Basinwide flood-risk mapping: beware hydropendicitis

Duncan W Reed

DWRconsult, 32 Ilges Lane, Cholsey, Oxfordshire, OX10 9PA, UK
duncanreed@dwrconsult.demon.co.uk

ABSTRACT

Basinwide flood-risk mapping has become semi-standard in the UK. The undue dominance of hydraulic modeling over hydrological analysis is discussed, and a number of flaws noted. It is suggested that the study of *inter-site dependence* in flooding can contribute to improved practice in flood-risk mapping. This will only happen if river modelers in the UK acknowledge the neglect of data analysis.

INTRODUCTION

Computational fluid dynamics is a large and important area of science. There are applications where a better understanding of fluid flow can save lives and, potentially, the planet. Mathematical modeling of flows and depths in rivers and floodplains is also valid, with important applications in design, real-time forecasting and control. But, when applied to flood-risk estimation*, basinwide river modeling* is a disease so virulent that it needs a name. *Hydropendicitis* is endemic in the UK. The obsession with modeling submerges the truth that flood-risk estimation is fundamentally a statistical problem.

Trends in flood-risk mapping

The desired end-product – a comprehensive map of flood risk – sweeps all before it. Hydraulic modeling comes to the front, flanked by riverine, topographic and infrastructural survey. Hydrological analysis is relegated to the chorus line: supplying inputs to the river modeler. Critically, frequency analysis retreats.

Spatial detail is valued. The division of river reaches and catchments into sub-reaches and subcatchments becomes routine. The number of *intervening catchments* – from which inflows to the river model have to be synthesized – escalates. Yet these are false catchments to which methods for real catchments may not transfer.

33rd IAHR Congress: Water Engineering for a Sustainable Environment

ISBN: 978-94-90365-01-1

Symptoms of addiction to basinwide river modeling include: peculiar language (e.g. *FEH rainfall-runoff boundary*), scaling factors (to adjust hydrographs to a best-estimate *T*-year flood peak), subtractions (to infer contributions from intervening catchments) and iterations (to determine the design storm duration yielding the largest flood level in the particular reach). The detail is difficult to digest and is typically consigned to appendices: hence the name *hydropendicitis*.

In the UK, the client purrs at the visual quality of the maps and is content that the contractor has followed guidelines to use Flood Estimation Handbook (FEH) methods. Yet the FEH maxims on flood frequency estimation (Reed and Houghton-Carr, 1999) relate to site-focused not basinwide application:

- Flood frequency is best estimated from gauged data;
- While flood data at the subject site are of greatest value, data transfers from a nearby site, or a similar catchment, are also very useful;
- Estimation of key variables … from catchment descriptors alone, should be a method of last resort; some kind of data transfer will usually be feasible and preferable;
- The most appropriate choice of method is a matter of experience, and may be influenced by the requirement of the study and the nature of the catchment; most importantly, it will be influenced by the available data;
- In some cases, a hybrid method – combining estimates by statistical and rainfall-runoff approaches – will be appropriate;
- There is always more information; an estimate based only on readily available data may be shown to be suspect by a more enquiring analyst.

The validation problem

Mathematical modelers are trained to distinguish calibration and validation phases. If the validation is skimped in a real-time forecasting application, one may wait months or years for a performance assessment. But feedback will arrive within hours of a flood warning being issued or a flood arriving unannounced.

Validating a flood-risk map is much more problematic. The *spatial element* of a map can sometimes be tested. Documentary evidence (ancient or modern) of a major flood may confirm or contradict the general configuration of the mapped footprint. Higher resolution topographic survey can also help to test its reasonableness. In contrast, the *frequency element* of a flood-risk map can never be validated. If the estimate is very poor (and especially if the flood extent is grossly underestimated), it can sometimes be *invalidated*.

Basinwide modeling approach

The basinwide modeling approach to flood-risk mapping seeks to be generic. The goal is to model *T*-year flood flows, levels and flood extents throughout a river basin: or at least along much of the main stem. A mathematical model of the river channel and floodplain is linked to representations of flood flows in various tributaries. It is a natural approach: one that exploits detailed survey data and the hydraulician's drive to model. Success requires an iterative approach so that the final outputs reflect:

- The detailed simulations of the hydraulic model;
- The *T*-year flood estimates from the hydrological analysis of flow data;
- Such local/historical flood data as are available.

There is a tension between the regulator's wish to have a flood-risk map that is unified (though monolithic) and one that is technically and legally supportable (by respecting local information and/or more detailed studies). The contradiction is perhaps at its most obvious in the (lack of) combined mapping of fluvial, pluvial, groundwater and sewer-related flood risk.

Because it cannot be validated, the frequency element of a flood-risk map can be challenged only by listing flaws in the basinwide modeling approach. In the UK at least, so much is invested in the approach that criticism is ignored or misconstrued.

FLAWS IN THE BASINWIDE MODELING APPROACH

Double-accounting for floodplain storage

In the 20-year to 200-year frequency range typical of basinwide flood-risk maps, floodplain storage tends to delay and attenuate the passage of a flood. The effect of storage is already embedded in the flood peak data used in site or regional flood frequency estimation. Where the river modeler explicitly models flow into and across the floodplain, the attenuating effect of storage is represented twice. In the absence of other defects, flood risk will be underestimated.

Data disrespecting

In intensively developed river systems, water levels are measured at many sites. It is commonplace for there to be ten or more river-flow measurement stations sites in major UK basins. Inevitably, some stations measure flood flows better than others.

The selection of stations requires more than hydrometric understanding. An experienced flood hydrologist will seek to exploit *all* data, taking due account of hydrometric quality, length of record and hydrological similarity/relevance. This record is so close to the subject site that it must be considered. That station is of poor quality but there are historical (i.e. pre-instrumental) flood data also. This site gauges only 20% of the catchment but its long-term record makes it highly relevant.

The lack of spatial focus inhibits similar judgements in a basinwide study. If the river model is adjusted to conform to a best estimate of flood flow frequency and flood level frequency at one site, there will be anomalies elsewhere. Instead of using data from all sites in the basin, the tendency is to major on just a few stations and to find reason to disregard those that appear anomalous. Too often, judgements in the basinwide approach lean towards promoting conformity within the hydraulic model and away from hydrological reasoning. This degrades flood-risk estimation.

Rating wrecking

Some river modelers reduce or extinguish anomalies by using the basinwide hydraulic model to condemn or redefine the flood rating at a gauging station. Hydraulic understanding, detailed site-survey and mathematical/physical modeling of channel and floodplain flow may all have valid roles in the *interpretation* and *extrapolation* of stage-discharge relationships. However, it is a scandal that some river modelers no longer distinguish site-specific and generic models, and assassinate data in the belief that modeled values are superior. How can a professional reject a rating curve without examining and rejecting its supporting data? How can *modeled* values be more valid than *measurement* on the prototype?

Other concerns

The Environment Agency of England and Wales strongly discourages the use of steady-state methods where flood storage is present. In consequence, hydrodynamic models are routinely used for basinwide flood-risk mapping, with the demand for the hydrologist to supply sets of inflow hydrographs rather than peak flows.

Several features of current practice can be considered reasonable in the small river basins (~ 100 to 1000 km^2) typical of UK conditions:

- A design event method (i.e. a rainfall-runoff method) is used and a search made for the design storm duration yielding the highest modelled flood level in the relevant reach;
- Inflow hydrographs combined in a particular model-run derive from a single catchment-wide design storm;
- The entire procedure is repeated reach by reach;
- The outputs from several separate runs of the river model are merged to form the final flood-risk map.

But this counts for nothing if the modeler neglects relevant information on flood-risk or overlooks that a reach is sensitive to partial-area floods (see Box 1).

A SITE-FOCUSED APPROACH TO BASINWIDE FLOOD-RISK MAPPING

An alternate approach to flood-risk mapping is to treat each important section of the river as a separate flood-risk assessment problem. Studies are repeated for each important site in the river basin. Rather than invoking a basinwide river model, hydraulic methods are used to achieve a basinwide map by interpolating and integrating the resultant flood-risk estimates along the river.

Box 1 **Pronounced storage in upper catchment leads to sensitivity to heavy rainfall events on lower catchment**

The upper section of the Letcombe Brook in central Southern England drains a highly permeable ~17 km^2 section of the scarp slope of the Berkshire Downs. Through rapid interchange with groundwater, it also drains about 8 km^2 of the dip slope. The brook then descends onto the Vale of White Horse. This is relatively flat, and with soils that are much less permeable. It immediately passes through the ancient but developing town of Wantage and the newer town of Grove.

Because of the contrasting geologies, and the disposition of urban areas, Grove is sensitive both to (typically) winter flooding from the whole catchment, and to (typically) summer flooding from an intense storm on the lower catchment. This dual sensitivity increases the flood risk notably. Even if the partial-area scenario is recognised, and identified as important, the practice of basing the flood-risk map on the worse of the two cases will *underestimate* the total flood risk.

Of course, there will be inconsistencies. The important difference is that the anomalies will lead the hydrologist and hydraulician to work together to resolve them through enquiry and further study. Attention will focus on significant rather than cosmetic features. How does flood frequency change at that major confluence? Have historical flood data at this site been given too much weight? In rivers with large storage in their headwaters, at what stage – *down* the river system, and *up* the return-period axis – does the flood risk presented by the whole catchment begin to rival and then eclipse that presented by the local (i.e. intervening) catchment?

Sadly, the dominance of modeling over analysis, of hydraulician over hydrologist and of appearance over content has all but outlawed this approach from UK practice. Even in a lowland river having more than a century of head-water and tail-water level records at 44 weirs along its course, the approach taken to flood-risk mapping is dominated by modeling rather than data analysis. A Planning Inspector finds that the Lower Thames flood-risk map is contradicted by water-level records and upholds an appeal (Newman, 2008). Under guidance from the Environment Agency of England and Wales, the contractor adjusts how flood flows at a key site are estimated. The flood-risk mapping continues to major on modeling and to disrespect data.

NON-STATIONARITY

It is often stated that *changes* – in the river, its catchment or climate – undermine the relevance of past behaviour. While there is some truth in this, the implication that modeling should displace analysis is over-stated.

An attempt can be made to use models to adjust past data to the current or projected condition. This is preferable to the alternative of deleting data. It is shameful that older data are sometimes ignored without even testing that the effect of doing so is consistent (in the *sign* of the change in flood risk) with the change purported!

HOW DEPENDENCE MODELING MIGHT HELP

Inter-site dependence

Correlation is an association between variables. The word dependence carries a similar but less rigid meaning. This is helpful when trying to think more widely about relationships and behaviours. Inter-site dependence is the tendency for behaviour at one site to be linked to behaviour at another.

The study of inter-site dependence in extremes has typically been driven by application. Fricke *et al.* (1983) assess the vulnerability of a mineral railway to flood-induced failure along its route. Dales and Reed (1989) study inter-site dependence across networks of sites to gain understanding of the clustering in space and time to be expected of extreme rainfalls. Stewart *et al.* (1999) present a wider review.

Inter-site dependence in river flooding is more complicated than inter-site dependence in rainfall extremes. It reflects spatial dependence in rainfall (and snowmelt), spatial dependence in antecedent conditions, spatial variation in catchment properties, and, of course, river-network structure.

Types of dependence relevant to basinwide flood-risk mapping

Two types of inter-site dependence are relevant to basinwide modelling: the primary dependence between sites lying upstream-downstream, and the secondary dependence between flows in confluent tributaries. The first kind is relevant to determining the reasonableness of attempting to model a given chunk of river basin within a single river model. The second kind is relevant to judging rules for combining tributary and main-stem flood hydrographs in river models.

Following the approach of Reed (2002), inter-site dependence is here summarized by the rank correlation, r, of annual maximum floods. A value of 1.0 indicates complete dependence, a value of 0.0 indicates independence, and a value of -1.0 indicates complete counter-dependence. r is a simple and relatively robust measure, e.g. it is largely insensitive to systematic error in rating curves. Robustness is relevant when many station-pairs are being studied.

Generalizing a model for upstream-downstream dependence

Using HiFlows-UK (see http://www.environment-agency.gov.uk/hiflows/) data, 504 upstream-downstream station-pairs in Great Britain were found to have complete annual maximum series for 1981 through 2000. Appreciable dependence is, of course, expected for most upstream-downstream station-pairs. The median value of across the 504-pair dataset is 0.71. Only one station-pair yields a value of significantly less than zero: a value of -0.20 for the large upland (heavily regulated) Tay at Ballathie catchment and a minor lowland tributary (the Dean Water).

After exploratory data analysis, and considering a wide range of pairwise catchment descriptors, the following model was derived by multiple regression analysis:

$$= 0.556 + 0.273\, AREA_{\mathrm{rat}} + 0.449\, SAAR_{\mathrm{rat}} - 0.278\, SPRHOST_{\mathrm{rat}} - 0.00485\, ICD \quad [1]$$

This explains 46.1% of the variation in r across the 504 upstream-downstream station-pairs. *AREA* is drainage area, *SAAR* is average annual rainfall and *SPRHOST* is standard percentage runoff estimated by Boorman *et al.* (1995) from soil maps. *ICD* is inter-centroid distance in km between upstream and downstream catchments.

The terms $AREA_{\mathrm{rat}}$, $SAAR_{\mathrm{rat}}$ and $SPRHOST_{\mathrm{rat}}$ are ratios of the relevant catchment descriptor values at upstream and downstream sites: *the ratio in each case being calculated as the smaller value divided by the larger*. Defining the descriptors in this manner ensures that the model of pairwise dependence respects the commutative nature of inter-site dependence, i.e. A is to B as B is to A.

The generalized model represents the greater dependence expected between catchments that almost coincide (i.e. as $AREA_{\mathrm{rat}}$ increases towards 1.0 and *ICD* reduces). Remarkably, Equation 1 precisely meets the criterion $r = 1$ when upstream and downstream sites coincide. [With r, $AREA_{\mathrm{rat}}$, $SAAR_{\mathrm{rat}}$ and $SPRHOST_{\mathrm{rat}}$ each replaced by their complement, the intercept term in the regression was found to be not significantly different from zero.]

The sign of the $SAAR_{\mathrm{rat}}$ term is consistent with homogeneity in topography and climate promoting dependence. It should be recalled that dependence in flooding reflects spatial dependence in catchment wetness as well as that in heavy rainfall.

The sign of the $SPRHOST_{\mathrm{rat}}$ term is more difficult to interpret. It seems curious that the degree of dependence is modeled to be greater when the soils intervening between the upstream and downstream sites contrast with those of the upstream catchment. One possibility is that the term reflects that pre-event catchment wetness is more influential (in promoting upstream-downstream dependence in flooding) in river basins of mixed permeability (i.e. with heterogeneous soils).

As hinted at in Box 1, the configuration of any major storage or intensive urbanization can be expected to influence the degree of upstream-downstream dependence. Such effects are not explicitly represented in Equation 1. That the model yields a value of exactly 1.0 when upstream and downstream site coincide does, however, encourage a degree of belief in its usefulness.

Dependence maps

Though instructive and analytically precise, studies of pairwise dependence can be difficult to summarize and digest. Reed (2008) uses *multi-dimensional scaling* (e.g.

Cox and Cox, 2000) to map inter-site dependence in flood extremes across specific river basins: both primary (upstream-downstream) and secondary (inter-tributary).

CONCLUSIONS

Some aspects of UK practice in basinwide flood-risk mapping have been reviewed. It is suggested that more attention be paid to data analysis and less to river modeling.

Studies of inter-site dependence have relevance for deciding how to structure design inflows to a river model and how large a chunk of river basin can sensibly be treated in any one river model.

REFERENCES

Boorman, D.B., Hollis, J.M. and Lilly, A. (1995). *Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom*. Rep. No. 126, Institute of Hydrology, Wallingford, 137pp.

Cox, T.F. and Cox, M.A.A. (2000). *Multidimensional scaling*. 2nd edn, Chapman and Hall, 328pp.

Dales, M.Y. and Reed, D.W. (1989). *Regional flood and storm hazard assessment.* Rep. No. 102, Institute of Hydrology, Wallingford, 159pp.

Fricke, T.J., Kennedy, M.R. and Wellington, N.B. (1983). The use of rainfall correlation in determining design storms for waterways on a long railway line. *Proc. Hydrol. & Wat. Resour. Symp.*, Hobart, Nov 1983, 5pp.

Newman, A.S. (2008). Appeal Decision ref: APP/Q3630/A/07/2049482. UK Planning Inspectorate, 25 Mar 2008.

Reed, D.W. (2002). Why analyse inter-site dependence in river flooding? *Proc. 8th BHS National Hydrol. Symp.*, Birmingham, 8–11 September 2002, 169-174.

Reed, D.W. (2008). Inter-site dependence in extremes: unlocking extra information. *Proc. FLOODrisk2008 Internat. Conf.*, Oxford, 30 Sep - 2 Oct 2008.

Reed, D.W. and Houghton-Carr, H.A. (1999). Maxims for flood frequency estimation. Section 2.2 in *Overview*, Vol. 1, Flood Estimation Handbook, Institute of Hydrology, Wallingford, 5-6.

Stewart, E.J., Reed, D.W., Faulkner, D.S. and Reynard, N.S. (1999). The FORGEX method of rainfall growth estimation, I: Review of requirement. *Hydrol. and Earth System Sci.*, 3, 187-195.