts. This is presented for the Lavant in Figures 5.1 and 5.2 for the water years 1993/4 to 1995/6 and 1999/2000 to 2000/1 respectively. In order to convert the flow for Costers Brook at Cocking into mm water over the Lavant, it has been assumed that the ratio of average import (264 mm) to discharge (700.8 mm) at Cocking is applicable at all times. Therefore the Cocking flow is multiplied by 264/700.8 before conversion into mm water using the Lavant catchment area. These figures show some interesting behaviour of the Cocking record in relation to the Lavant at Graylingwell. In particular Figure 5.1 indicates that there may be significant groundwater exports occurring prior to the rise of the hydrograph at Graylingwell (e.g. Q4 1993, Q2 1994 and Q4 1994). This information can be used to assess the external spring flow component of the extended PDM, helping strengthen the form of the PDM conceptualisation to be applied.

It is fortunate for the Lavant to Graylingwell catchment that there are good daily records for the principal pumped abstractions from the Lavant and Brick Kiln wells. These records have been reviewed in Section 3.6. The Ems catchment to Westbourne also is subject to significant pumping but a low-flow groundwater augmentation scheme prevents ephemeral flow from occurring. Combining the effects of augmentation and abstraction needs to be considered when applying the extended PDM to the Ems catchment. This has been discussed in Section 3.6 where augmentation flows are identified as a minor component of the water balance, and unlikely to need modelling explicitly for flood forecasting applications.

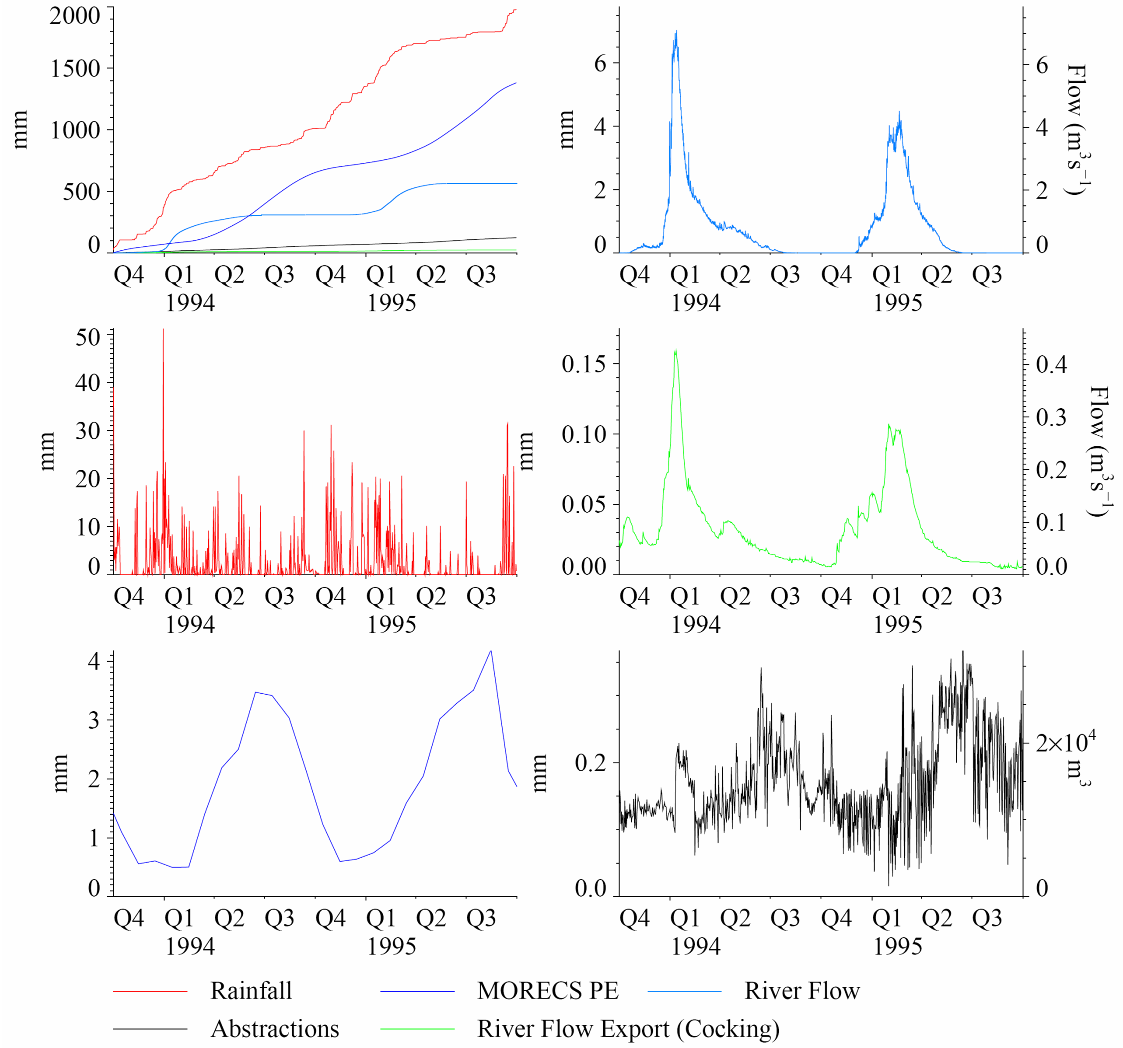

Figure 5.1 Individual components of the water balance for the Lavant catchment over the water years 1993/4 and 1994/5. The left hand scales are in units of mm over the Lavant catchment area (87.2 km^2). The top left plot shows the cumulative totals whilst the remainder show time-series of daily totals.

Recommendations

- **Model conceptualisation**. An aim will be to quantify component processes where possible (e.g. pumped abstractions). Catchment water balances and use of additional data sources (e.g. Costers Brook at Cocking) will be used to quantify unaccounted for water transfers. The modelled water balance will be used to help clarify the form of these transfers.

- **Model conceptualisation.** Combining the effects of augmentation and abstraction in the extended PDM needs to be considered as part of the model application to the Ems catchment.

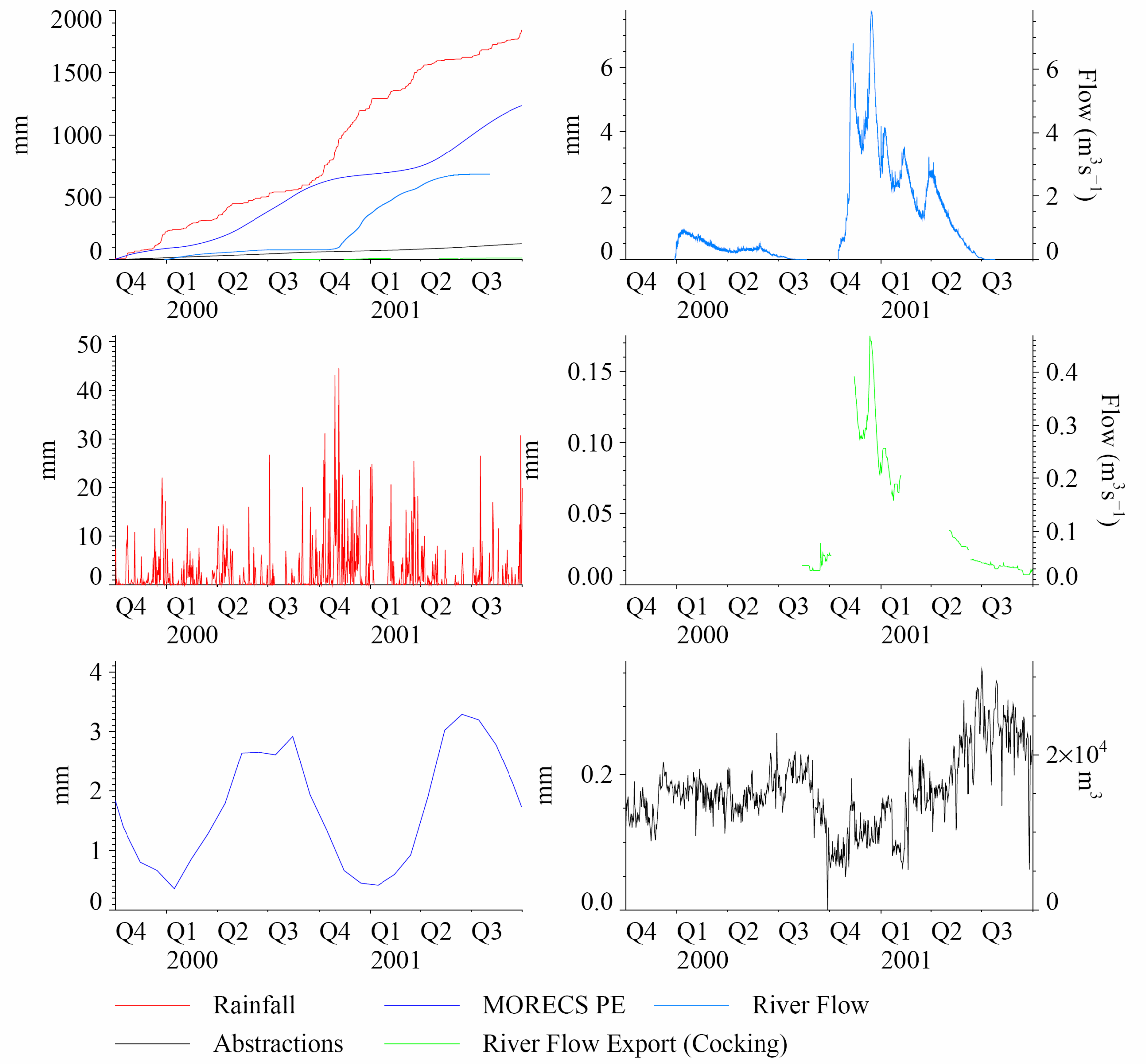

Figure 5.2 Individual components of the water balance for the Lavant catchment over the water years 1999/2000 and 2000/1. The left hand scales are in units of mm over the Lavant catchment area (87.2 km^2). The top left plot shows the cumulative totals whilst the remainder show time-series of daily totals.

5.4 Hydrogeological support to model conceptualisation

The previous section has focussed on available time-series data support to model conceptualisation. A broader information source is provided through an understanding of the hydrogeological controls operating in and around the Lavant and Ems catchments. Figure 5.3 provides a map of the solid geology and drift cover for an area encompassing the Lavant and Ems catchments. This figure has been produced using the British Geological Survey digitised 1:50000 scale map (for “sheets” 316 and 317) and their records of spring locations. It highlights the occurrence of springs within the main valleys and a second group along the spring line of the north-facing escarpment of the South Downs. The flow records for the spring at Cocking have been discussed previously in Section 5.3.

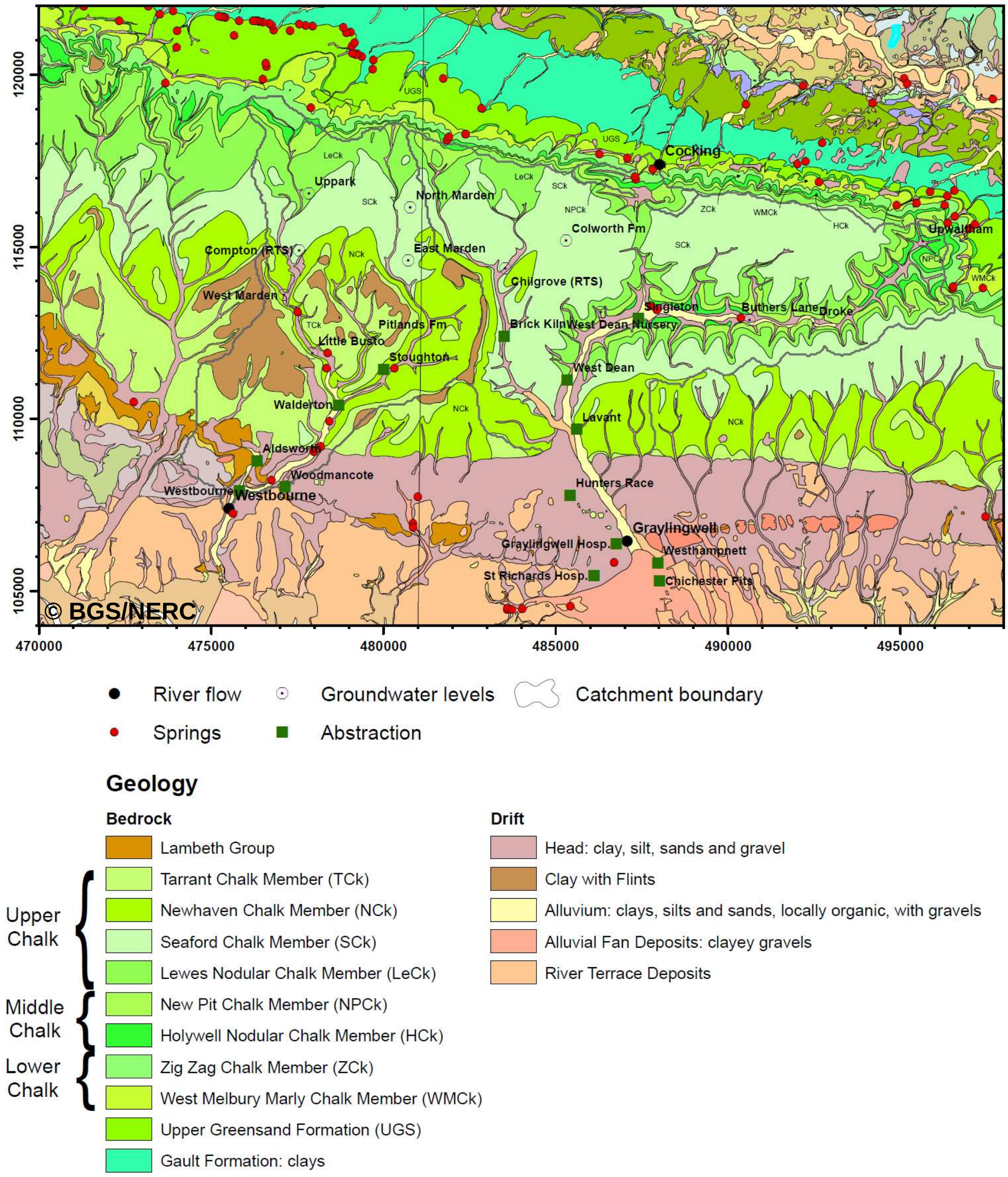

Figure 5.3 Solid geology and drift cover map showing spring locations in the vicinity of the Lavant and Ems catchments.

A key hydrogeological characteristic of the Chalk is its particular form of dual porosity. The Chalk matrix is so fine-grained and the pore throats so small in size that the pore water suctions remain high, stopping the pores from draining fully. This means that even above the water table the matrix remains largely saturated and evaporation rates are maintained. This is represented in the PDM model by the tension water component controlled by the storage tension threshold parameter, S_t, below which free drainage is inhibited whilst water is made available for evaporation.

The zone above the water table (at atmospheric pressure) is still described as unsaturated, since pore water pressures are less than atmospheric pressure. At high pore water suctions (potentials of less than -5 kPa) hydraulic conductivity is quite constant at between 1 and 6 mm d^{-1}. With decreasing suctions a rapid increase in conductivity occurs with typical values in the range 100 to 1000 mm d^{-1} as the fracture network become saturated and dominates the flow regime. It is estimated that 10 to 30% of recharge is via fracture or bypass flow rather than as “piston” flow through the Chalk matrix. This is not explicitly represented in the current form of the extended PDM model.

Since the high porosity of the matrix (15 to 45%) is not readily drained, the effective groundwater storage depends primarily on the fracture network and larger pores and is probably only 1% of the total saturated Chalk volume. Pumping tests yield typical values of 0.002 for the storage coefficient and 500 m^2 d^{-1} for transmissivity. However, estimates of hydraulic conductivity using a gas permeameter give typical values of 0.0025 m d^{-1}, implying a very low transmissivity of 0.25 m^2 d^{-1} for a 100 m thick aquifer. This serves to highlight the importance of secondary permeability to groundwater flow in Chalk. Further details of the Chalk aquifer of the South Downs can be found in the recent survey edited by Jones and Robins (1999) and in Thompson *et al.* (1988).

Further evidence of the hydrogeological response of the Chalk to storm rainfall comes from insights gained from the analysis of records from notable extreme floods. The “Chichester Flood” of January 1994, whilst modest by international standards, was noteworthy in the UK and resulted in relatively large damages in the Lavant catchment and Chichester in particular (Posford Duvivier, 1994). Whilst groundwater levels were fairly low at the start of the winter, these rose quickly from 28 November to mid January as a result of 350 mm of rain, 40% of which fell in just six days. The well at Chilgrove became artesian from 7 January for 18 days and flows in the Lavant rose from 0.3 m^3 s^{-1} in mid-December to an peak of 8.1 m^3 s^{-1} on 10 January, as estimated by Taylor (1995). The normally slow-responding flow regime became flashy as the Chalk became saturated. Above a well level of 69.5 mAOD at Chilgrove, river flows started to increase markedly faster than groundwater levels. It has been speculated that above this level a zone of high permeability Chalk functions as an overflow, providing a rapid flow path to the river system. Such threshold effects are difficult to anticipate without long records of flooding and their explicit inclusion in the extended PDM is problematic for this same reason.

6 Model application to the Lavant and Ems

The strategy to be used for calibrating and assessing the extended PDM has previously been formulated and set out in Section 5.2. The basic idea is to employ a “split sample scheme” where independent periods of record are used for model calibration and evaluation.

A further form of assessment employs sensitivity analyses to explore the different forms of data input to the model including additional raingauges, use of weather radar, the form of PE estimate and the value of near real-time access to abstraction data. The model assessments and sensitivity analyses applied to the Lavant and Ems catchments are used to draw conclusions and recommendations for the future operational application of the extended PDM rainfall-runoff model.

Following the assessments and sensitivity analyses, a “recalibration” of the PDM parameters for the Lavant is presented in Section 6.3. This recalibration has more of a focus on modelling the short-term flashy response and rising limbs of significant flood events. Finally all the models are assessed in “forecast mode”, emulating how the models will be used in real-time in support of flood warning and alleviation scheme operation.

6.1 Model calibration and assessment

6.1.1 Lavant catchment

A initial calibrated form of the extended PDM existed for the Lavant at Graylingwell as described by Moore and Bell (2002). This “Moore-Bell calibration” used a different approach and datasets to those agreed during this project and which resulted in the “Project calibration” discussed in this section. The main differences are summarised in Table 6.1.

Table 6.1 Summary of main differences in the approach and datasets used to calibrate the extended PDM for the Lavant between the Moore-Bell calibration (2002) and the project calibration.

	Moore-Bell calibration	Project calibration
Raingauge data	• Chichester (weight 1.0). • No additional QC of EA data.	• Chichester (weight 0.45), Walderton (0.55). • Additional QC and infilling performed by CEH.
Potential Evaporation data	• Sine curve profile. • Annual PE of 511mm. • PE distributed evenly through the day.	• Historical MORECS PE data. • Long term (1971-2007) annual average is 615mm. • Diurnal profile imposed.
Calibration Period	8 Dec 1991 to 1 Jan 1997	1 Oct 1991 to 30 Sep 1996

The Moore-Bell calibrated model used West Dean Nursery as the source of well level data. This was chosen over other well level sites within the Lavant catchment as it exhibited good behavioural agreement with the flow record, partly due to its proximity

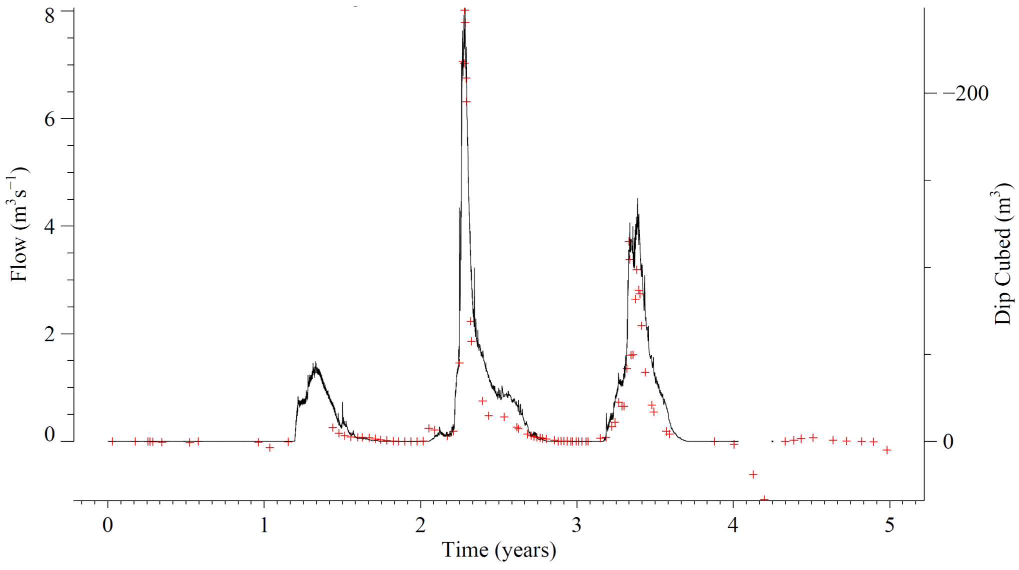

Figure 6.1 Observed hydrographs of flow in the Lavant and well levels (after transformation) at West Dean Nursery over the calibration period (water years 1991/92 to 1995/96).

to the river channel. Hydrographs of the Graylingwell flow and West Dean Nursery well level are presented in Figure 6.1. Well levels have been transformed using a datum shift of -33.5m and then cubed so as to highlight the good correspondence with river flow. This dominance of groundwater level control led to the calibrated model having its fast response flow captured primarily through the groundwater, with correspondingly little "surface" flow. The large periods of missing flow data during the water year 1995/6 (see Section 4.3.1) are also evident.

The Moore-Bell calibration was used as the starting point in developing the project calibration. A mixture of manual and automatic calibration has been used to explore the parameter space and arrive at the final set of calibrated model parameters. Both sets of model parameters are presented in Table 6.2.

The MORECS PE used in the present study has a 20% (104 mm) larger annual average compared to the sine curve profile used by Moore and Bell (2002); the latter had an annual total of 511 mm, taken as typical for the UK. This resulted in changes needing to be made to the model parameters to align the water balance of the model closer to the observations. This was principally achieved by adjusting the rainfall factor (f_c) and evaporation exponent (b_e) parameters. Specifically, to compensate for PE data that was too low in the Moore-Bell calibration the conversion to actual evaporation needed to be maintained closer to potential levels, decreasing less slowly with increasing soil moisture deficit (achieved through a high value for the exponent).

A further change worth noting was introducing a non-zero minimum store capacity c_{min} of 54 mm to delay the onset of modelled flow. Note that the maximum water holding capacity of the catchment, $S_{\max} = (bc_{\min} + c_{\max})/b+1$, where $c_{\max}$ is the maximum store

Table 6.2 Extended PDM model parameters for the Lavant and Ems catchments.

Model parameter	Symbol	Lavant Moore and Bell (2002)	Lavant	Ems
Rainfall factor	f_c	0.87	1.0	1.19
Time delay	τ_d	0.0	0.0	0.0
Soil moisture				
min. depth	c_{min}	0.0	54.0	54.0
max. depth	c_{max}	430.0	669.0	505.0
Exponent	b	0.25	0.51	0.05
Evaporation exponent	b_e	1000.0	20.0	17.0
Recharge model				
time constant	k_g	227600.0	220000.0	300000.0
soil tension threshold	S_t	85.0	119.0	107.0
Exponent	b_g	13.0	5.87	2.05
Surface storage coefficient	k_s	925.0	1000.0	6.1
Groundwater storage				
Exponent	m	3.0	3.0	3.0
coefficient	k_b	340.0	349.0	360.0
Underflow				
time constant	k_u	38850.0	32500.0	218000.0
maximum deficit	D_u	1712.0*	1456.0	900.0
Spring fraction	α	0.0	0.0	0.0
Abstraction				
Constant	c_A	0.0	0.0	0.0
Factor	f_A	1.0	1.0	1.0
Well level		West Dean N.	West Dean N.	Pitlands Farm
max. groundwater storage	S^g_{max}	1192.0	1074.0	261.0
specific yield	Y_s	0.0286	0.032	0.14
Datum	h_w	83.76	83.76	62.43
Constant flow	q_c	0.0	0.0	0.0

* Note that the parameter D_u (previously $D_{\max}$) was incorrectly reported as $D_u - S^g_{\max}$ =1712-1192=520 in Moore and Bell (2002)

capacity and b is a shape parameter that controls how the frequency of store sizes varies between c_{min} and $c_{\max}$ across the catchment ($b=1$ gives the same frequency for all store sizes). For the Moore-Bell calibration $S_{\max}$ has a value of 344 mm compared to 461 mm for the project calibration, about a ¼ less storage capacity.

In common with the Moore-Bell calibration, it was found that there was not enough evidence to quantify the "external springs" component explicitly and therefore it was not invoked (i.e. the spring fraction α was set to zero). In this regard the "underflow component" is best considered as being a gross measure of the net water transfers out of the catchment not measured at the gauged outlet. Note that an attempt was made to quantify spring flows via analysis of the Costers Brook at Cocking record (Section 5.3) and through mapping spring locations (Section 5.4), but this proved insufficient to introduce as model support.

The performance of the model over calibration and evaluation periods is assessed using the R^2 Efficiency and *rmse* performance measures in Table 6.3 These measures are calculated both for flow and well level as simulated by the model, using West Dean Nursery as the well level site. With R^2 values in excess of 0.9 the flow performance can be judged as very good and demonstrates good consistency across calibration and evaluation periods. Good performance is also achieved for the flood water years of 1993/94 and 2000/01, although not quite so good for the latter. Similar comments can be made when well levels are used for assessment, although the evaluation period performance drops to 0.761 for R^2 Efficiency. This value is affected by periods of missing well level data over which the statistic is not calculated.

Table 6.3 R^2 and *rmse* statistics for flow in the Lavant and well levels at West Dean Nursery.

Period	Flow		Well level	
	R^2	*rmse*	R^2	*rmse*
Calibration	0.934	0.266	0.965	0.704
Evaluation	0.907	0.333	0.761	1.228
Water Year 1993/94	0.948	0.350	0.918	2.098
Water Year 2000/01	0.889	0.597	0.873	0.770

The R^2 Efficiency measure arguably gives a biased good impression of performance for groundwater catchments due to the long periods of receding and zero flows; it is possible to threshold the statistic to consider flows only above a minimum level but this has not been done here. A more revealing assessment of model performance during floods is achieved through visual inspection of the flow and well level hydrographs. These are shown in Figure 6.2 for the calibration period and Figure 6.3 for the evaluation period. The right column of Figure 6.4 provides more detail for the water years 1993/94 (in calibration period) and 2000/01 (in evaluation period). Signatures of performance - such as the times of start and cessation of flow, magnitudes of the flow peaks and the peaks and troughs of the well level – are all seen to be reasonably well reproduced by the model.

These figures also include time-series of the rainfall and abstraction data used as input and the modelled soil moisture deficit and underflows. It is of interest to consider in more detail the constituents of the water balance of the catchment in terms of the forcing variables (rainfall, PE and abstractions), the modelled flows and underflows and the observed flows at Graylingwell. These are summarised as catchment totals in mm separately for the calibration and evaluation periods in Table 6.4. To assess the relative magnitudes of the constituent model outputs (actual evaporation, abstraction, underflow and river flow), these are expressed as a fraction of the rainfall input in brackets. Thus in broad terms actual evaporation dominates at 60%, river flow is next at 20%, underflow at 14% and abstraction least at 7%; there is an implied loss of water to catchment storage of 2%.

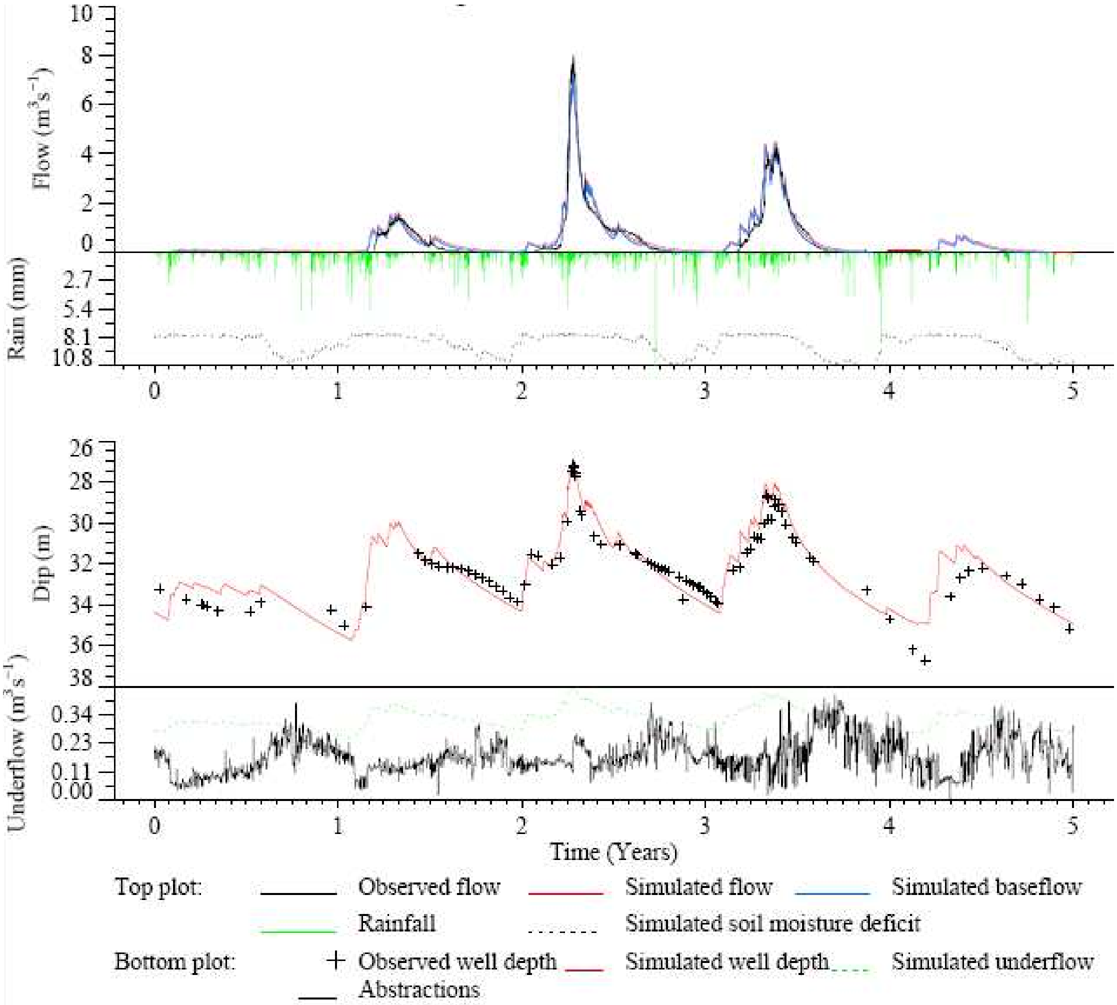

Figure 6.2 PDM model simulations for the Lavant during the calibration period (water years 1991/92 to 1995/96). Observed well depths are for West Dean Nursery.

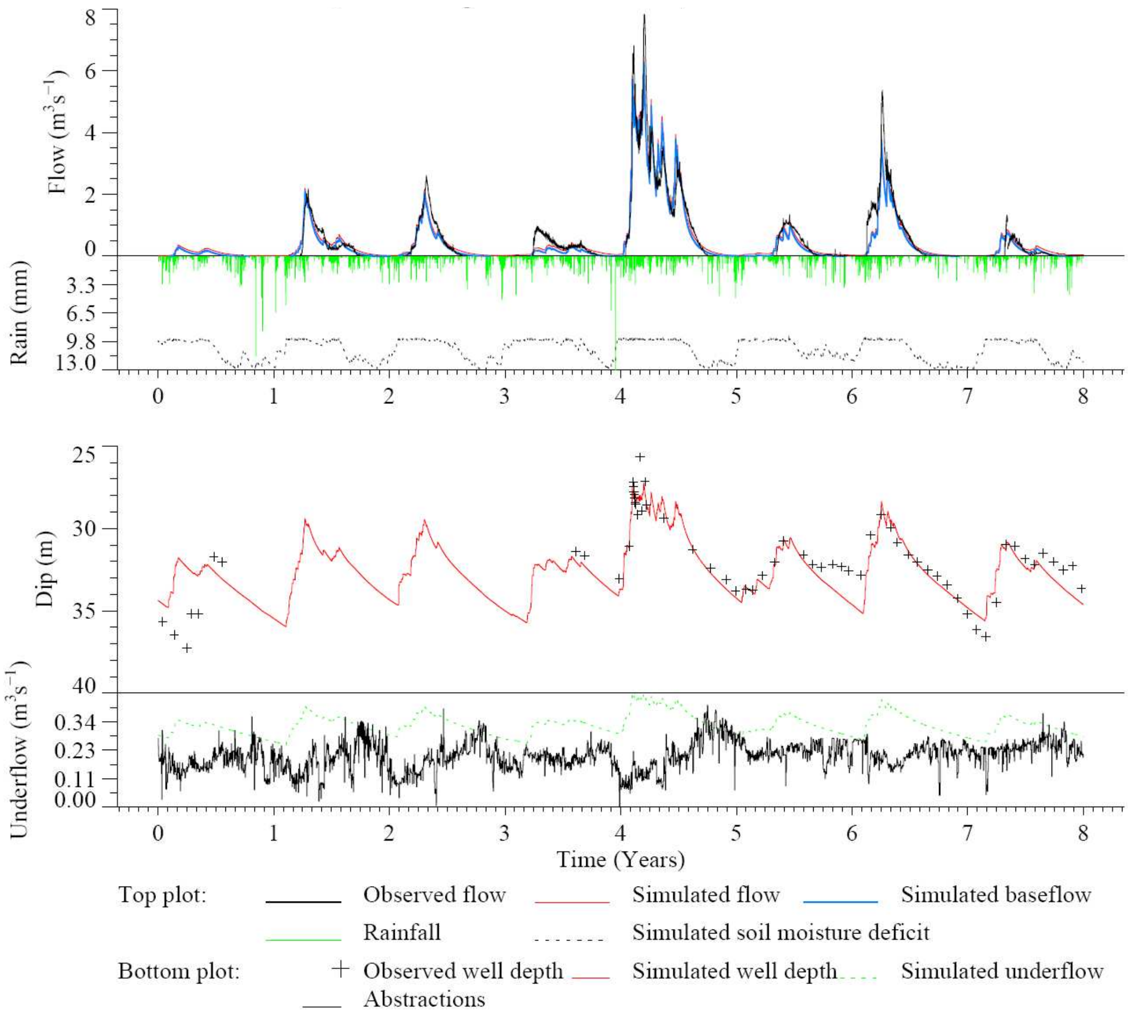

Figure 6.3 PDM model simulations for the Lavant during the evaluation period (water years 1996/97 to 2003/04). Observed well depths are for West Dean Nursery.

When compared to observed river flows Table 6.4 shows there is little bias in the modelled flows over the evaluation period, but a 33% overestimate for the calibration period. This is not clearly apparent in the hydrograph plots and deserves further investigation, but may be related to modelled recessions being too protracted.

It was felt that this model calibration performed sufficiently well to be used for the purpose of sensitivity analysis. For use in flood forecasting, a recalibration has been performed which addresses some issues arising from the approach to calibration presented here. Details can be found in Section 6.3.

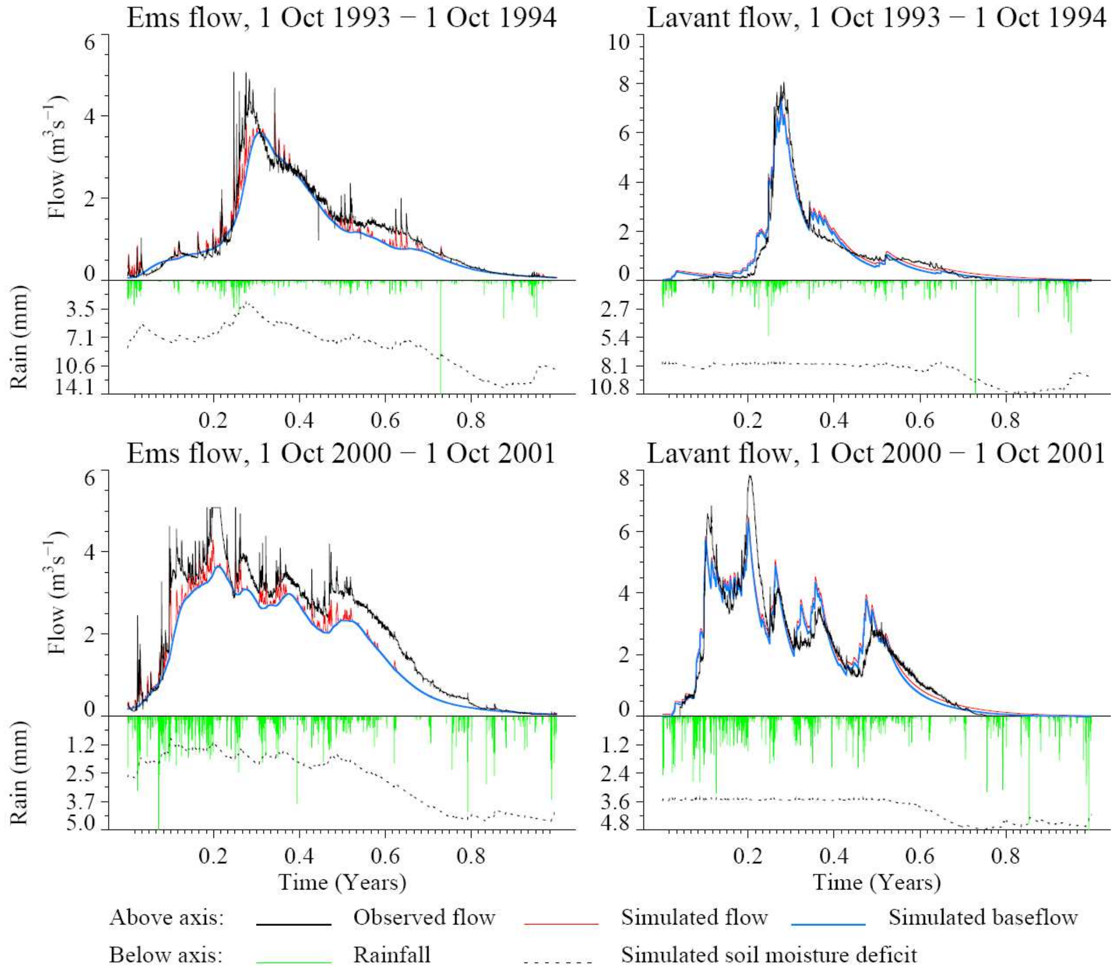

Figure 6.4 PDM model simulations for the Lavant (right- column) and Ems (left-column) over the water years 1993/94 (top row, calibration period) and 2000/01 (bottom row, evaluation period).

Table 6.4 PDM model water balances (mm total) for the Lavant over the calibration and evaluation periods. In brackets is the output component as a fraction of the rainfall input.

	Calibration Period	Evaluation Period
Rainfall	4134	6861
Potential Evaporation	3269	5177
Actual Evaporation	2488 (0.602)	4154 (0.605)
Net Rainfall	1646	2707
Abstraction	278 (0.067)	521 (0.076)
Underflow	589 (0.143)	938 (0.137)
River flow	898 (0.217)	1350 (0.197)
Observed river flow	676	1302
Implied storage change	-119 (-0.029)	-102 (-0.015)

6.1.2 The Ems catchment

Calibration of the Ems to Westbourne catchment began by taking the Project calibrated model parameters for the Lavant at Graylingwell, treating it as essentially as an ungauged catchment transfer. The model calibration was then refined to overcome the shortcomings observed leading to the final parameter set presented in Table 6.2.

Some of the calibration issues encountered are best understood by first looking at the observed flow and well level hydrographs over the calibration period shown in Figure 6.5. Here, well levels at Pitlands Farm have been transformed using a datum shift of -36.5m and then cubed so as to highlight the good correspondence with river flow. The broader rise and fall of the dominant groundwater flow response is clearly reflected in the well level observations. Superimposed on this is a spiky response with very short duration peaks; occasionally the spikes have an anomalous downward behaviour. It is thought that the flashy response component is in part associated with the areas of Clay with Flints cover overlying the Chalk within the Ems catchment but absent from the Lavant (see Figure 5.3).

As with the Lavant, a mixture of manual and automatic calibration has been used to obtain the final calibrated model parameter set presented in Table 6.2. An important difference from the model for the Lavant is the low value (0.05) of the shape parameter b that controls how the frequency of store sizes varies between c_{min} and $c_{\max}$ across the catchment ($b = 0$ gives the same store size throughout the catchment so $S_{\max} = c_{\max}$). With $b = 0.05$ there is a high frequency of stores close to $c_{\max} = 505$ but some stores

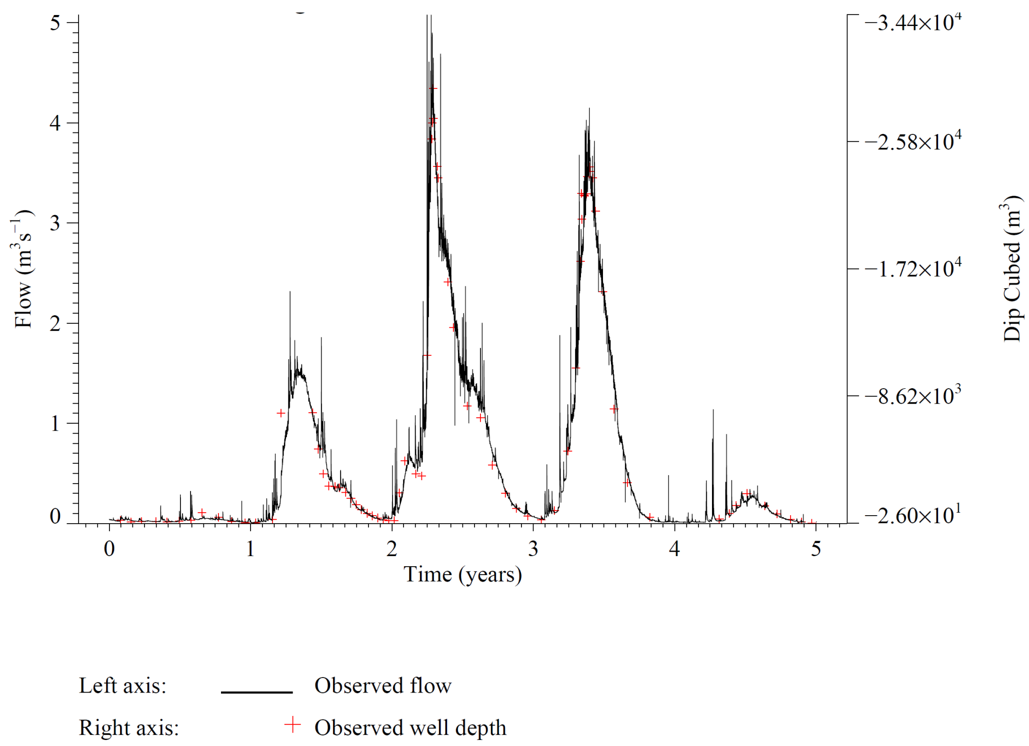

Figure 6.5 Observed hydrographs for flow in the Ems and well levels (after transformation) at Pitlands Farm over the calibration period (water years 1991/92 to 1995/96).

still at capacities down to $c_{min} = 54$ mm. Note that S_{max} has a value of 484 mm, similar to the value of 461 mm for the Lavant. Another important difference is in the surface storage coefficient, $k_s = 6.1$, which generates the flashy surface runoff necessary to capture the fast response highlighted above. In the Lavant this parameter was set to $k_s = 1000$, which led to a smooth surface runoff component. During calibration the possibility of including the effects of augmentation were considered and deemed unnecessary to include. This is due to the small volumes of water involved in the augmentation of 0.013 m^3s^{-1} which is barely distinguishable when inspecting the observed flows and has a negligible impact on flood peaks and their rising limbs.

The performance of the model for the Ems catchment over calibration and evaluation periods was assessed using the R^2 Efficiency and *rmse* performance measures and the results presented in Table 6.5. These measures are calculated both for flow and well level as simulated by the model, using Pitlands Farm as the well level site. As with the Lavant, with R^2 values in excess of 0.9 the flow performance can be judged to be very good and good consistency is obtained across calibration and evaluation periods. Good performance is also achieved for the flood water years of 1993/94 and 2000/01, although, as with the Lavant, not quite so good for the latter. Similar comments can be made when well levels are used for assessment.

Table 6.5 R^2 and *rmse* statistics for flow in the Ems and well level at Pitlands Farm

Period	Flow		Well level	
	R^2	*rmse*	R^2	*rmse*
Calibration	0.937	0.216	0.948	2.084
Evaluation	0.913	0.272	0.949	2.024
Water Year 1993/94	0.940	0.263	0.960	1.585
Water Year 2000/01	0.882	0.506	0.918	2.098

As with the Lavant, a more revealing assessment of model performance is achieved through visual inspection of the flow and well level hydrographs. These are shown in Figure 6.6 for the calibration period and Figure 6.7 for the evaluation period. The left column of Figure 6.4 (presented previously) provides more detail for the water years 1993/94 (in calibration period) and 2000/01 (in evaluation period). Broad signatures of performance - such as the times of start and cessation of flow, magnitudes of the flow peaks and the peaks and troughs of the well level – are all seen to be reasonably well reproduced by the model. On the negative side, the simulated baseflow appears to peak a little late and rather underestimates the observed peak flow. The model is seen to have some ability to reproduce the flashy component of flow but not in detail. Unlike the PDM for PCs software, the research PDM code does not allow interactive 'zooming' to individual peaks or rising limbs. Therefore use of the research PDM code has restricted what it has been feasible to focus on during this calibration. Revisiting the Ems calibration using the PDM for PCs environment would allow a more detailed focus on the flashy response of the model and may result in an improved calibration. This is discussed further in Section 6.5 and forms part of the final recommendations of Section 7.3.

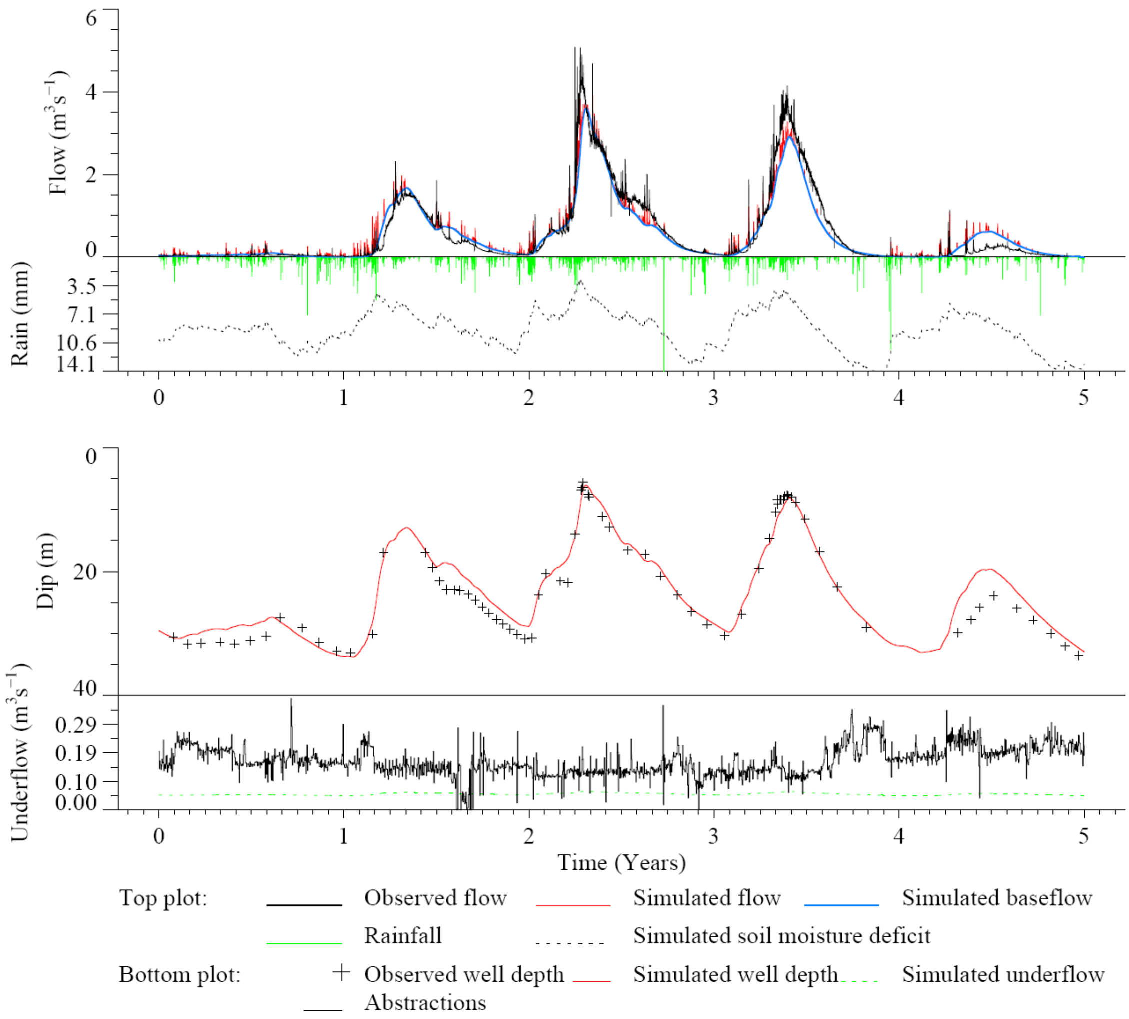

Figure 6.6 PDM model simulations for the Ems over the calibration period (water years 1991/92 to 1995/96). Observed well depths are for Pitlands Farm.

These figures also include time-series of the rainfall and abstraction data used as input and the modelled soil moisture deficit and underflows. As with the Lavant, it is of interest to consider in more detail the constituents of the water balance of the Ems catchment in terms of the forcing variables (rainfall, PE and abstractions), the modelled flows and underflows and the observed flows at Westbourne. These are summarised as catchment totals in mm separately for the calibration and evaluation periods in Table 6.6. To assess the relative magnitudes of the constituent model outputs (actual evaporation, abstraction, underflow and river flow), these are expressed as a fraction of the rainfall input in brackets. Thus in broad terms actual evaporation dominates at 60%, river flow is next at 30%, abstraction at 8 to 9% and underflow least at 3%; there is an implied loss of water to catchment storage of 1 to 2%.

When compared to observed river flows Table 6.6 shows there is little bias in the modelled flows over the calibration period, but an 18% underestimate for the evaluation period. Similarly to the Lavant, simulated flow decreases in relation to observed flow when moving from the calibration to the evaluation period.

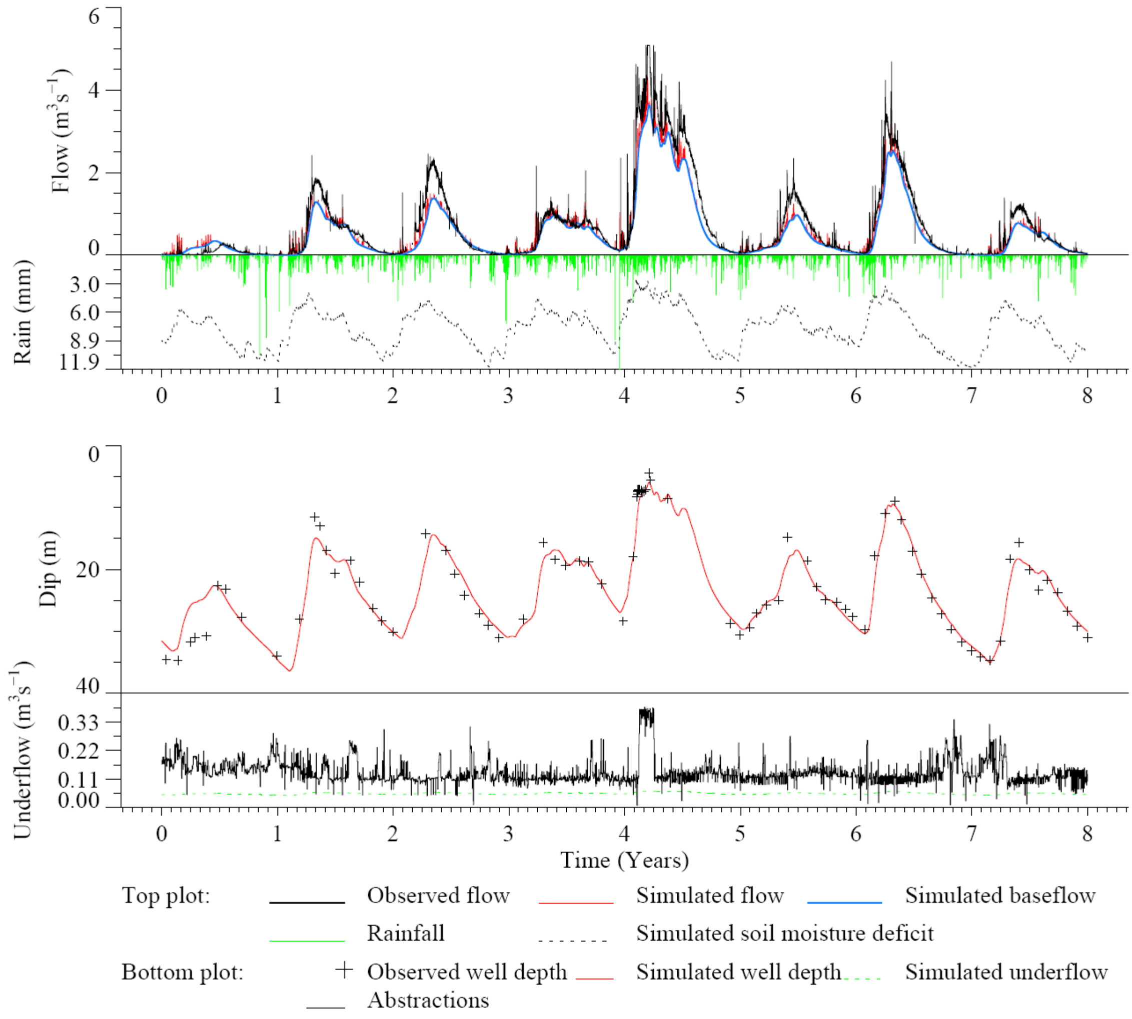

Figure 6.7 PDM model simulations for the Ems over the evaluation period (water years 1996/97 to 2003/04). Observed well depths are for Pitlands Farm.

Table 6.6 PDM model water balances (mm total) for the Ems over the calibration and evaluation periods. In brackets is the output component as a fraction of the rainfall input.

	Calibration Period	Evaluation Period
Rainfall	4869	8146
Potential Evaporation	3269	5177
Actual Evaporation	2918 (0.599)	4879 (0.599)
Net Rainfall	1951	3267
Abstraction	463 (0.095)	671 (0.082)
Underflow	147 (0.030)	235 (0.029)
River flow	1468 (0.301)	2401 (0.295)
Observed river flow	1454	2916
Implied storage change	-127 (-0.026)	-40 (-0.005)

6.2 Model sensitivity analyses

The validity of the various sensitivity analyses are limited by the period of record available for performing each analysis and whether this includes a significant flood peak (e.g. 2000/01). The main reasons for this are: (i) it can be misleading to only look at a few small flow peaks when assessing a model: the ideal situation is to have a long period with several large flow peaks, (ii) the Lavant and Ems models can require some time to 'warm up' in simulation-mode because of the large model storages needed to model the observed seasonal baseflow responses, and (iii) some readjustment of the model parameters may be required for different data sources, e.g. for the different rainfall estimators the rainfall factor may need reassessing.

6.2.1 Raingauge data

As discussed in Section 4.1.4, the raingauge network has improved over the modelling period studied. Therefore a model sensitivity analysis has been recommended using the improved raingauge network: this analysis is presented here. The raingauge weights trialled for the Ems and Lavant catchments have been listed in Table 4.2. For the Lavant this included and excluded the Chichester raingauge as it is not currently part of the telemetry network. The sensitivity analysis is discussed for each catchment in turn below.

Lavant catchment

For the Lavant catchment there are several recent additions to the raingauge network that are obvious candidates for improving the catchment average rainfall estimation. In particular the raingauge at Chilgrove is situated inside the catchment and Duncton is just to the North East as shown in Figure 3.1. These two raingauges also have relatively high elevations (see Table 3.1) so are more representative of the wetter portions of the catchment. It should be noted that all raingauges have been quality controlled by CEH for the modelling period except for Westergate. However, Westergate only contributes 8 or 12% to the weighting schemes used so this is not a major concern.

The most recent addition to the raingauge network is Duncton which was installed in June 2002: see Table 4.1. The remaining period of evaluation (June 2002 to October 2004) includes a reasonable flow peak during the 2002/03 water year. However, as the period available is not particularly long, it is not possible to perform a meaningful sensitivity analysis or to consider adjustment of the rainfall factor. To allow the PDM to 'warm-up' sufficiently before the 2002/03 flow peak for the weighting schemes that use Duncton, the PDM simulations were run over the entire evaluation period and treated the Duncton record as missing until June 2002.

The PDM simulations using the three different weighting schemes listed in Table 4.2 are presented in. Figure 6.8. This clearly shows the difficulty in attempting to ascertain which raingauge weighting scheme is optimal when only such a short record is available for analysis, especially as it does not encompass either of the recent major flow peaks. Therefore, it is recommended for operational implementation of the extended PDM that it should employ the raingauge weighting scheme used in model calibration. This means that the Chichester raingauge would need to be added to the telemetry network.

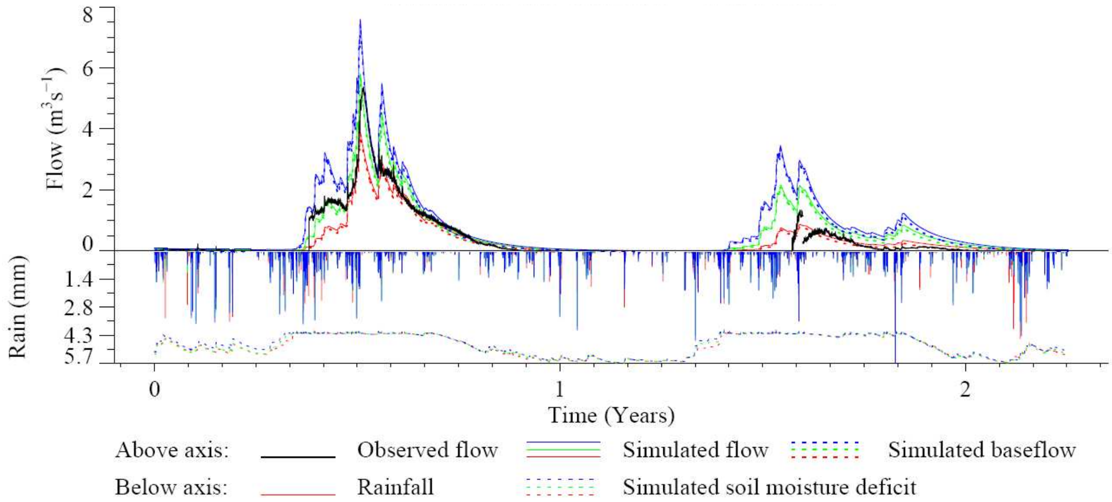

Figure 6.8 Raingauge sensitivity analysis: PDM model simulations for the Lavant (period 1 July 2002 to 1 October 2004) using different raingauge weighting schemes. Red line is the scheme used during calibration, green line uses the improved network including Chichester, blue line uses the improved network excluding Chichester.

Figure 6.8 highlights that if a different data source is used as input to the PDM, then some model recalibration is likely to be necessary. For the case of using different raingauge networks, the expected change in catchment average rainfall can be accommodated by adjusting the rainfall factor f_c with reference to SAAR information in Table 4.2. The results including this SAAR-adjusted rainfall factor are presented in Figure 6.9. The two improved networks now appear to show very similar behaviour which is clearly different from that of the original network.

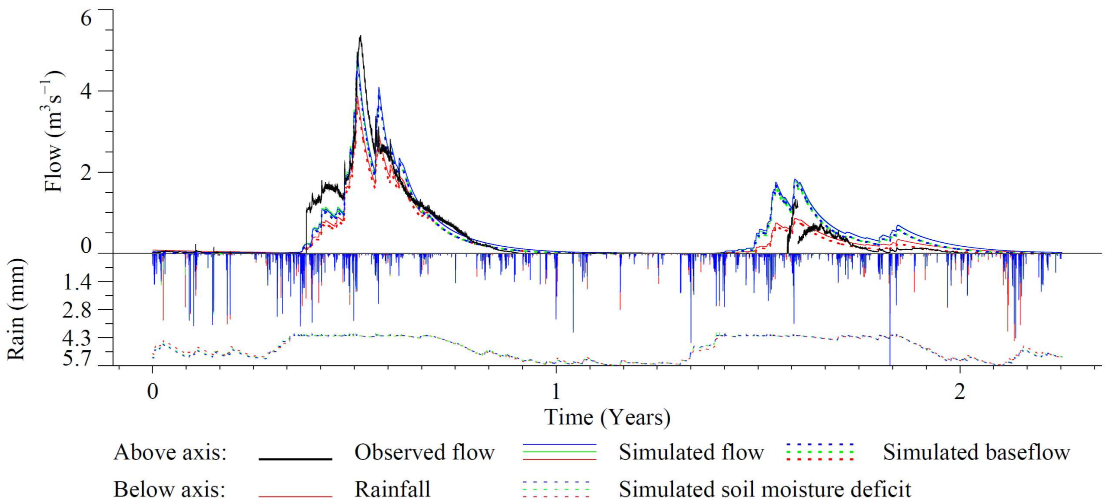

Figure 6.9 Raingauge sensitivity analysis: SAAR-adjusted PDM model simulations for the Lavant (period 1 July 2002 to 1 October 2004) using different raingauge weighting schemes. Red line is the scheme used during calibration, green line uses the improved network including Chichester, blue line uses the improved network excluding Chichester.

Recommendation

- **Raingauge scheme for the Lavant catchment**. It is recommended that the Chichester raingauge be put on telemetry and used in the weighting scheme for the Lavant catchment using the following weights: Chichester 0.55 and Walderton 0.45.

Ems catchment

For the Ems catchment the most obvious raingauge for improving the catchment average rainfall estimation is Chilgrove which is situated just to the east of the catchment as shown in Figure 3.1. Chilgrove also has a significantly higher elevation and SAAR compared to Walderton and Havant (see Table 3.1) so is more representative of the wetter portions of the catchment.

The Chilgrove record begins 2 October 1999: see Table 4.1. Therefore there is long enough period available to perform a meaningful sensitivity analysis on its inclusion. The remaining period of evaluation (October 1999 to October 2004) also includes the 2000/01 major flood peak. The PDM simulations using the two different weighting schemes listed in Table 4.2 are presented in Figure 6.10; Figure 6.11 shows the equivalent results after an adjustment for gauge to catchment SAAR has been included in the model formulation. These results clearly show the benefit to the PDM simulations of including Chilgrove in the raingauge weighting scheme. For example, the simulated peaks during the first water year (1999/2000) are similarly good for both weighting schemes whilst the Chilgrove based scheme performs notably better for the remaining years. This is confirmed by the R^2 and *rmse* statistics presented in Table 6.7 with a significant improvement in R^2 from 0.921 to 0.961 (0.936 with SAAR adjustment) obtained when the Chilgrove raingauge is included.

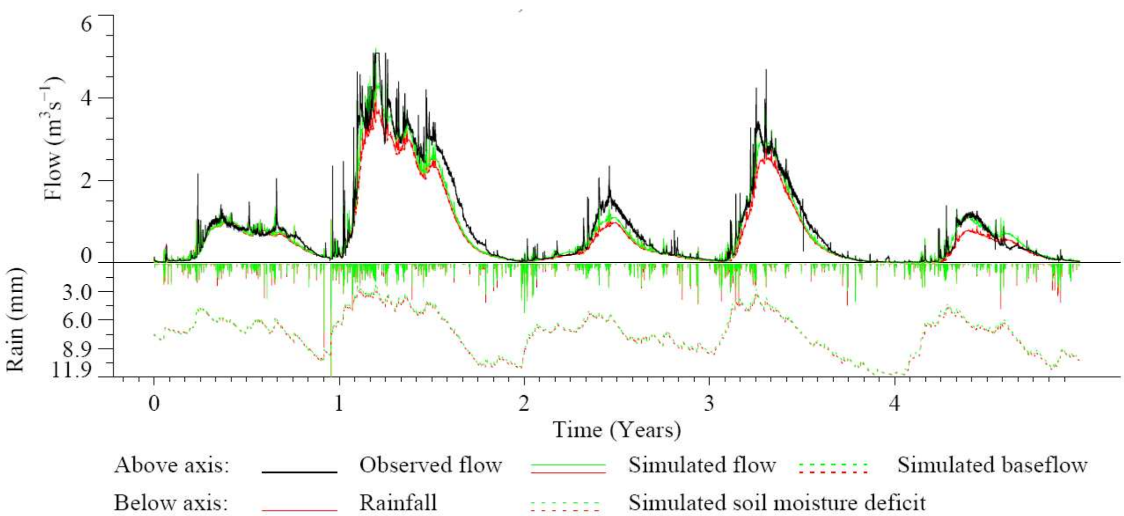

Figure 6.10 Raingauge sensitivity analysis: PDM model simulations for the Ems using different raingauge weighting schemes. Red line is the scheme used during calibration, green line uses the improved network. The period shown covers water years 1999/2000 to 2003/04.

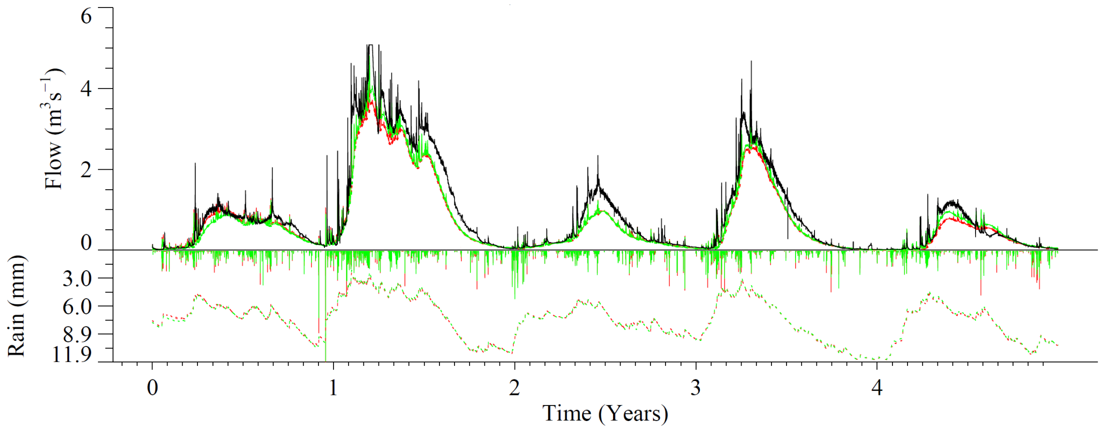

Figure 6.11 Raingauge sensitivity analysis: SAAR-adjusted PDM model simulations for the Ems using different raingauge weighting schemes. Red line is the scheme used during calibration, green line uses the improved network. The period shown covers water years 1999/2000 to 2003/04.

Table 6.7 R^2 and *rmse* statistics (for flow) for different raingauge weighting schemes for the Ems over the evaluation period (water years 1999/2000 to 2003/04).

Raingauge weighting scheme	**Ems**	
	R^2	*rmse*
Modelling	0.921	0.293
Improved Network	0.961	0.205
Improved Network (SAAR-adjusted)	0.936	0.264

Recommendation

- **Raingauge scheme for the Ems catchment**. It is recommended that the Chilgrove raingauge be used in the weighting scheme for the Ems catchment using the following weights: Walderton 0.51, Chilgrove 0.36 and Havant 0.13.

6.2.2 Radar data

Section 3.2.3 recommended that a sensitivity analysis on the use of radar rainfall as input to the extended PDM be restricted to use of the Nimrod composite radar data for forming catchment average rainfall. This type of radar data became available in November 2003, so less than a year of data overlaps with the model evaluation period (November 2003 to October 2004) and this includes only a very small flow peak. As suggested in Section 3.2.3 it is not possible to form a meaningful sensitivity analysis under these conditions. Figure 6.12 presents the PDM simulations obtained using both the radar and raingauge data for the Ems catchment. This clearly shows the limitations of the analysis and it is unwise to draw any conclusion from these hydrographs. This sensitivity analysis is not worth revisiting until further radar records encompassing significant flood events become available.

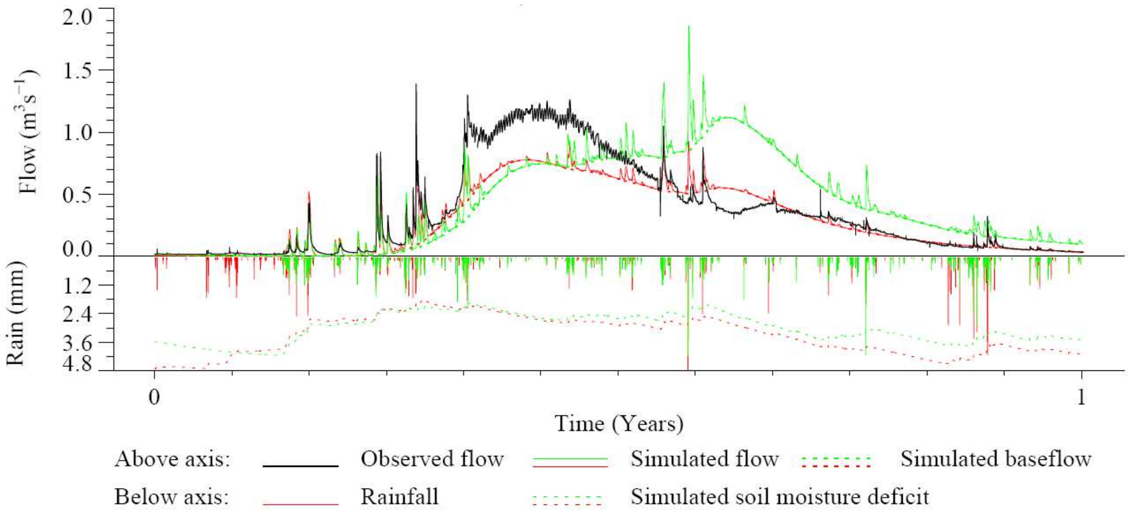

Figure 6.12 Radar rainfall sensitivity analysis: PDM model simulations for the Ems using radar and raingauge based rainfall estimates. Red line is the raingauge weighting scheme used during calibration, green line uses radar data. The period shown is the water year 2003/04.

6.2.3 Potential evaporation data

A potential evaporation profile has been used for modelling that is based on use of the historical time-series of MORECS PE monthly totals for MORECS square 183 over the Lavant and Ems catchments. This time-series has been interpolated between months and a standard diurnal profile imposed to obtain 15 minute totals. This historical PE profile was recommended as a consequence of the review of alternatives presented in Section 3.4. Also recommended was to perform a sensitivity analysis using alternative profiles based on long-term average MORECS PE and using a standard sine curve annual profile respectively. These sensitivity analyses are reported on here. As discussed in Section 3.4 a sensitivity analysis using MOSES PE will not be carried out since these estimates only became available in July 2005 and there have been few notable flood peaks since then.

Table 6.8 presents the model performance statistics obtained when using as PE input to the models the three PE estimators: MORECS historical, MORECS long-term average and the standard sine curve. Figure 6.13 contrasts hydrographs obtained using MORECS historical and MORECS long-term average PE as input to the models whilst

Figure 6.14 compares the hydrographs obtained using MORECS historical with the sine curve profile of PE.

It is seen that the switch from MORECS historical to the long-term average annual MORECS profile makes little difference to the simulated hydrographs and the R^2 Efficiency performance measure changes by less than 2%. Slightly larger changes are noticeable when the MORECS historical profile is switched to the sine curve profile. For the Ems over the evaluation period the change is to actually improve the R^2 and *rmse* statistics, since the flow was underestimated in this case (see Section 6.1.2). The overall degradation in performance when switching to use the sine curve PE profile can be attributed to its use of a typical UK annual average value of 511 mm: it was this profile that was used by Moore and Bell (2002). This value is not representative of PE over the Lavant and Ems as discussed in Section 6.1.1 and clearly adversely affects the modelled water balance. A recalibration of the PDM parameters for use with this sine curve profile would result in improved model performance, serving to compensate for the poor PE estimate.

Recommendation

- **Potential evaporation profile**. It is recommended that the MORECS long-term annual average profile be used for future forecasting, as readily available in real-time. In unusual years, a tactical review of this recommendation might be considered. A future trial of MOSES PE, available in near real-time, should be made when sufficient records and flood events are to hand.

Table 6.8 R^2 and *rmse* statistics (for flow) for different sources of potential evaporation data over the evaluation period (water years 1995/96 to 2003/04).

Source of potential evaporation	Lavant		Ems	
	R^2	*rmse*	R^2	*rmse*
Historical MORECS	0.907	0.333	0.913	0.272
Long-term annual MORECS profile	0.896	0.351	0.912	0.274
Sine curve	0.827	0.454	0.917	0.265

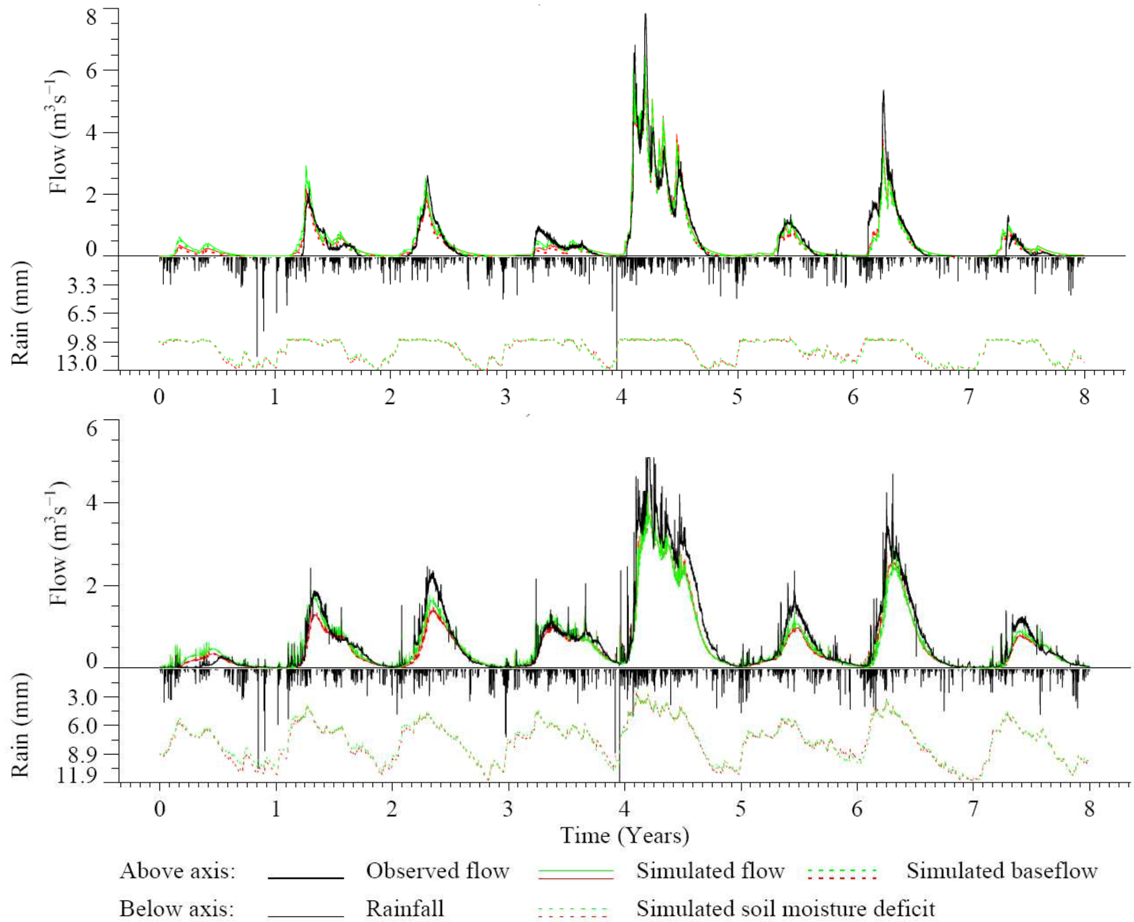

Figure 6.13 Potential evaporation sensitivity analysis: PDM model simulations for the Lavant (top) and Ems (bottom) using MORECS historical PE (red line) and the MORECS long-term average annual profile (green line) over the evaluation period (water years 1996/97 to 2003/04).

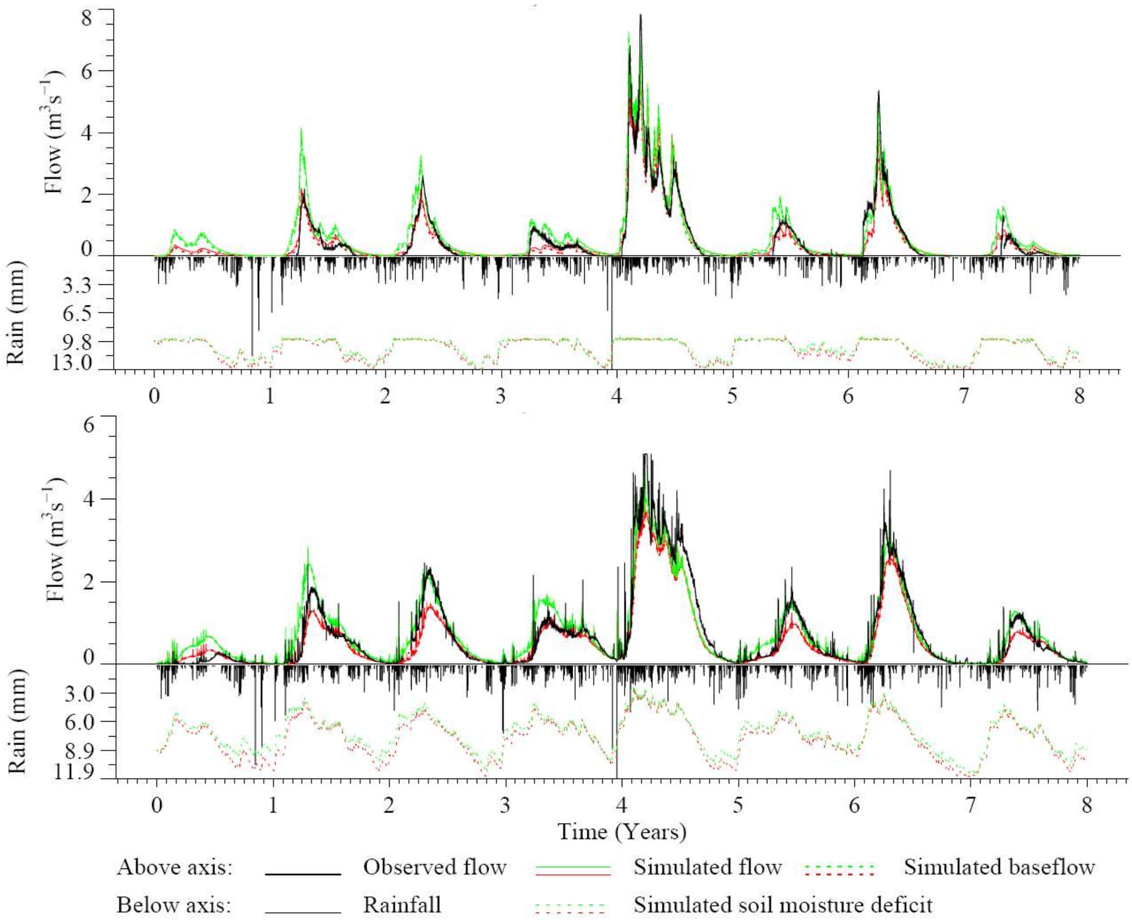

Figure 6.14 Potential evaporation sensitivity analysis: PDM model simulations for the Lavant (top) and Ems (bottom) using MORECS historical PE (red line) and a standard sine curve profile (green line) over the evaluation period (water years 1996/97 to 2003/04).

6.2.4 Abstraction data

A sensitivity analysis has been carried out using a long-term annual abstraction profile in place of the actual time-series of abstractions, as previously recommended in Section 3.6.1. This has relevance to the real-time application of the models when timely access to the abstraction data may not be straightforward. The annual profile was derived for each abstraction location in turn by interpolating between the long-term average monthly abstractions. The interpolation method used is the same as that for the long-term MORECS profile which ensured the monthly long-term totals were preserved: see Section 3.4.

The annual abstraction profile for the Ems is presented as a green dashed line in the bottom plot of Figure 6.15 and is clearly smoother than the actual daily abstraction data (red dashed line). However, the impact on the simulated flows or well levels of using this annual profile rather than the actual abstraction data is barely detectable. The Lavant is equally insensitive to use of the annual abstraction profile as confirmed by the R^2 and *rmse* statistics presented in Table 6.9 for the flow data and Table 6.10 for the well level data (the apparent sensitivity for the Lavant in part reflects the periods of missing well level records previously commented on).

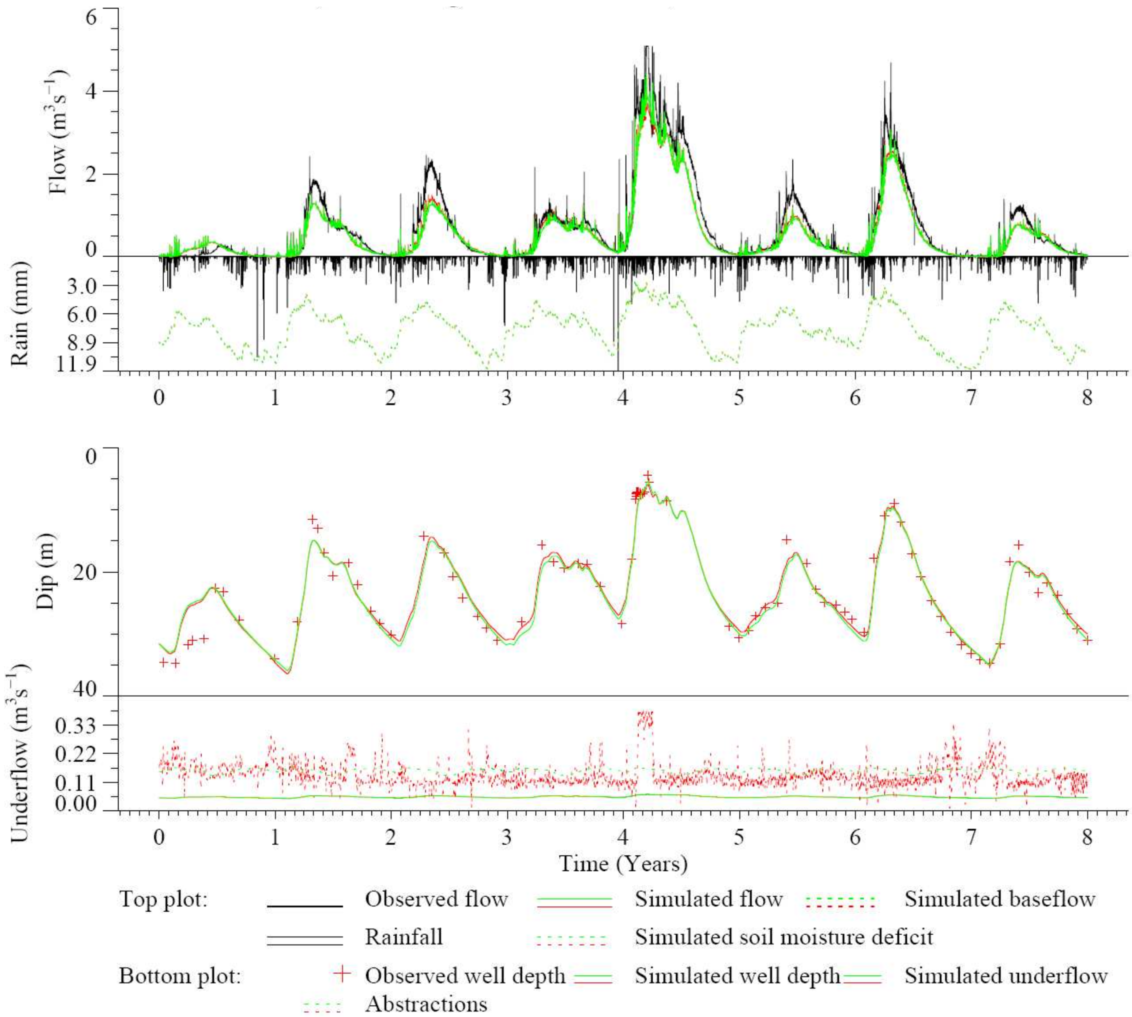

Figure 6.15 Abstraction data sensitivity analysis: PDM model simulations for the Ems using actual daily abstraction data (red lines) and a long-term annual profile (green lines) over the evaluation period (water years 1996/97 to 2003/04).

Table 6.9 R^2 and *rmse* statistics (for flow) for different abstraction profiles over the evaluation period (water years 1996/97 to 2003/04).

Source of abstraction data	Lavant		Ems	
	R^2	*rmse*	R^2	*rmse*
Historical daily data	0.907	0.333	0.913	0.272
Long-term annual abstraction profile	0.910	0.328	0.901	0.290

Table 6.10 R^2 and *rmse* statistics (for well level) for different abstraction profiles over the evaluation period (water years 1996/97 to 2003/04).

Source of abstraction data	Lavant		Ems	
	R^2	*rmse*	R^2	*rmse*
Historical daily data	0.761	1.228	0.945	2.036
Long-term annual abstraction profile	0.828	0.767	0.935	2.215

Due to the success of modelling using the annual abstraction profile it is recommended that this approach be used during the typically two-month delay in receiving the abstraction data from the water companies. Further, if there are significant costs or difficulties in supplying the daily abstraction data to the NFFS system then the annual profile can be used with little or no loss in modelling performance (but this would need to be reviewed if the abstraction regime changed significantly).

Recommendation

- **Annual abstraction profile for PDM modelling**. The long-term annual abstraction profile is recommended to be used in forecasting until abstraction data are received from the water companies, typically two-months in arrears of real-time. Further, if there are significant costs or difficulties in supplying the daily abstraction data to the NFFS system then the annual profile can be used with little or no loss of modelling performance (but this would need to be reviewed if the abstraction regime changed significantly).

6.3 Model recalibration

Calibration of the PDM models presented for the Lavant and Ems in Section 6.1 focussed on obtaining good R^2 Efficiency and visual performance over the entire calibration period. This was deemed sufficient to perform the sensitivity analyses of Section 6.2. For use in flood forecasting, where the response of the modelled flows to rainfall events over short time scales is important, it is apparent that more attention must be paid to calibrating the fast response parameters of the PDM. In this section, a recalibration of the parameters of the PDM model for the Lavant is presented, focussing on those short time scales as well as taking the opportunity to address other issues with the model of Section 6.1.1. A similar recalibration for the Ems has not been performed due to limitations of the project scope, but similar outcomes would be expected should this be done in the future.

6.3.1 Lavant model recalibration

A number of shortcomings in the calibration of the model for the Lavant were recognised (henceforth referred to as the ‘original’ calibration). These included the effect of a biased rainfall estimator on the water balance of Table 6.4 and problems with prediction of dry periods. To address these, a recalibration was performed with rather different priorities to those focussed on in Section 6.1.1.

The original calibration paid attention to obtaining good R^2 Efficiency and visual performance over the entire calibration period. However, the resulting catchment model has a small and smooth surface flow component with the main simulated flow variability being represented through the baseflow component. Also, requiring that the rainfall factor f_c be unity did not recognise that the weighted combination of raingauge values would be biased as an estimator of the topographic catchment rainfall (note that the topographic and subsurface catchment boundaries may differ). Specifically, with reference to Table 4.2, the two raingauges used would lead to an expected catchment annual average rainfall of 782mm, compared to the standard (SAAR 1961-90) value of 922mm. This discrepancy is compensated for in the model calibration so as to reduce actual evaporation and underflow accordingly. However, there was interest not only in the flow simulation but also in understanding the make-up of the catchment water balance. Moreover, by paying attention to the model's physical interpretation at each step, the model would be more amenable to physically-based adjustment (rather than recalibration), for example when using an alternative catchment average rainfall estimator (e.g. radar rainfall).

Against this background, a recalibration was performed with the rainfall factor set at 1.18 to align the raingauge rainfall estimator to the topographic catchment SAAR over the long-term. More effort was made to resolve the flashy response of the surface runoff. Greater attention was also placed on getting the initiation and cessation of flow right, rather than optimising the R^2 statistic, and a closer eye was kept on the water balance. As shown in Figure 6.1, the well level observations were transformed to visually match the 'baseflow' component of the observed flow record. This allowed identification of the approximate well depth (33.5m) at which the observed flow initiated and ceased. In terms of the extended model parameters, this depth corresponds to the product $S^g_{\max} Y_s$ (see equations 2.8 and 2.11) and therefore reduces the number of parameters that need to be calibrated by one. Although not done here, it would also be possible to estimate the product $Y_s k_b$ from a plot of flow against well depth. These two products would allow both S^g_{max} and Y_s to be estimated via k_b and would reduce the number of model parameters by two. This approach to calibration more fully highlights the utility of well level data for calibrating the extended PDM and avoids attempting an 'independent' calibration to the well level observations.

Model calibration of the PDM can be a delicate procedure, with the additional parameters of the extended PDM bringing further parameter interdependence. Unfortunately, the CEH research code does not include the full range of visualisation support tools enjoyed by the PDM for PCs product software such as the interactive 'pan and zoom' functionality that aids the model calibration task. Development of the product code to embrace the extended PDM model for groundwater catchments would improve the ease and success of calibration considerably.

The parameters of the recalibrated model are compared with those of the original model in Table 6.11. Almost all parameters have been changed somewhat, though most variation is seen in f_c, k_s, S^g_{max} and Y_s mentioned above. Significantly, the probability-distributed soil moisture storage component is greatly increased in depth, with $S_{\max}$ now equal to 834mm for the catchment.

Flow and well level hydrographs are shown in Figure 6.16. The visual impression of model performance remains good, though some problem with an overly large flashy response prior to commencement of flow is apparent. More detailed flood hydrographs for much shorter periods are shown in Figure 6.17 and Figure 6.18, where the potential for the model to capture flashy responses is well demonstrated.

Table 6.11 Extended PDM model parameters for the Lavant catchment before and after recalibration.

Model parameter	Symbol	Original Calibration	Recalibration
Rainfall factor	f_c	1.0	1.18
Time delay	τ_d	0.0	0.0
Soil moisture			
min. depth	c_{min}	54.0	137.0
max. depth	c_{max}	669.0	1417.1
Exponent	b	0.51	0.71
Evaporation exponent	b_e	20.0	21.4
Recharge model			
time constant	k_g	220000.0	301535.0
soil tension threshold	S_t	119.0	99.4
Exponent	b_g	5.87	2.69
Surface storage coefficient	k_s	1000.0	5.0
Groundwater storage			
Exponent	m	3.0	3.0
coefficient	k_b	349.0	413.4
Underflow			
time constant	k_u	32500.0	12683.8
maximum deficit	D_u	1456.0	2049.8
Spring fraction	α	0.0	0.0
Abstraction			
Constant	c_A	0.0	0.0
Factor	f_A	1.0	1.0
Well level		West Dean N.	West Dean N.
max. groundwater storage	S^g_{max}	1074.0	1641.0
specific yield	Y_s	0.032	0.0204
Datum	h_w	83.76	83.76
Constant flow	q_c	0.0	0.0

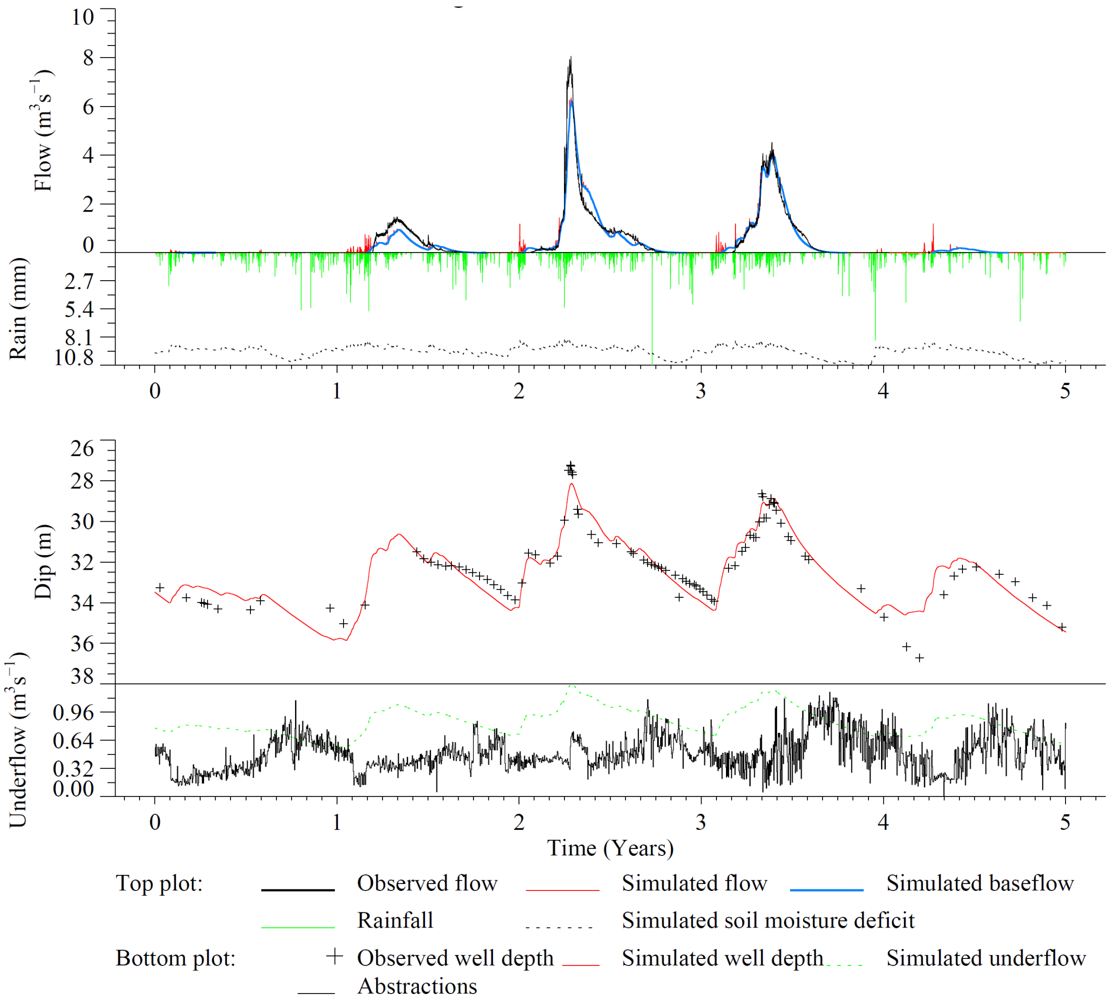

Figure 6.16 Recalibrated PDM model simulations for the Lavant during the calibration period (water years 1991/92 to 1995/96). Observed well depths are for West Dean Nursery.

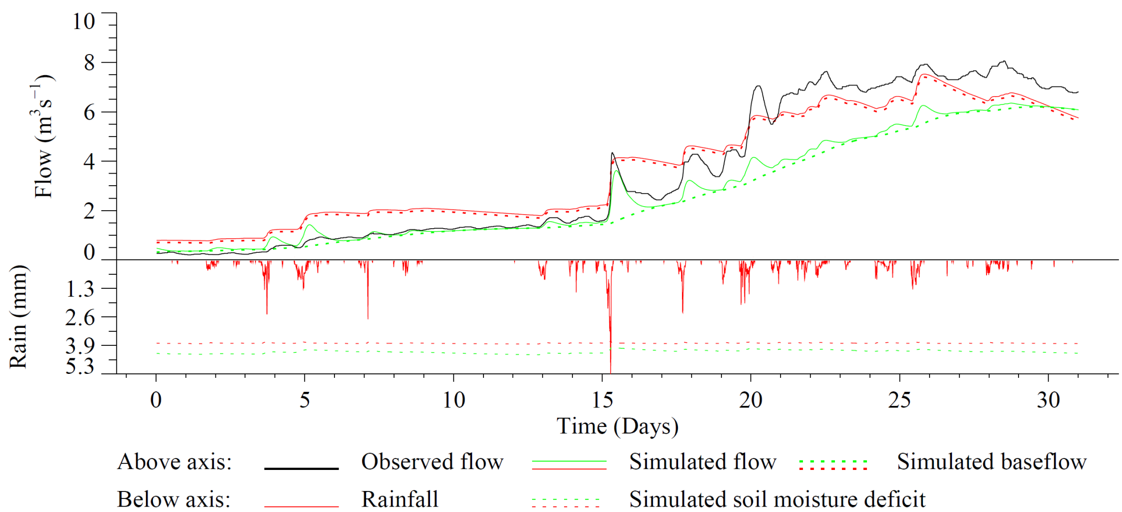

Figure 6.17 Recalibrated PDM model simulation for the Lavant (green line). For reference, the red line shows the simulation obtained with the original calibration. The period shown is 15 December 1993 to 15 January 1994.

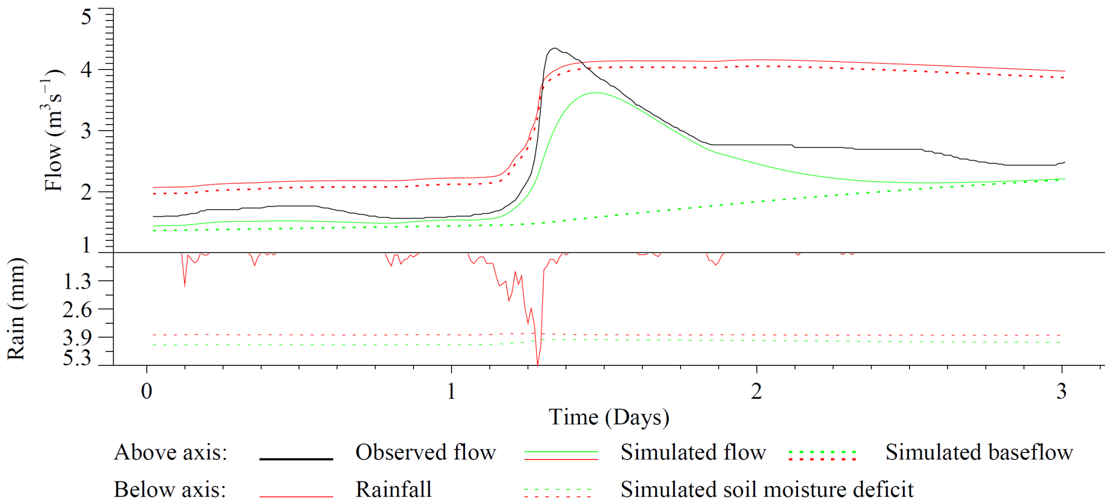

Figure 6.18 Recalibrated PDM model simulation for the Lavant (green line). For reference, the red line shows the simulation obtained with the original calibration. The period shown is 29 December 1993 to 1 January 1994.

In terms of performance measures, Table 6.12 indicates slight improvement relative to the original calibration, for flow over the calibration period and for well level overall, but performance is rather worse for flow over the evaluation period. This is due to a general underestimation of flow, which may be due to overestimating underflow as evidenced in the water balance shown in Table 6.13. Although the balance is now good over the calibration period, there is a 25% underestimation of flow during the evaluation period. Comparing this water balance to that presented in the project tender, it is apparent that underflow is overestimated as about 31% of the water input rather than the 26% expected. However, decreasing underflow was found to generate significant simulated flow during the 1995/96 water year, when it is believed that the Lavant was dry.

Table 6.12 R^2 and *rmse* statistics, obtained from the recalibrated model, for flow in the Lavant and well levels at West Dean Nursery. For reference, statistics for the original calibration are given in brackets.

Period	Flow		Well level	
	R^2	*rmse*	R^2	*rmse*
Calibration	0.938 (0.934)	0.257 (0.266)	0.973 (0.965)	0.613 (0.704)
Evaluation	0.860 (0.907)	0.408 (0.333)	0.740 (0.704)	1.280 (1.228)

Table 6.13 PDM model water balances (mm total) for the Lavant over the calibration period for two model calibrations. In brackets is the output component as a fraction of the rainfall input.

	Original calibration: calibration period	Recalibration: calibration period	Original calibration: evaluation period	Recalibration: evaluation period
Rainfall	4134	4878	6861	8095
Potential Evaporation	3269	3269	5177	5177
Actual Evaporation	2488 (0.602)	2552 (0.523)	4154 (0.605)	4269 (0.527)
Net Rainfall	1646	2326	2707	3826
Abstraction	278 (0.067)	278 (0.057)	521 (0.076)	521 (0.064)
Underflow	589 (0.143)	1531 (0.314)	938 (0.137)	2425 (0.300)
River flow	898 (0.217)	675 (0.138)	1350 (0.197)	983 (0.121)
Observed river flow	676	676	1302	1302
Implied storage change	-119 (-0.029)	-158 (-0.032)	-102 (-0.015)	-103 (-0.013)

A significant improvement in predicting initiation and cessation of flow is achieved through the recalibration of the PDM model for the Lavant. A comparison of times where modelled baseflow is zero to times of zero observed flow is presented in Table 6.14. It is worth mentioning that although the original model calibration does not capture the dates accurately, the modelled flow is nevertheless very low during these periods. The recalibrated model occasionally suffers from excessive surface runoff which leads to some flashy flow during periods when the river was observed to be dry.

Table 6.14 Dry periods for the Lavant over the calibration period estimated from the observed record and from two model calibrations.

Observed	Modelled (original calibration)	Modelled (recalibration)
Dry until 02:30 7 Dec 1992	Dry until 08:45 18 Nov 1992	Dry until 21:00 29 Nov 1992
09:00 21 Jul 1993 to 17:15 9 Oct 9 1993	07:00 10 Sep 1993 to 22:15 1 Oct 1993	21:00 13 Jul 1993 to 19:00 5 Oct 1993
06:15 11 Aug 1994 to 22:00 30 Nov 1994	09:00 5 Oct 1994 to 14:15 31 Oct 1994	05:00 21 Aug 1994 to 07:00 7 Nov 1994
20:15 17 Jun 1995 to end of calibration period	13:00 24 Aug 1995 to 02:45 22 Dec 1995	05:00 10 Jul 1995 to 22:00 8 Jan 1996

6.4 Forecasting performance

The assessment of model performance has focussed up to now on the ability of a model to transform rainfall and PE to river flow at the catchment outlet, without use of observed river flow except for model initialisation: the so-called simulation-mode forecast. In real-time it is possible to improve the forecast through use of river flow observations up to the time the forecast is made (the "forecast time-origin"): such "updated" forecasts are called forecast-mode forecasts. Section 5.2.2 discussed the assessment of such forecasts and their importance for real-time flood forecasting. Here, forecast-mode results have been obtained using state-correction as the updating method. Note also that perfect foreknowledge of rainfall is assumed so as not to confound the assessment with errors due to rainfall forecasting.

Both *fixed lead-time variable time-origin* and *fixed-origin variable lead-time forecasts* have been obtained using the models for the Lavant and Ems with state-correction applied. Table 6.15 presents the results of forecasts using various lead-times, applied with forecast origins at every 15 minute time-step over the water year 2000/2001.

Table 6.15 R^2 and *rmse* statistics (for flow) for the fixed lead-time forecasts over the water year 2000/01).

Lead-time, h	Lavant (original)		Lavant (recalibration)		Ems	
	R^2	*rmse*	R^2	*rmse*	R^2	*rmse*
0.25	1.000	0.009	1.000	0.010	1.000	0.014
1	1.000	0.032	1.000	0.028	0.999	0.038
3	0.999	0.062	0.998	0.072	0.997	0.086
6	0.997	0.099	0.995	0.124	0.993	0.123
12	0.993	0.148	0.989	0.188	0.991	0.142
24	0.987	0.201	0.982	0.242	0.991	0.136
48	0.974	0.292	0.969	0.314	0.987	0.168

The gradual deterioration of forecast quality with increasing forecast lead-time is demonstrated in Figure 6.19, which plots the R^2 Efficiency performance statistic against lead-time. Forecasts for the Ems are only better than those for the Lavant for lead-times exceeding 16 hours, when forecasts approach the simulation-mode model performance. At the shorter lead-times, most relevant to flood forecasting, the quality of the forecast for the Ems drops off twice as quickly as for the Lavant, highlighting the greater difficulty of forecasting for this flashier responding catchment. Results for the recalibrated PDM model for the Lavant show slightly worse behaviour than for the original model at the level of R^2 Efficiency, at lead-times of greater than 1 hour. This may be due to the overall lower R^2 Efficiency score of the recalibrated model compared to the original model over the evaluation period (see Table 6.12). The visual impression of the forecasting potential of the recalibrated Lavant model from hydrographs on short time scales relevant for flood forecasting and warning shows improvement over the original model and is presented in Section 6.4.1

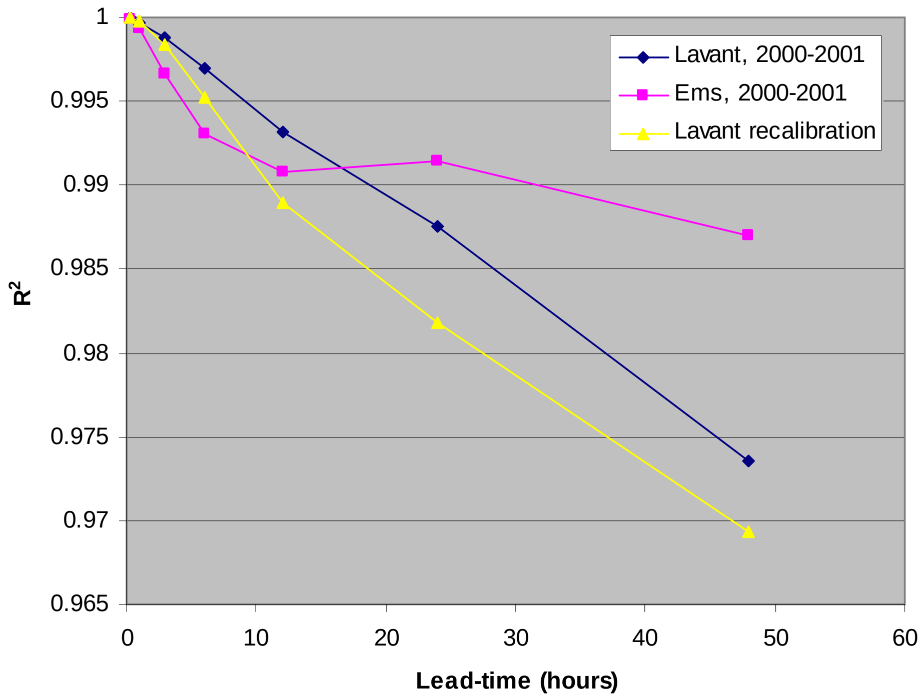

Figure 6.19 ***R^2*** **Efficiency against forecast lead-time for flow forecasts over the water year 2000/01.**

Model simulations corresponding to lead-times of 6 and 12 hours are shown in Figure 6.20 and Figure 6.21 for the Lavant (original calibration) and Ems respectively. Here the time period has been reduced to three months so that the variation from the observed flow can be clearly distinguished. These forecasts provide a visual impression of the forecaster's ability to forecast flows at realistic lead-times for which reasonable rainfall forecasts should be available. The corresponding R^2 and *rmse* performance measures are presented in Table 6.16. Again, the recalibrated model for the Lavant performs slightly worse than the original model at this level of assessment. A figure corresponding to Figure 6.20 is not included since the visual performance is very close to that of the original model.

6.4.1 Fixed-origin forecasts for the Lavant

Figure 6.22 presents fixed-origin forecasts made at 09:00 hours every day for lead-times out to 24 hours ahead, over the flood event on the Lavant in December 2000. The close shadowing of the observed flow over periods such as day 11 highlights the potential for such forecasts to forewarn of rapid rises in river flow. Comparison with the simulated flow (the red line) reveals the tendency of these emulated real-time forecasts to regress to the simulation-mode values at long lead-times. The model does not capture the timing of the peak flow very well, predicting recession from about day 12 whilst the observed flow continues to rise for another two days. The recalibrated PDM model presented in Section 6.3.1 forecasts the timing and duration of the flood peak much better whilst still capturing the flashy response; the corresponding results are shown in Figure 6.23.

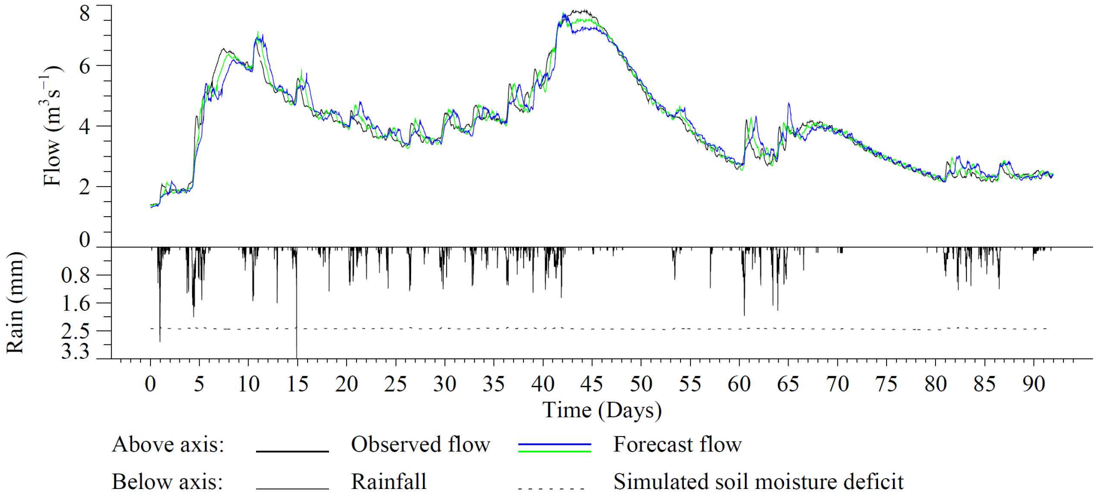

Figure 6.20 Fixed lead-time variable time-origin forecasts for the Lavant using lead-times of 6 hours (green line) and 12 hours (blue line). The period shown is 1 November 2000 to 1 February 2001.

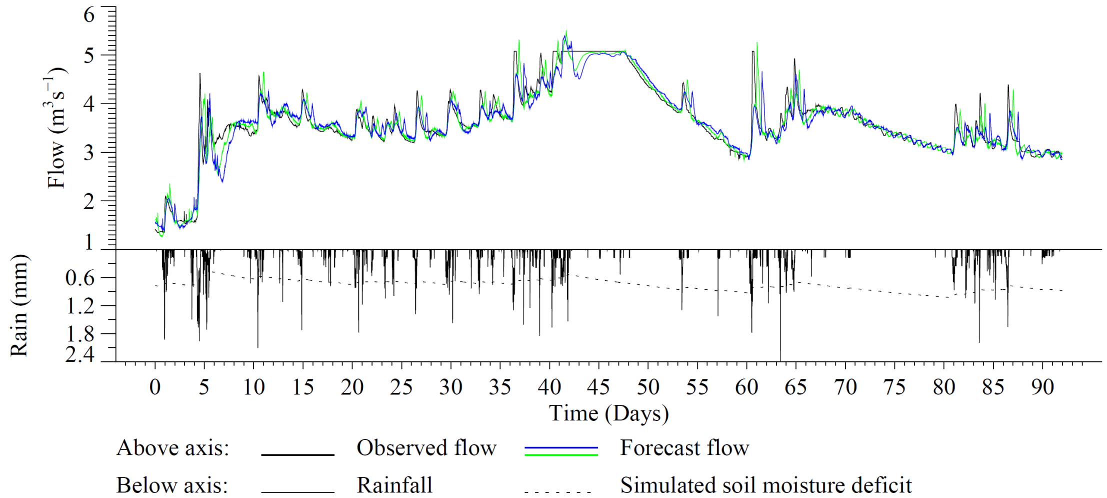

Figure 6.21 Fixed lead-time variable time-origin forecasts for the Ems using lead-times of 6 hours (green line) and 12 hours (blue line). The period shown is 1 November 2000 to 1 February 2001.

Table 6.16 R^2 and *rmse* performance statistics for fixed-lead time flow forecasts over the period 1 November 2000 to 1 February 2001.

Lead time, h	Lavant		Lavant recalibration		Ems	
	R^2	*rmse*	R^2	*rmse*	R^2	*rmse*
6	0.990	0.153	0.981	0.205	0.928	0.195
12	0.975	0.235	0.956	0.314	0.905	0.224

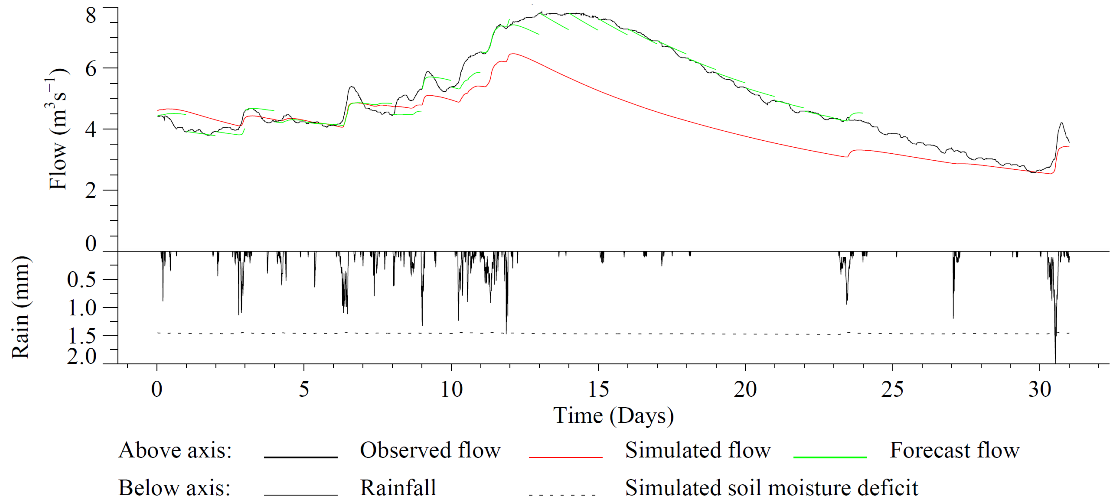

Figure 6.22 Fixed-origin variable lead-time forecasts out to 24 hours for the Lavant (original calibration) using forecast time-origins at 09:00 each day (green lines). The period shown is 1 December 2000 to 1 January 2001 and the simulation-mode forecast is shown as a red line.

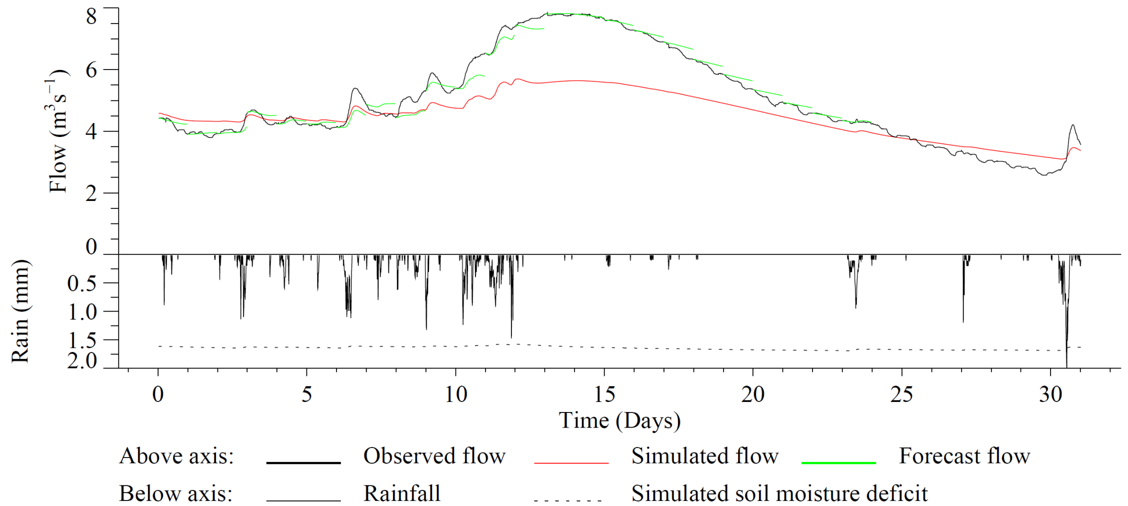

Figure 6.23 Fixed-origin variable lead-time forecasts out to 24 hours for the Lavant using recalibrated parameters and forecast time-origins at 09:00 each day (green lines). The period shown is 1 December 2000 to 1 January 2001 and the simulation-mode forecast is shown as a red line.

For the purpose of flood forecasting, it is important to assess the performance of the model over shorter periods of time during which the main hydrograph rise occurs as this has particular relevance for flood alleviation operations. Focussing on the rapid rises in flow during the early stages of the 1993 and 2000 flood events, a series of forecasts out to 24 hours have been made from forecast origins at 3-hourly intervals. Figure 6.24 and Figure 6.25 present these forecasts for the Lavant, using the original model calibration. The results are encouraging, with the initial rise being well predicted over the range at which flood mitigating mechanisms become active (2.5-3.5 m^3s^{-1}; see Section 1.2). However, persistence in the model maintains flow at a higher level after this rise, whereas the observed flow exhibits a drop and subsequent fluctuations on a finer scale. This is partly due to the model for the Lavant being more able to reproduce the long-term baseflow rather than fast surface runoff.

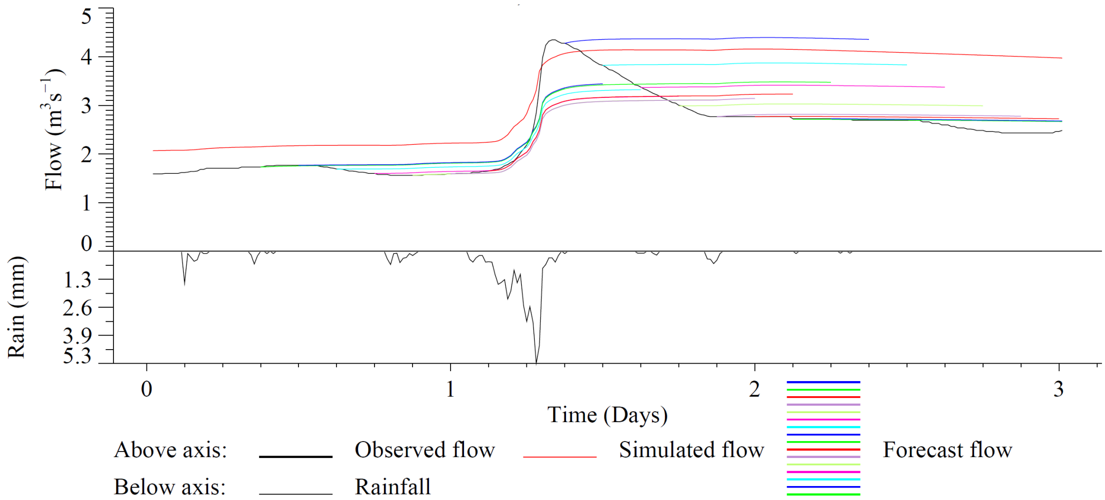

Figure 6.24 Fixed-origin variable lead-time forecasts out to 24 hours for the Lavant (original calibration), using state-correction. Forecast time-origins are at 3 hour intervals from 18:00 29 December 1993 up to 15:00 31 December 1993 (coloured lines). The simulation-mode forecast is shown as a red line over the whole period.

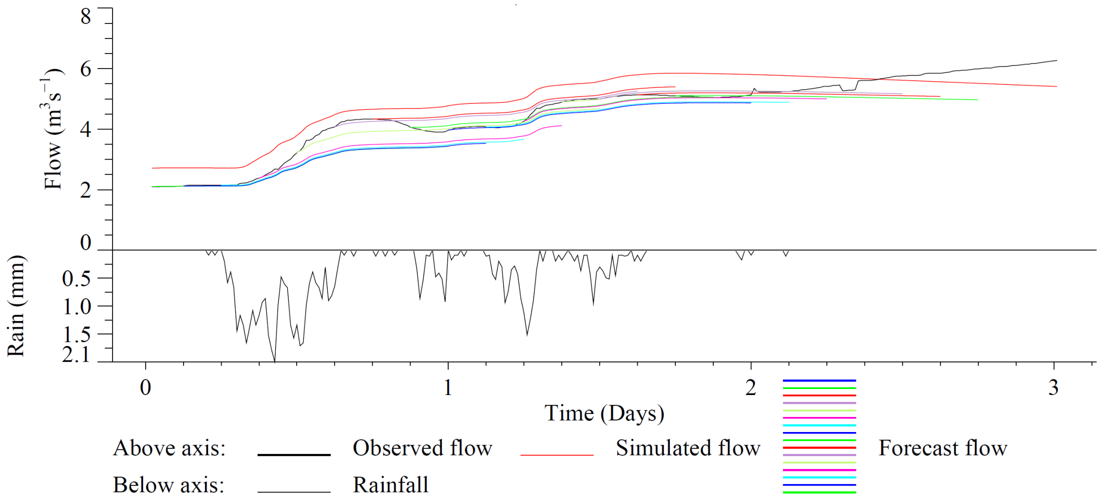

Figure 6.25 Fixed-origin variable lead-time forecasts out to 24 hours for the Lavant (original calibration), using state-correction. Forecast time-origins are at 3 hour intervals from 09:00 5 November 2000 up to 06:00 7 November 2000 (coloured lines). The simulation-mode forecast is shown as a red line over the whole period.

Again, the recalibrated PDM model presented in Section 6.3.1 fares better here, the corresponding results being presented in Figure 6.26 and Figure 6.27. These highlight how the recalibrated model captures the shape of the hydrograph better, particularly for the initial rising limb in Figure 6.27. In Figure 6.26, the recalibrated model forecasts lose the steepness of the hydrograph rising limb but far better predict the peak and recession over this short time period, when compared to the original model forecasts in Figure 6.24.

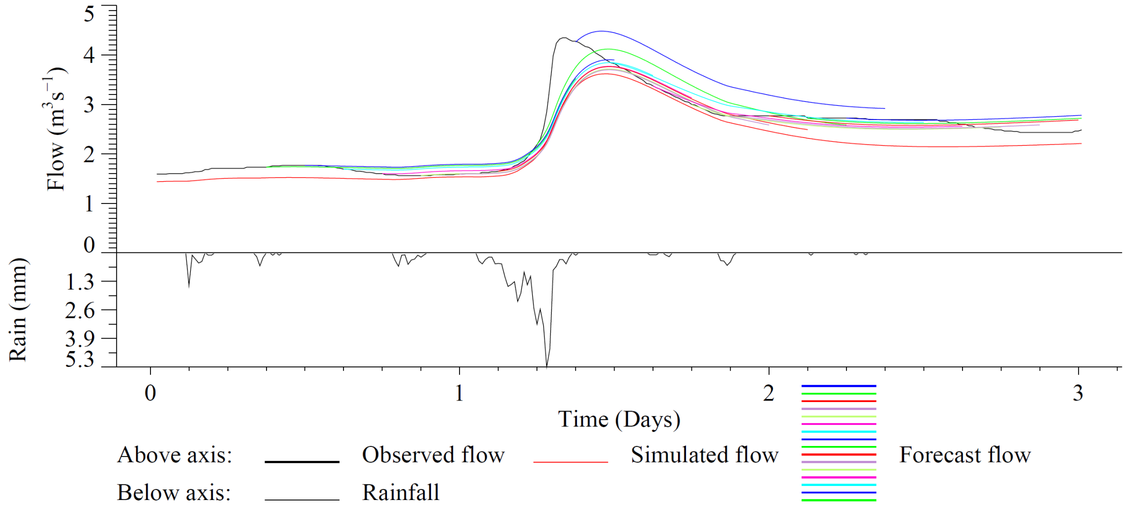

Figure 6.26 Fixed-origin variable lead-time forecasts out to 24 hours for the Lavant, using recalibrated parameters and state-correction. Forecast time-origins are at 3 hour intervals from 18:00 29 December 1993 up to 15:00 31 December 1993 (coloured lines). The simulation-mode forecast is shown as a red line over the whole period.

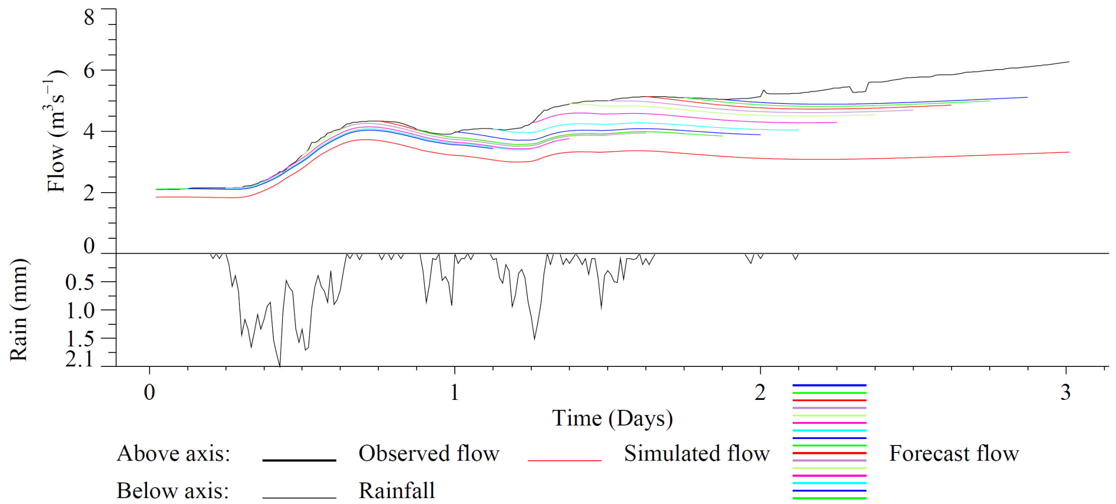

Figure 6.27 Fixed-origin variable lead-time forecasts out to 24 hours for the Lavant, using recalibrated parameters and state-correction. Forecast time-origins are at 3 hour intervals from 09:00 5 November 2000 up to 06:00 7 November 2000 (coloured lines). The simulation-mode forecast is shown as a red line over the whole period.

6.4.2 Fixed-origin forecasts for the Ems

Figure 6.28 and Figure 6.29 present forecasting results for the Ems over the same two short periods as shown for the Lavant in the previous section. Overall, a reasonable set of forecasts is obtained: the general shape and level of the flood hydrograph is captured to some degree but the rapid rise is not forecast particularly well.

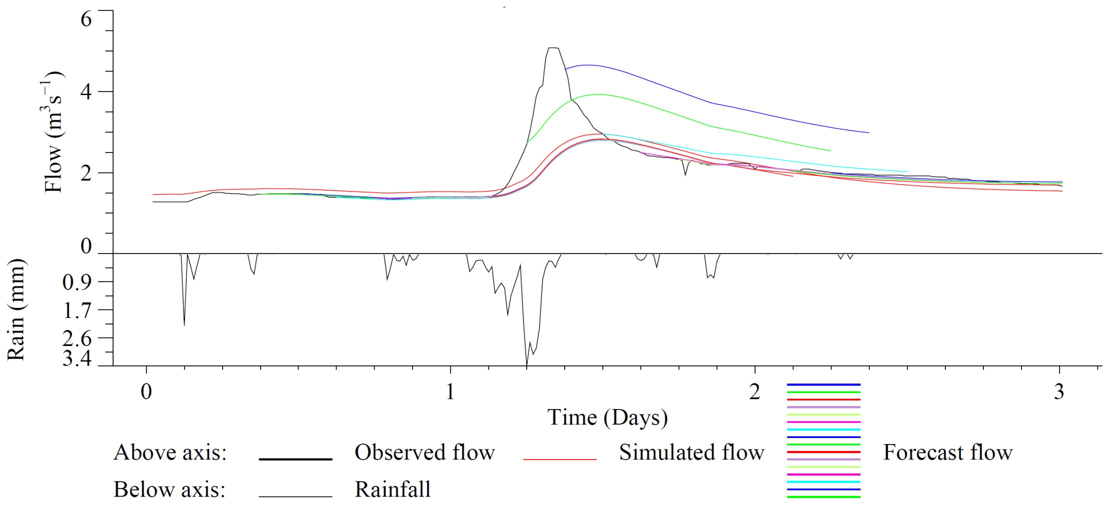

Figure 6.28 Fixed-origin variable lead-time forecasts out to 24 hours for the Ems, using state-correction. Forecast time-origins are at 3 hour intervals from 18:00 29 December 1993 up to 15:00 31 December 1993 (coloured lines). The simulation-mode forecast is shown as a red line over the whole period.

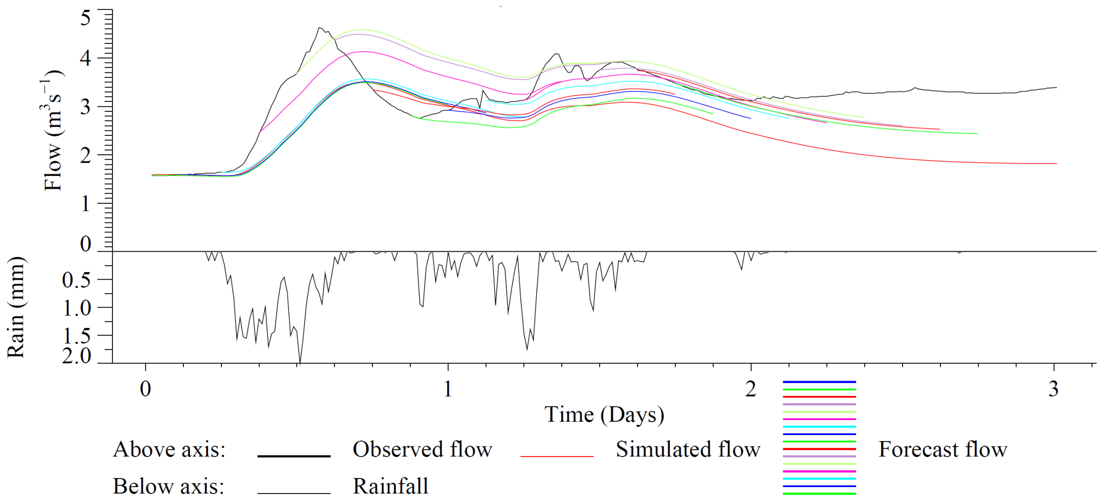

Figure 6.29 Fixed-origin variable lead-time forecasts out to 24 hours for the Ems, using state-correction. Forecast time-origins are at 3 hour intervals from 09:00 5 November 2000 up to 06:00 7 November 2000 (coloured lines). The simulation-mode forecast is shown as a red line over the whole period.

However, the performance for the Ems is less satisfactory than for the Lavant, despite the model capturing the fast surface flow response of the catchment to some extent. In this case, a recalibration has not been performed as it was for the Lavant in Section 6.3.1. Improved forecasting performance, of a similar nature to that seen for the Lavant, would be expected in this case too. This issue is only considered to be worth revisiting once the extended PDM model is incorporated into the PDM for PCs software, as this would allow access to improved calibration tools (e.g. the ‘zoom’ facility to focus on the short-term response).

6.5 Model performance summary

Initial simulation-mode calibration of the PDM models presented for the Lavant and Ems in Section 6.1 focussed on obtaining good R^2 Efficiency and visual performance over the entire calibration period. The simulation-mode performance of the models for the Lavant and Ems is reasonably good at capturing the broad behaviour of flow variations. The model can be calibrated to predict with some success the timing of onset and cessation of flow under ephemeral streamflow conditions. R^2 Efficiency values are consistently above 0.9 for both calibration and evaluation periods: see Table 6.3 for the Lavant and Table 6.5 for the Ems. However, this performance statistic has a favourable bias for groundwater catchments due to the long periods of hydrograph recession (and zero flows for the Lavant), these being easier to model than the rising limb of the flood hydrograph. Some shortcomings in simulating the flood hydrograph over shorter time scales relevant to flood forecasting were observed.

An attempt to address these shortcomings for the original Lavant model via recalibration was presented in Section 6.3. During recalibration more attention was paid to calibrating the fast response parameters of the PDM. In terms of performance measures, Table 6.12 indicates slight improvement relative to the original Lavant calibration, for flow over the calibration period, but performance is rather worse for flow over the evaluation period. However, the visual impression of simulation-mode performance for the recalibrated Lavant model remains good, though some problem with an overly large flashy response prior to commencement of flow is apparent. More detailed flood hydrographs for much shorter periods are shown in Figure 6.17 and Figure 6.18, where the potential for the recalibrated model to capture flashy responses is well demonstrated. A significant improvement in predicting initiation and cessation of flow is also achieved through the recalibration of the PDM model for the Lavant, as indicated by Table 6.14.

A similar recalibration for the Ems has not been performed due to limitations of the project scope. Unfortunately, the CEH research code does not include the full range of visualisation support tools enjoyed by the PDM for PCs product software such as the interactive ‘pan and zoom’ functionality that aids the model calibration task. Development of the product code to embrace the extended PDM model for groundwater catchments would improve the ease and success of calibration considerably. Revisiting the Ems calibration using the PDM for PCs environment would allow a more detailed focus on the flashy response of the model and may result in an improved calibration.

The forecast-mode performance of the extended PDM models is presented in Section 6.4. From a flood forecasting and warning perspective, the fixed-origin variable lead-time forecasts during the early stages of the 1993 and 2000 flood events are most relevant and are presented in sections 6.4.1 and 6.4.2. These results show that all the PDM models have some ability to forewarn the rapid rise in flows during the onset of major flooding incidents. The forecast-mode results are more successful for the Lavant catchment and, in particular, using the recalibrated Lavant model. During the 1993 event Figure 6.27 highlights how the recalibrated model captures the shape of the hydrograph rising limb well and is reasonably successfull at predicting the observed peak. Also, Figure 6.26 shows a very good forecast of the first flow peak and recession at the start of the 2003 flood event. The Lavant forecast results are encouraging, with the initial rise in flow being well predicted over the range at which flood mitigating mechanisms become active (2.5-3.5 m^3s^{-1}; see Section 1.2).

However, the forecast performance for the Ems is less satisfactory. In this case, a recalibration has not been performed as it was for the Lavant in Section 6.3.1. Improved forecasting performance, of a similar nature to that seen for the Lavant, would be expected following recalibration in this case too. This issue is only considered to be worth revisiting once the extended PDM model is incorporated into the PDM for PCs software, as this would allow access to improved calibration tools (e.g. the 'zoom and pan' facility to focus on the short term response) that are not available within the research PDM code.

This summary of model performance allows the following recommendations to be made.

Recommendation

- **Forecast performance and operational implementation**. When assessed in forecast-mode, the potential of the extended PDM models for the Lavant and Ems to forewarn of rapid rises in river flow has been illustrated. The simulation- and forecast-mode performance obtained using the models is sufficiently strong to justify further work aimed at operational implementation of the extended PDM within the Environment Agency's National Flood Forecasting System (NFFS), including incorporation within the PDM for PCs software to support model calibration and assessment.

- **Future assessment of model calibrations**. Once the extended PDM has been incorporated into the PDM for PCs software it will allow access to improved calibration tools (e.g. the 'zoom and pan' facility). It is then recommended to reassess the Lavant and Ems model calibrations and investigate if further improvements in model performance can be achieved with particular focus on the short-term model response important for flood warning.

7 Summary and recommendations

7.1 Summary

This Report outlines work undertaken for the Environment Agency under the Project "Hydrological Modelling for the Rivers Lavant and Ems". It starts by preparing the ground and developing a strategy for the modelling work that follows. The overall aim is to calibrate extended PDM rainfall-runoff models for the Lavant and Ems catchments and assess their utility for real-time flood forecasting and warning. Data required for modelling are identified and their availability and quality reviewed. This has involved collation of relevant data available from the Environment Agency and the Centre for Ecology & Hydrology.

Rainfall data are given particular attention in relation to providing a long time-series of consistent form for modelling purposes. The basic raingauge data are subject to an extensive data quality control check. This exposed shortcomings in present processing procedures and lead to recommendations for overcoming these that are relevant to both the modelling work that follows and to wider hydrometric practices within the Environment Agency. A method is proposed to obtain a consistent and continuous time-series of catchment average rainfall for use in modelling, and that takes account of data availability and suspect periods. A comparison between raingauge and radar estimates of rainfall reveals a general underestimation of rainfall by the radar in the vicinity of the Lavant and Ems catchments. Due to the short record of radar data, a full model sensitivity analysis is judged not to be warranted as part of the modelling work, but considerations for the future real-time use of radar data are given.

The river flow data for the Lavant at Graylingwell and Ems at Westbourne are analysed. The Grayling record is compared to data previously supplied to CEH as part of the Moore and Bell (2002) study and reveals some outstanding issues pertaining to the rating curve: these are resolved through adoption of a consistent single rating for use in modelling. Well level data for the Lavant and Ems catchments are reviewed and additional records obtained.

Time-series of potential evaporation data derived from MORECS and MOSES are considered alongside standard profiles in use by the Environment Agency. It is noted that for the Lavant and Ems catchments, the standard Southern Region profile overestimates summer PE and underestimates winter PE relative to the long-term average (1971-2007) MORECS profiles. A strategy for use of MORECS monthly time-series disaggregated in time using linear interpolation and a diurnal profile is formulated for use in modelling. Comparison between MORECS and MOSES PE data indicates that MOSES consistently estimates more PE than MORECS. The consequences of this for the future operational use of MOSES PE data are discussed. As with the radar data, the short period for which MOSES data are available means that a meaningful model sensitivity analysis is not possible at present.

A strategy for modelling is developed and the periods of records to be used for model calibration and independent evaluation are selected. The model performance assessment methods to be used are detailed. The strategy also considers the problem of model conceptualisation for groundwater catchments with ephemeral streamflows affected by pumped abstractions, external springs and underflows, and low-flow augmentation from wells. A need to impose a conceptualisation supported by data and information is recognised due to identifiability problems. The value of a detailed catchment water balance to identify unaccounted for water transfers is highlighted in this model conceptualisation process. In addition, the benefits of using flow records from a nearby spring-fed stream - Costers Brook at Cocking - are discussed. They give some insight into groundwater exports from the Lavant catchment. The modelling work that follows seeks to clarify the nature of these transfers further with the help of the modelled water balance. Any needs for further model development is judged best explored as an intrinsic part of the modelling activity, paying particular attention to state-updating methods and incorporating the effects of flow augmentation. Insights to be gained from information sources on hydrogeological controls are considered. These extend from simple inspection of maps of solid geology and drift cover, the locations of springs, through to consideration of the hydrogeological properties of the Chalk together with the analysis of notable extreme flood events.

The calibration and assessment of the extended PDM model to the Lavant and Ems provided good results, capturing the main features of the catchment response reasonably well such as the initiation and cessation of ephemeral river flows and the peak and troughs of the well levels. Assessments were carried out in relation to both the model simulation of river flows and well levels. Sensitivity analyses on the forms of model input to use operationally led to recommendations relating to the combination of raingauges to use, the value of radar rainfall, and the profiles of potential evaporation and abstractions to employ. Some shortcomings in the short-term responses of the models were recognised. This was improved for the Lavant model through a targeted recalibration. An emulation of the real-time application of the models in forecast-mode demonstrated their potential to forewarn the rapid rise of river flows during the onset of major floods and supports the recommendation for future operational application.

7.2 Recommendations

Throughout the Report, recommendations have been made and highlighted in grey boxes. They are repeated here in their entirety as a record of the project decision-making process, sometimes with an additional comment to indicate their status or outcome. Several of the recommendations have been addressed within the project, such as project take-on of more data of use to the modelling work. Others relate to the modelling strategy and how this has developed over the course of the project. Some are recommendations made to the Environment Agency, for example in relation to their hydrometric data records and practices. A further set relate to the use of the model in operational practice and what data inputs are required as profiles or as real-time data streams. Recommendations that form the outcome of the project and need addressing or noting by the Environment Agency are highlighted in red.

The final section that follows reviews those recommendations relevant to the future operational use of the extended PDM rainfall-runoff model leading to a consideration of the way forward.

1. Data requirements and availability for modelling

Radar data

Radar data sensitivity analysis. The model sensitivity analysis comparing raingauge and radar data will be restricted to using catchment average rainfall data using Nimrod composite radar data. This is due to the relatively short record of Nimrod composite radar data and the lack of significant flood events since 2003. Done.

River levels/flows

River Lavant at Graylingwell rating curve. The Mott McDonald rating should be used consistently throughout the Graylingwell stage record for this project. Done.

River Lavant at Graylingwell river flow data. The River Lavant stage time-series will be processed at CEH using the Mott McDonald rating to obtain a consistent river flow time-series for use in rainfall-runoff modelling. Done.

River Lavant at Graylingwell river level data. The river stage time-series for Graylingwell will be supplied to CEH. Done.

Potential evaporation (PE)

Standard daily PE profile. The current standard daily profile used by Southern Region overestimates during the summer and underestimates during the winter compared to the long-term monthly values of MORECS square 183. It is recommended that, if a daily profile is needed, the linear interpolation method which preserves the long-term monthly and annual MORECS PE totals be used for the Lavant and Ems catchments. Done.

MORECS PE profile for use in modelling. It is recommended that the historical daily PE profile is derived using the linear interpolation method which preserves the monthly totals. The 15 minute totals will be derived using the standard EA diurnal profile. Done.

MOSES PE data sensitivity analysis. A full model sensitivity analysis comparing MOSES and MORECS PE data is not warranted at this time. This is due to the relatively short record of MOSES data and the lack of significant flood events since 2005. Done. Future recommendation for a full model sensitivity analysis comparing MOSES and MORECS PE data when sufficient records are available.

MORECS PE data sensitivity analysis. A model sensitivity analysis should be performed within the project comparing the use of historical MORECS PE estimates with using a sine curve formulation and the long-term MORECS PE profile. Done.

Well levels

Chilgrove data. The time-series ‘245221099.WL.ir.P’ to be obtained. Done.

Compton data. The time-series ‘Compton.WL.Telemetry.60.P’ and ‘245121511.WL.60.P’ to be obtained. Done.

Chilgrove and Compton data. Definitions of the various different time-series supplied are to be obtained. Done.

West Dean Nursery. The time-series ‘WestDeanN.WL.ir.P’ to be obtained. Done.

Groundwater abstractions

Real-time use of abstraction data. The impact on the modelling of the 2 month delay in abstraction data being available in WISKI needs to be considered as part of the model investigation. Mitigating options such as a default abstraction profile or a persistence assumption also need to be considered. This is addressed under the model sensitivity analyses of Section 6.2.4.

2. Data quality control

Raingauge data

15 minute raingauge totals. The 15 minute totals generated by CEH from the time-of-tip data should be used as opposed to the EA generated 15 minute totals. Done.

WISKI. The method used to store and extract 15 minute totals within WISKI should be reviewed in relation to the handling of missing time-of-tip data. Action being addressed nationally by the Environment Agency.

Tipping bucket raingauge data. The two serious issues identified with the tipping-bucket records (points 1 and 5) should be investigated by the Environment Agency and an explanation for their occurrence sought. This has been reported to FMD and an investigation is ongoing.

Chichester raingauge. Check with Environment Agency regarding Chichester totals on 15 September 2000 (point 6). This check has been done and the totals have since been removed from the record at CEH.

WISKI quality flags. The quality control analysis summarised in Table B.3 should be considered for inclusion within the WISKI quality flag information where appropriate.

Rainfall input for rainfall-runoff modelling. A consistent time-series of raingauge rainfall data will be used for rainfall-runoff modelling. Gaps and suspect periods in the Chichester, Walderton and Havant raingauge records will be infilled using the approach recommended here. Done.

Raingauge network sensitivity analysis. Use of the improved raingauge network will be considered as part of the model sensitivity analysis. Done.

Well level data

Time-series ChilgrveGW.WL.ir.P: Well level data (m AOD) prior to 01/11/02 should be reprocessed with the correct datum of 76.88m AOD (this is 30cm lower than the historical datum used). CEH has reprocessed the data internally to support the modelling work.

Chilgrove RTS data. The EA time-series ‘CHILGROVE RTS mAOD.WL.15.P’ stored in WISKI should be reprocessed from 21 September 2007 onwards to switch the ‘Dip’ and ‘Well Level’ data columns. (Note this doesn’t affect the proposed calibration and evaluation periods for the PDM modelling). Done.

Compton RTS data. The EA time-series 'COMPTON RTS.WL.60.O' stored in WISKI should have spurious spikes manually removed (e.g. 20-26 July 2007). The period 14:00 01/12/2006 to 13:00 25/09/2007 (inclusive) should be treated as suspect. Note that whilst spikes are present in the original series (marked 'O'), these have been removed in the production series (marked 'P') so no action is required.

Compton RTS data. The Environment Agency time-series 'Compton.WL.Telemetry.60.P' should have spurious spikes manually removed (e.g. 20-26 July 2007). The Environment Agency has addressed this.

River level/flow data

Lavant at Graylingwell. The Environment Agency should review the problem records on 16 October 2000, 17 November 2002 and 5 February 2004 and take appropriate action (e.g. add comments to WISKI). The missing data in the level and flow records should also be reviewed and replaced with zero where the stream is known to have been dry.

Ems at Westbourne. The Environment Agency should review their practice of capping the flow to that at the upper limit of the rating curve and allow the extrapolated rating curve to be used to estimate flows (with the knowledge that they are out of range).

3. Strategy for modelling

Model assessment

Model calibration and evaluation periods. A split-sample strategy for model assessment will be used, employing the five water years 1991/92 to 1995/96 for calibration and the eight water years 1996/97 to 2003/4 for independent evaluation. Done.

Model assessment. Model assessment will be carried out in simulation-mode and updating-mode. Done.

Model assessment. Visual assessment of modelled and observed hydrographs could be complemented by performance measures of continuous variable (*rmse*, R^2 Efficiency) and, where appropriate, categorical form (CSI, POD, FAR). The latter focus on the success of forecasting the crossing of critical flow/level thresholds; the relatively small number of threshold crossings for groundwater-dominated rivers can limit the usefulness of these statistics for typical record lengths. A limited set of measures will be used in this study tailored to what is judged useful for model assessment purposes. The ones chosen are R^2 Efficiency and *rmse* along with visual assessment. Done.

Model conceptualisation

Model conceptualisation. An aim will be to quantify component processes where possible (e.g. pumped abstractions). Catchment water balances and use of additional data sources (e.g. Costers Brook at Cocking) will be used to quantify unaccounted for water transfers. The modelled water balance will be used to help clarify the form of these transfers. Done.

Model conceptualisation. Combining the effects of augmentation and abstraction in the extended PDM needs to be considered as part of the model application to the Ems catchment. Done: flow augmentation proved not to be important to modelling the flood response of the Ems.

4. Model application

Model sensitivity analyses

Raingauge scheme for the Lavant catchment. It is recommended that the Chichester raingauge be put on telemetry and used in the weighting scheme for the Lavant catchment using the following weights: Chichester 0.55 and Walderton 0.45.

Raingauge scheme for the Ems catchment. It is recommended that the Chilgrove raingauge be used in the weighting scheme for the Ems catchment using the following weights: Walderton 0.51, Chilgrove 0.36 and Havant 0.13.

Potential evaporation profile. It is recommended that the MORECS long-term annual average profile be used for future forecasting, as it is readily available for real-time application. In unusual years, a tactical review of this recommendation might be considered. A future trial of MOSES PE, available in near real-time, should be made when sufficient records and flood events are to hand.

Annual abstraction profile for PDM modelling. The long-term annual abstraction profile is recommended to be used in forecasting until abstraction data are received from the water companies, typically two-months in arrears of real-time. Further, if there are significant costs or difficulties in supplying the daily abstraction data to the NFFS system then the annual profile can be used with little or no loss of modelling performance (but this would need to be reviewed if the abstraction regime changed significantly).

Model performance

Forecast performance and operational implementation. When assessed in forecast-mode, the potential of the extended PDM models for the Lavant and Ems to forewarn of rapid rises in river flow has been illustrated. The simulation- and forecast-mode performance obtained using the models is sufficiently strong to justify further work aimed at operational implementation of the extended PDM within the Environment Agency's National Flood Forecasting System (NFFS), including incorporation within the PDM for PCs software to support model calibration and assessment.

Future assessment of model calibrations. Once the extended PDM has been incorporated into the PDM for PCs software it will allow access to improved calibration tools (e.g. the 'zoom and pan' facility). It is then recommended to reassess the Lavant and Ems model calibrations and investigate if further improvements in model performance can be achieved with particular focus on the short-term model response important for flood warning.

7.3 Conclusions and the way forward

The study has developed extended PDM models for the Lavant and Ems catchments and assessed their performance as simulators of river flow and for making flood forecasts in real-time. Conclusions have been drawn on the best combination of raingauges to use as model input in real-time, along with their associated weightings. Recommendations have also been made on the potential evaporation and abstraction profiles to use in real-time implementation of the models.

The model performance obtained has led to a recommendation to the Environment Agency to progress implementation of the extended PDM within their National Flood Forecasting System (NFFS). Three main components of future work may be identified to this end. The first is to develop the research version of the extended PDM code, used here for model calibration and assessment, so that it is available in the product code "PDM for PCs" supported by CEH in the NFFS suite of models. Second is to develop the NFFS Module Adapter form of the PDM, used for forecast construction in real-time within the NFFS, to support the functionality of the extended PDM. The third component of work envisaged is application of the extended PDM to other groundwater catchments, situated both in Southern and other regions of the Environment Agency where flows are affected by groundwater pumping, external springs and water transfers across the catchment divide. This work would include operational trials of the models for these catchments along with those developed here for the Lavant and Ems.

Thus the following operational recommendations can be set down as a conclusion to this report.

Recommendations

- **PDM for PCs**. The extended PDM model, currently in the form of research code, should be incorporated into CEH's "PDM for PCs" product code used by the Environment Agency for model calibration in NFFS applications.

- **PDM Module Adapter**. The extended PDM model should be incorporated into CEH's PDM Module Adapter code used by the Environment Agency for forecast construction in real-time within the NFFS.

- **Operational trials.** Operational trials of the extended PDM within the NFFS should be carried out for the Lavant and Ems (including reassessment of the model calibrations using the additional tools of the PDM for PCs software) and for further catchments in Southern and other regions of the Environment Agency experiencing groundwater flooding. The Cam (Anglian) and Gypsey Race (North East) are possible candidates outside Southern Region.

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Appendix A Monthly MORECS and MOSES data

Table A.1 Monthly MORECS and MOSES Potential Evaporation estimates for grass (C3) over MORECS square 183 using data held at CEH.

Year	Month	Monthly PE		% of MOSES missing
		MORECS	MOSES	
2005	7	90.4	80.003	80.78%
2005	8	89.5	99.844	0.13%
2005	9	62.4	65.062	0.83%
2005	10	37.9	39.907	0.13%
2005	11	16.5	19.557	1.67%
2005	12	7.7	10.387	10.22%
2006	1	10.2	10.819	7.39%
2006	2	15.0	20.105	3.27%
2006	3	31.0	34.176	0.00%
2006	4	47.9	55.689	0.00%
2006	5	68.6	78.603	1.21%
2006	6	93.9	115.972	0.00%
2006	7	116.2	137.186	0.00%
2006	8	80.1	104.4	0.54%
2006	9	58.7	73.988	0.00%
2006	10	32.7	45.727	0.00%
2006	11	15.2	25.887	0.00%
2006	12	11.2	20.717	2.02%
2007	1	15.9	27.044	0.00%
2007	2	10.9	23.413	0.15%
2007	3	39.0	48.996	0.00%
2007	4	69.8	81.727	2.64%
2007	5	81.6	88.053	0.27%
2007	6	79.8	98.667	0.97%
2007	7	86.0	104.204	0.27%
2007	8	81.7	96.259	18.41%
2007	9	55.4	70.594	9.17%
2007	10	25.1	32.383	11.96%
2007	11	13.9	20.629	8.06%
2007	12	11.8	17.399	0.00%
2008	1	13.6	19.279	3.49%
2008	2	16.0	23.4	2.44%
2008	3	37.9	52.049	0.40%
2008	4	52.2	64.281	1.39%
2008	5	92.5	106.261	11.42%
2008	6	92.7	110.971	0.56%
2008	7	85.2	115.786	2.82%
2008	8	71.8	88.855	1.88%

Appendix B Raingauge data analysis supplementary information

Table B.1 Summary of raingauge data files contained on the CD provided by the EA dated 11/09/2008.

File name	Contents
*raingauge*TBRP.all	Time-of-tip data All time-of-tip data files had the same format except Chichester which was slightly different. The tip size was 0.2mm for all raingauges. The temporal resolution of the time-of-tip data changed during the records. The following resolutions were found: Data recorded as minute totals so could be more than one tip per record. The date stamp is assumed to be the end of the 1 minute interval. Data recorded at intervals 2 or 4 second past the minute (i.e. no odd seconds). Data recorded at intervals of 10 seconds past the minute so occasionally there is more than one tip per record. Data recorded by the second so should be one tip per record. Starts of missing periods are identified by a value field of --- and a quality flag of M.
*raingauge*TBR15.all	15 minute totals All files had the same format except for Duncton which was slightly different. The 15 minute totals are assumed to have been formed from the time-of-tip record. The date stamp is assumed to be the end of the 15 minute interval. Missing records are denoted by a value field of --- and a quality flag of M.
*raingauge*TBRD.all	Daily totals. All files have the same format. These are assumed to have been formed from the time-of-tip record with the date stamp at the start of the 24 hour period at 09:00 GMT. Missing records are denoted by a value field of --- and a quality flag of M.

Table B.2 Difference between CEH 15 minute totals calculated from the time-of-tip record and the 15 minute totals provided by the EA.

Raingauge	Time-of-tip record	Period of 15 minute accumulations	15 minute total	
			CEH	EA
Chichester	29/06/1999 12:07:40 0.40 G 30/06/1999 12:00:00 3.20 G 01/07/1999 17:07:40 --- M 03/07/1999 17:07:40 . G	1999,06,30,12,00 1999,06,30,12,15 to 1999,07,01,17,00 1999,07,01,17,30 to 1999,07,03,17,00	3.2 0.0 Missing	Missing Missing 0.0
	31/12/2000 23:23:04 0.20 G 01/01/2001 01:39:48 0.20 G	2001,01,01,00,15	0.0	0.2
	30/04/2003 04:27:20 0.20 G 01/05/2003 05:13:00 0.20 G 01/05/2003 07:10:30 0.20 G	2003,05,01,05,15	0.2	0.4
	30/12/2004 00:11:52 0.20 G 01/01/2005 15:12:28 0.20 G	2004,01,01,00,15	0.0	0.2
	09/12/2007 01:13:15 0.20 G 09/12/2007 01:43:10 0.20 G 09/12/2007 01:43:29 0.20 G 09/12/2007 01:44:05 0.20 G 09/12/2007 01:44:06 --- M 12/12/2007 01:01:04 . U	2007,12,09,01,45 2007,12,09,02,00 to 2007,12,12,01,00	0.6 Missing	Missing 0.0
Chilgrove	29/12/2003 16:48:40,0.20, G,., 01/01/2004 01:01:50,0.20, G,.,	2003,12,29,17,15 to 2004,01,01,01,00	0.0	Missing
	27/03/2004 06:51:20,0.20, G,., 30/03/2004 10:32:10,0.20, G,., 30/03/2004 10:32:11,0.20, G Ed,., 01/04/2004 19:00:39,0.20, G Ed,., 01/04/2004 19:00:40,0.20, G,., 01/04/2004 19:03:50,0.20, G,., 01/04/2004 19:04:40,0.20, G,., 01/04/2004 19:07:00,0.20, G,., 01/04/2004 19:12:00,0.20, G,., 01/04/2004 19:13:00,0.20, G,., 01/04/2004 19:14:00,0.20, G,., 01/04/2004 19:21:40,0.20, G,.,	2004,03,30,10,45 2004,04,01,19,15	0.4 1.6	0.2 1.4
	30/04/2004 12:08:40,0.20, G,., 30/04/2004 12:30:50,0.20, G,., 30/04/2004 12:30:51,0.20, G Ed,., 03/05/2004 10:37:59,0.20, G Ed,., 03/05/2004 10:38:00,0.20, G,., 03/05/2004 11:05:40,0.20, G,.,	2004,04,30,12,45 2004,05,03,10,45	0.4 0.4	0.2 0.2
Duncton	N/A CEH and EA 15 minute totals agreed			
Fishbourne	09/12/2007 01:44:30,0.20, G,., 09/12/2007 01:49:38,0.20, G,., 09/12/2007 01:49:39,---, M,---, 20/12/2007 01:01:47,., G,.,	2007,12,09,02,00 2007,12,09,02,15 to 2007,12,20,01,00	0.2 Missing	Missing 0.0

Havant	30/05/1995 20:21:00,0.20, G,., 01/06/1995 09:05:00,---, M,---, 11/07/1995 09:00:00,., G,.,	1995,05,30,20,45, to 1995,06,01,09,00, 1995,06,01,09,30, to 1995,07,11,08,45	0.0 Missing	Missing 0.0
	10/02/1997 09:00:00,1.20, S,., 10/02/1997 09:05:00,---, M,---, 11/02/1997 09:00:00,., G,.,	1997,02,10,09,30, to 1997,02,11,08,45,	Missing	0.0
	05/12/2000 17:37:20,0.20, G,., 06/12/2000 10:58:00,---, M,---, 25/01/2001 19:00:32,0.20, G,.,	2000,12,05,18,00, to 2000,12,06,10,45, 2000,12,06,11,15, 2001,01,25,19,00,	0.0 Missing	Missing 0.0
	11/02/2005 20:56:49,0.20, G,., 12/02/2005 04:43:40,---, M,---, 10/03/2005 21:51:01,0.20, G,.,	2005,02,11,21,15, to 2005,02,12,04,30, 2005,02,12,05,00, to 2005,03,10,21,45,	0.0 Missing	Missing 0.0
Walderton	13/01/1998 23:22:00,0.20, G,., 14/01/1998 00:44:00,0.20, G,., 14/01/1998 00:59:00,---, M,---, 03/02/1998 14:20:00,., G,.,	1998,01,14,00,45 1998,01,14,01,00 1998,01,14,01,15 to 1998,02,03,14,15	0.2 Missing Missing	Missing Missing 0.0
	28/10/2007 19:20:16,0.20, G,., 29/10/2007 00:43:57,0.20, G,., 29/10/2007 00:43:58,---, M,---, 03/11/2007 00:45:04,., G,.,	2007,10,29,00,45 2007,10,29,01,00 to 2007,11,03,00,45	0.2 Missing	Missing 0.0
	13/11/2007 00:35:44,0.20, G,., 13/11/2007 01:40:57,0.20, G,., 13/11/2007 01:41:28,0.20, G,., 13/11/2007 01:41:29,---, M,---, 15/11/2007 00:54:35,., G,.,	2007,11,13,01,45 2007,11,13,02,00 to 2007,11,15,00,45	0.4 Missing	Missing 0.0
	09/12/2007 01:44:02,0.20, G,., 10/12/2007 01:12:39,0.20, G,., 10/12/2007 01:12:40,---, M,---, 19/12/2007 00:59:42,., G,.,	2007,12,10,01,15 2007,12,10,01,30 to 2007,12,19,00,45	0.2 Missing	Missing 0.0

Table B.3 Summary of raingauge data quality control.

Raingauge	Period in file	Comment
Chichester	14/09/1994 00:45:00 0.20 to 08/10/1994 15:06:00 0.20	Suspect. Raingauge appears to be blocked, treat as missing for modelling. Use Walderton.
	13/11/1995 02:17:00 0.20 to 01/12/1995 05:36:00 0.20	Suspect. Does not agree with daily raingauge record or Walderton. Treat as missing.
	01/12/1995 05:36:00 0.20 04/01/1996 15:41:00 0.20	Suspect. No data for this period but 70mm+ at Walderton and rain at daily gauges. Treat as missing.
	05/11/1996 00:01:00 0.20 11/01/1997 11:02:00 0.20	Treat as missing. No rain for 2 months but rain at daily gauges. Note Walderton missing for the same period.
	11/01/1997 11:02:00 0.20 to 17/02/1997 17:41:00 0.20	Suspect. Chichester and Walderton time-of-tip records are identical for this period. Daily gauges suggest Chichester data.
	17/02/1997 18:43:16 0.20 to 04/07/1997 08:16:32 0.20	Suspect. Chichester and Walderton 15 minute totals are almost identical for this period.
	01/05/1998 12:02:05 0.20 24/06/1998 09:07:08 0.20	Suspect. Only 5 tip values during this period and all are over 0.2mm. Treat as missing.
	27/06/1999 12:00:00 2.20 G 28/06/1999 17:07:40 14.60 GEd 29/06/1999 12:07:40 0.40 G 30/06/1999 12:00:00 3.20 G	Suspect sequence of tip values. Look like valid daily totals. Record is missing afterwards.
	19/05/2000 09:17:40 0.20 27/05/2000 15:24:36 0.20	Suspect. Appears blocked and much less rain than other sites (including daily gauges). Treat as missing.
	13/08/2000 20:21:44 0.20 28/08/2000 11:27:20 0.20	Appears to have a blockage. Cumulative totals may be ok.
	15/09/2000	Chichester had 70-80mm less rainfall than Walderton and Chilgrove. Checked daily data with EA and treated as missing.
	07/01/2001 06:18:12 0.20 S 03/02/2001 03:47:04 0.20 S	Treat as missing. No data for this period which rain at Fishbourne + daily gauges. Suspect in EA notes.
	11/10/2001 12:37:55 . G 17/10/2001 23:25:00 0.20 G	Suspect. Appears to be missing for this period. Coincides with a value of "." - does this mean missing?
	05/12/2001 15:56:58 . G 09/12/2001 09:25:20 0.20 S 09/01/2002 19:44:30 0.20 G	Suspect. Treat as missing. Rain at Fishbourne + daily gauges. Suspect in EA notes.
	20/05/2002 19:20:50 0.20 G 22/05/2002 15:36:50 0.20 G	Appears to have a blockage. Cumulative totals may be ok.
	22/10/2002 04:45:00 0.20 G to 29/11/2002 15:28:00 0.20 G	Suspect. Raingauge is blocked. Cumulative totals may be ok. Suspect in EA notes.
	22/09/2003 14:52:10 0.20 G 11/01/2004 03:00:00,., U	Suspect. Raingauge is blocked. Cumulative totals may be ok.
	10/09/2004 00:36:53 0.20 G to 24/12/2004 13:21:52 0.20 G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn't tie in with radar.
	24/10/2005 18:04:41 0.20 G to 31/12/2005 04:08:28 0.20 G	Suspect raingauge is blocked. Cumulative totals may be ok.
	08/11/2007 01:40:05 . G to 27/06/2008 02:04:30 0.20 G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn't tie in with radar.

Chilgrove	04/09/2001 04:15:02,0.20, G 11/09/2001 09:00:00,---, M	No data for this period but rain elsewhere and for daily gauges (CEH). Treat as missing.
	29/05/2002	Suspect values all > 0.2mm including 15.4mm. No rain at other gauges, assume incorrect and missing.
	20/11/2003 01:10:00,0.20, G to 27/11/2003 13:30:10,0.20, G Ed	Raingauge is blocked. Cumulative totals maybe ok.. Noted in EA comments.
	25/09/2004 01:15:42,., G,to 02/11/2004 01:27:13,., G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn't tie in with radar.
	21/08/2006 07:23:49,0.20, G to 03/10/2006 06:15:54,0.20, G	Suspect. Raingauge blocked. Also noted in EA comments.
	11/10/2007 13:04:28,0.20, G to 17/10/2007 05:02:25,0.20, G	Suspect. Records 22.0mm on 11th when no little or no rain (radar + other rgs). Under-records on 16/17th.
Duncton	07/08/2002	30.6mm in 1.5 hours. No rain at other stations. Storage gauge and radar suggest this was due to an isolated shower. No action required.
	25/03/2003 13:15:20,0.20, G 31/05/2003 10:53:10,0.20, G	Suspect recording rain when dry. Treat as missing. Doesn't agree with storage gauges (CEH) or radar. The Environment Agency believe that May 2003 was mistakenly entered as April 2003 – FMD have been informed.
	29/10/2003 22:39:40,0.20, G 09/11/2003 11:17:20,0.20, G	Suspect. Treat as missing. No data for this period but rain at others and on radar/daily gauges (CEH).
	29/11/2003 06:52:10,0.20, G to 01/12/2003 22:36:00,0.20, G	Suspect Duncton over-recording rain during this period. Compared to daily (CEH), radar and other rgs.
	01/12/2003 22:36:00,0.20, G to 15/01/2004 14:56:00,0.20, G	Only a few tips recorded by Duncton but rain at daily gauges and radar so treat as missing.
	25/08/2004 04:03:11,., G Ed 10/09/2004 22:17:43,., G	Suspect, treat as missing. No data recorded for this period but rain on radar and other rgs.
	25/10/2005 09:17:05,0.20, G to 03/11/2005 14:52:30,0.20, G	Suspect raingauge is blocked. Cumulative totals may be ok.
	30/11/2005 18:00:51,., G to 30/03/2006 18:51:10,0.20, G	Suspect raingauge is blocked. Cumulative totals may be ok. (EA comment says blocked in Mar 2006).
Fishbourne	06/11/2002 03:00:50,0.20, G to 20/11/2002 07:17:30,0.20, G	Suspect. Raingauge is blocked. Cumulative totals may be ok.
	30/10/2003 12:01:40,0.20, G to 27/11/2003 10:42:50,0.20, G	Suspect. Raingauge is blocked. Cumulative totals may be ok.
	22/06/2004 16:01:30,0.20, G 07/07/2004 14:30:48,0.20, G	Suspect. Raingauge is blocked. Cumulative totals may be ok.
	06/10/2004 09:10:34,0.20, G 04/11/2004 10:16:15,0.20, G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn't tie in with radar.
	19/05/2005 07:02:42,0.20, S to 25/05/2005 20:06:58,0.20, S	Suspect raingauge is blocked. Also noted by EA as under recording (6/4/05-1/5/06). Treat as missing.
	01/05/2006 07:47:28,0.20, S 24/05/2006 17:44:55,0.20, G	No data for this period but rain elsewhere and at daily (CEH) and radar. Also noted by EA as under recording (6/4/05-1/5/06). Treat as missing.
	08/11/2007 01:36:59,0.20, G 27/06/2008 00:54:56,0.20, G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn't tie in with radar.

Havant	11/08/1991 01:20:00,0.20, G, 27/08/1991 13:45:00,0.20, G 24/09/1991 15:00:00,0.20, G	Only one tip recorded for over a month but rain 22-23/08 and 14-16/09 at daily gauges (CEH). Treat as missing and use Walderton.
	28/09/1991 04:04:00,0.20, G to 29/09/1991 05:37:00,0.20, G	Suspect. Heavy rain at daily gauges (CEH). Treat as missing and use Walderton.
	04/01/1992 02:21:00,0.20, G to 02/03/1992 22:11:00,0.20, G	Suspect blocked. Daily totals look ok.
	25/08/1992 04:40:00,0.20, G to 01/09/1992 15:35:00,0.20, G	No rain recorded for a week but rain at daily gauges (CEH). Treat as missing and use Walderton.
	05/02/1997 09:00:00,14.60, S to 11/02/1997 09:00:00,., G	Suspect. Daily totals may have been used. Suspect in EA notes too. Use Chichester (Walderton not available).
	17/02/1997 12:48:04,0.20, G to 19/02/1997 14:11:30,0.20, G	Suspect blocked. Daily totals may be ok.
	17/08/1999 19:05:04,0.20, G to 08/09/1999 07:48:48,0.20, G	No rain recorded but rain at daily gauges (CEH). Treat as missing and use Walderton.
	20/05/2000 21:54:48,0.20, G to 21/05/2000 17:12:04,0.20, G	Suspect blocked. Daily totals may be ok.
	09/07/2000 21:46:40,0.20, G to 08/08/2000 08:15:52,0.20, G	Suspect. No rain recorded but some rain at daily gauges (CEH). Treat as missing and use Walderton.
	05/07/2004 04:52:33,0.20, G to 17/07/2004 10:08:38,0.20, G	Suspect. No rain recorded but rain 07/07 at daily gauges (CEH) and at Walderton. EA notes RTS data being used. Treat as missing and use Walderton.

Walderton	26/11/1991 08:41:00,0.20, G 04/01/1992 02:04:00,0.20, G	No rain recorded for over a month but rain at Chichester 14-20/12 + daily gauges. Treat as missing.
	19/10/1992 07:28:00,0.20, G 09/07/1993 12:03:00,0.20, G	Walderton should be treated as missing between these dates.
	18/12/1994 07:56:00,0.20, G to 30/12/1994 04:00:00,0.20, G	Walderton appears to be blocked. Treat as missing and use Chichester.
	10/02/1995 03:02:00,0.20, G to 16/02/1995 15:37:00,0.20, G	Walderton appears to be blocked. Treat as missing and use Chichester.
	04/06/1995 11:39:00,0.20, G 23/08/1995 14:55:00,0.20, G	No rain for ~2 months, whilst rain at Chichester and daily gauges (CEH). Treat as missing.
	04/11/1996 13:20:00,0.20, G 11/01/1997 11:02:00,0.20, G	Treat as missing. No rain for 2 months but rain at daily gauges. Note Chichester missing for the same period.
	11/01/1997 11:02:00,0.20, G to 17/02/1997 17:41:00,0.20, G	Suspect. Chichester and Walderton time-of-tip records are identical for this period.
	17/02/1997 18:43:00,0.20, G to 04/07/1997 08:16:00,0.20, G	Suspect. Chichester and Walderton 15 minute totals are almost identical for this period.
	04/07/1997 08:16:00,0.20, G 18/11/1997 15:44:00,0.20, G	Walderton should be treated as missing between these dates.
	04/01/1999 07:07:01,0.20, G 21/03/1999 07:54:04,0.20, G	Walderton should be treated as missing between these dates.
	04/01/2001 11:12:57,0.20, G to 13/02/2001 03:36:52,0.20, G	Suspect blocked. Treat as missing.
	31/07/2003 09:11:00,0.20, G to 04/09/2003 10:27:00,0.20, G	Suspect not recording. Only one tip in this period when should have rain on 28-29/08. Treat as missing.
	06/10/2004 13:24:24,0.20, G 04/11/2004 08:00:00,0.20, G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn’t tie in with radar.
	10/03/2005 14:09:59,0.20, G to 10/03/2005 15:30:15,0.20, G	Suspect, treat as missing. Recorded 14.4mm in 1h 20min when little rain on radar or at other rgs.
	03/11/2007 00:45:04,., G to 30/05/2008 00:32:56,0.20, G	15 minute totals suspect. Daily totals appear ok but all recorded during a small window of time (typically 00 – 02 hours) that doesn’t tie in with radar.
	08/02/2008 00:37:32,., G 16/04/2008 01:10:43,0.20, G	Suspect under-recording. EA note indicate vandalism during this period.