ADVANCES IN THE ESTIMATION OF RIVER FLOWS WITHIN UNGAUGED CATCHMENTS: LOW FLOWS 2000

Dr. Andrew R. Young, Centre for Ecology and Hydrology – Wallingford.
Matthew G.R. Holmes, Centre for Ecology and Hydrology – Wallingford.
Dr. Robert Grew, Environment Agency National Hydrology and Hydrometry Policy

ABSTRACT

Information on the magnitude and variability of flow regimes, at the river reach scale is a central component of most aspects of water resource and water quality management. At the broadest scale, natural river flow regimes are dependent on rainfall, temperature and evaporation. At the catchment scale, the flows will be controlled by the physical properties of a catchment, including geology and land use. River flow regimes are also affected directly and indirectly by human activities.

The Environment Agency of England and Wales have developed a number of initiatives to assist in implementing the Water Framework Directive (2000/60/EC) including the development of Catchment Abstraction Management Strategies (CAMS). The main aims of CAMS are to make information on water resources and licensing practice available to the public, to provide a consistent approach to local water resources management, recognising the reasonable needs of water users and the environment, and to provide the opportunity for greater public involvement in managing the water resources of a catchment.

As part of the derivation of a CAMS for a catchment the natural flow regime has to be estimated at key assessment points within the catchment and then an assessment is made of the environmental flow requirements at each point and hence the resource available for abstraction within the catchment. In addition to overarching strategies, such as CAMS, flow estimates are required on a routine basis to support abstraction licencing and discharge consenting. The majority of these flow estimates are required for small catchments with little, or no measured flow data.

This paper summarise a suite of new modelling techniques to assist in the estimation of natural and artificially influenced river-flows within ungauged catchments and how they are incorporated within the GIS framework of the Low Flows 2000 software package. The paper will also summarise the implementation of Low Flows 2000 within England and Wales by the Environment Agency to support current Agency water resource programmes.

Key Words
Water resources; flows regimes; ungauged catchments; flow duration curves; Low Flows 2000

INTRODUCTION

In the latter half of the last century the management of water resources in the United Kingdom (UK) has progressed from a municipal level, dealing with pollution and land drainage schemes, to pioneering one of the world's first catchment-based water management schemes with the formation of the National Rivers Authority (NRA) in 1989, (Williams, 2001). The Environment Agency for England and Wales (the Agency) was formed out of the NRA, the Inspectorate of Pollution and various waste regulation authorities in 1995 and has a wide remit including the management of water resources through integrated catchment management. The Scottish Environmental Protection Agency (SEPA) operates under different legislation and has a less rigorously defined remit with respect to catchment based water resource management.

At the broadest scale, natural river flow regimes are dependent on rainfall, temperature and evaporation. At the catchment scale, the flows will be controlled by the physical characteristics of a catchment. River flow regimes are also affected directly and indirectly by human activities. The Water Framework Directive (2000/60/EC) (the Directive) adopted by the European Parliament and the Council of the European Union in September 2000 establishes a strategic framework for the sustainable management of both surface and groundwater water resources. Within England and Wales, the Agency has developed a number of initiatives to implement the Directive, which include the development of Catchment Abstraction Management Strategies (CAMS).

Low Flows 2000 is an important decision support tool currently used by the Agency, within the resource assessment component of CAMS to aid the assessment of water availability throughout England and Wales. The software is also widely used to support the determination of small abstraction licences and discharge consents within small, ungauged catchments. This paper provides some background to the CAMS process, summarises the hydrological models underpinning Low Flows 2000 and describes the implementation of the system within the Agency

BACKGROUND

The main aims of CAMS are to make information on water resources and licensing practice available to the public, to provide a consistent approach to local water resources management, recognising the reasonable needs of water users and the environment, and to provide the opportunity for greater public involvement in managing the water resources of a catchment. (Environment Agency, 2001). The technical approach for water resource assessment is defined within the Resource Assessment and Management (RAM) framework.

Implicit within any water resource management analysis, such as the RAM framework, is the need to differentiate between the natural and artificial components of stream flow. The artificial component is the influence of water use within the catchment from features such as surface and groundwater abstractions, discharges from sewage treatment plants and industrial sources and impounding reservoirs. This separation of flow components enables practitioners to assess the available resource of the catchment. In gauged catchments this separation may be accomplished by decomposition, a process of adding abstractions and subtracting discharges from a time series of gauged flow data. However, water resource assessments are often required in catchments without gauged records.
In the RAM framework river flow objectives are developed for catchments based on the sensitivity of the aquatic environment to changes in the flow regime. These are then used to identify the portions of the natural flow regime, defined by the natural flow duration curve (FDC), that are available for abstraction. An FDC is an expression of a frequency distribution of flows at a point on a river and defines the relationship between a flow of a given magnitude and the probability of exceedence. For example, the Q95 is the flow that will be equalled or exceeded 95 percent of the time. The impacts of water use scenarios on the natural flow regime are then compared to the river flow objectives to assess the resource status of the catchment. The results of this resource assessment are used within the overarching CAMS process to develop catchment scale abstraction licensing strategies.

The need to develop a rapid, nationally consistent approach to estimating natural and artificially influenced flow regimes within ungauged catchments led to the development of the Micro LOW FLOWS system in the early 1990's, Young *et al.* (2000). A revised technical specification, together with a high level of end-user consultation led to the subsequent development of Low Flows 2000, which was designed to provide an improved decision support system for the water resource managers in the UK. The system is underpinned by regionalised hydrological models, used to estimate the natural long term FDC for any UK river reach, mapped at a 1:50,000 scale, at both annual and monthly resolutions. The impact of artificial influences is simulated using a geographically referenced database that quantifies seasonal water use associated with individual features. Low Flows 2000 is a flexible system, well suited to the inclusion of additional modules, such as water quality models, in a generic GIS based environmental modelling shell.

While Low Flows 2000 was not developed specifically for the RAM framework and is not designed to provide the basis for calculating components like the environmental river flows it is a very important tool that is particularly useful in the early stages of the process. In addition to providing a consistent source of natural flow statistics, it also enables a conceptual model of each catchment to be developed, suitable assessment points located, the water balance within the catchment visualised and different water-use scenarios to be modelled. The system combines flow estimates and artificial influence data in a geographically-referenced environment to create an effective tool for identifying critical river reaches within the catchment that are most in need of protection.

LOW FLOWS 2000

Overview

A review of techniques for estimating low flow statistics for ungauged catchments from gauged catchments in the same physiographic region and/or with similar climatic characteristics is beyond the scope of this paper. However, Smakhtin (2001) provides an extensive review of low flow hydrology, including the estimation of low flows at ungauged sites. Young *et al*. (2000) present a review of the history of regionalisation of flow duration statistics in the UK in the context of models implemented within a predecessor to Low Flows 2000, Micro LOW FLOWS. Previous studies have clearly demonstrated that when flow duration curves are expressed as a percentage of the long-term mean flow (standardised), to reduce the influence of scale dependencies, the shape of the resultant standardised flow-duration curve gives a good indication of the characteristic relationship between precipitation and stream flow for a catchment. This relationship is strongly influenced by the hydro-geology of the catchment.

The natural flow statistics that may be estimated for an ungauged catchment in Low Flows 2000 include the long term mean flow and flow duration curve, monthly mean flows and flow duration curves and flow frequency curves. For this paper, the discussion is restricted to flow duration and mean flow statistics. In common with previous models, the models for estimating flow duration statistics within Low Flows 2000 are based on explaining the relationships between the curve shape (a measure of variance) and catchment hydrogeology with the estimate of a standardised flow duration curve being subsequently re-scaled by an estimate of mean flow. The models within Low Flows 2000 use a dynamic algorithm for selecting the gauged catchments used to estimate the flow duration statistics for the ungauged catchment. This represents a significant departure from previously reported regional models which all use a-priori statistical (normally multivariate regression) relationships between the flow statistics and catchment characteristics for a fixed sample of gauged catchments. Furthermore, Low Flows 2000 uses the output of a dynamic soil moisture accounting model to estimate long term mean flow rather than the simple average annual water balance formulation previously used. These hydrological models are described in detail by Holmes *et al.* (2002a & b) and are summarised in this paper in the context of the implementation within Low Flows 2000.

The Low Flows 2000 software system is a PC based package written in *Microsoft Visual Basic* that uses *Microsoft Access* for data basing and *ESRI Map Objects* for mapping and the geographical analysis. Within Low Flows 2000, a digital river network is used in conjunction with a digital terrain model (DTM) to define a catchment boundary. This boundary is then used to extract catchment values from digital grids of the catchment characteristics required as inputs to the hydrological models. The catchment boundary is also used to identify artificial influences (groundwater and surface water abstractions, discharges and impounding reservoirs) within the catchment from geo-referenced digital data sets of these influences. The models for estimating both natural flow statistics within an ungauged catchment and the impact of artificial influences are hence managed within Low Flows 2000 by a process of catchment definition, estimation of natural flow statistics and influenced flow statistics, as follows.

Catchment Definition

The first stage is to define and describe the catchment that drains through the site of interest. The catchment outlet is defined by selecting a river reach either by entering a grid reference or interactively using the mouse. Two methods of defining the catchment above the chosen point are provided: an 'analogue' climb, based on river network drainage-density, and a 'digital' climb, based on a grid derived from a digital elevation-model. Both climb methods may be used to define the same catchment and hence enable the comparison of resultant boundaries. Contextual information, such as Ordnance Survey data sets, can be displayed to assist in the selection of the most appropriate boundary.

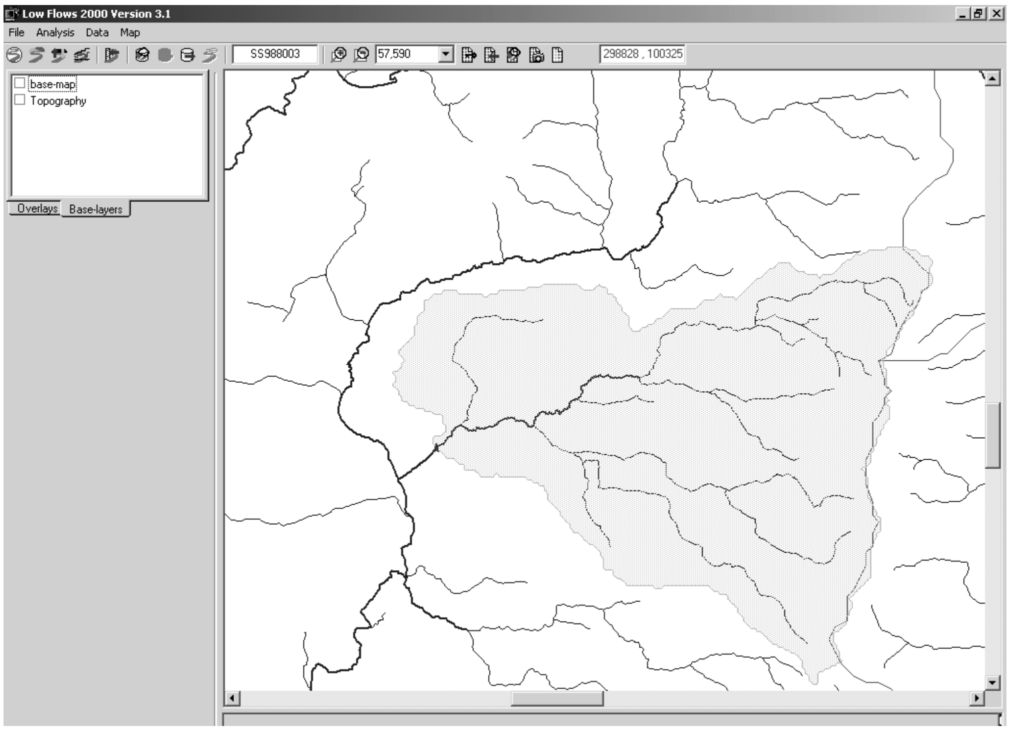

Figure 1: Example of catchment boundary definition using the Digital Terrain Model.

Within the 'analogue' method (Sekulin *et al*., 1992) a catchment is defined using the structure of a set of vectored digital river networks digitised from the 1:50 000 scale Ordnance Survey maps. The contributing catchment is estimated through the automatic assignment of cells from a grid of pre-defined resolution to individual reaches within the network. The grid cells are assigned to each reach based on a shortest distance algorithm constrained by digitised coastlines and catchment boundaries. The advantage of this method is that it relies only on the availability of a vector-layer of rivers for the study area. The accuracy of the method is constrained by the density of guiding boundaries, the density (and spatial variation in density) of the river network and the resolution of the grid used within the method. Within Low Flows 2000 a grid resolution of 200m is used as the best compromise between speed of application and accuracy of estimation within small catchments.

The 'digital' climb seeks to define a catchment on the basis of a grid of flow-directions inferred from the CEH digital terrain model. This model translates UK Ordnance Survey elevation data (50m horizontal resolution), together with the digital rivers into a network describing the inflow / outflow patterns throughout the UK (Morris & Heerdegen, 1988, Morris & Flavin, 1990). In this method catchments are defined by building-up the set of points with flow-directions leading toward the chosen outlet. Figure 1 shows an example of catchment boundary definition from Low Flows 2000 using the DTM for a sub-catchment of the River Exe, Devon. The figure presents the river networks together with the defined catchment as shaded polygon.

In practice, the DTM may fail to define an appropriate catchment boundary in low relief areas (particularly in wide alluvial valleys). Furthermore, the method defines an accurate topographic boundary which may not be relevant in groundwater fed catchments where the groundwater boundary might not coincide with the topographic boundary. By an appropriate use of constraining boundaries, the analogue method can be used to resolve many of these problems.

Estimation of Natural Flow Statistics

A catchment climb using the analogue or digital method generates a two-dimensional array of grid cells describing the extent of the ungauged catchment, around which a vector-polygon is drawn to represent the catchment boundary. This boundary is overlaid on one kilometre resolution spatial digital grids to develop a set of key catchment characteristics. These characteristics are the Meteorological Office Standard period 1961-90 Average Annual Rainfall, (SAAR (61-90); Spackman, 1993), 1961-90 Average Annual Run-Off (ARRO(61-90); Holmes *et al*., 2002b) and the fractional extents of the 30 class Hydrology Of Soil Types soils classification (HOST; Boorman *et al*., 1995). HOST consists of 29 soil classes and one class representing surface waters and is held in Low Flows 2000 as a set of 30 grids detailing the fractional extent of individual classes within each 1-km^2 cell. HOST is used as a surrogate for an equivalent hydro-geological classification of the UK and substrate hydro-geology is a key classification element within HOST.

The long term standardised natural flow duration curve is estimated for the ungauged catchment by selecting a group of ten similar catchments from a reference source pool of gauged catchments and taking a weighted average of the observed flow statistics for the selected catchments. The dynamic construction of a group/region, based upon the similarity of the characteristics of the gauged catchments to those of an ungauged catchment, was originally termed the Region of Influence (ROI) approach by Burn (1990). The ROI method has been used in flood estimation, for example by Robson and Reed (1999) and Burn and Goel (2000). The adaptation and use of the approach for estimating flow duration statistics is described fully by Holmes *et al.* (2002a). In the context of estimating flow duration statistics, catchment similarity is evaluated using a weighted Euclidean distance measure, based on the similarity of soil classes as represented by HOST classes, between the ungauged catchment and the candidate gauged catchments from a reference pool of catchments. The observed flow duration statistics for the ten most similar gauged catchments are then averaged, weighted by Euclidean distance, to produce an estimate of the flow duration curve at the ungauged catchment.

An estimate of the long term natural mean flow for an ungauged catchment is obtained by re-scaling an estimated value of ARRO by the catchment area calculated from the boundary generated by the catchment climb process. The ARRO grid was derived from the output of a daily time-step, regionalised soil moisture accounting model based on Penman drying curve theory (Grindley, 1970) and calibrated against stream flow data (Holmes *et al.*, 2002b).

Long term natural mean monthly flows are calculated using a ROI approach where similarity is measured with respect to both HOST classes and average annual rainfall. Long term natural average flow duration curves for specific calendar months, are generated in an identical manner to the long term average flow duration curves. These standardised curves are re-scaled by the long term natural mean monthly flows.

The use of the ROI technique in Low Flows 2000 requires the observed flow duration statistics for the reference pool of gauged catchments, together with the requisite catchment characteristics of catchment HOST classes and average annual rainfall, to be stored within a database. The estimated natural flow statistic are presented by the software through a synoptic report-form which supports visualisation and manipulation of the data including the generation of 'seasonal' flow-duration series by the aggregation of monthly series.

Estimation of artificially influenced flow statistics

To incorporate the impact of artificial influences on the natural flow regime, the catchment boundary is used to query a geo-referenced database of influence features within the software. These features currently include surface and groundwater abstractions, impounding reservoirs and discharges. The information held for these features may be very complex; for example, a licence to abstract may relate to as many as 40 distinct sites which in turn may be licensed for abstraction relating to multiple purposes. The licensed quantities for the whole licence, its constituent sites and individual purposes may also be highly inter-dependent. These features, attributes and relationships, are stored within a data-model based on the Water Information System (WIS) (Moore, 1997). The strength of the data-model lies in its ability to associate any number of attributes with a given feature, including time-series at any resolution. Information relating to artificial influences may be bulk loaded into this database or entered interactively via the software.

Artificial influence sites are quantified in terms of a typical monthly volume for each calendar month within the year; this is termed a monthly profile. In the case of abstraction licences and discharge consents the monthly volumes relate to water that is either abstracted or discharged. The software will use actual recorded data, if loaded, to represent the monthly profile for a site, or if no actual data is available the software will estimate a profile based on authorised volumes and patterns observed in historical data (Bullock *et al.*, 1994). For reservoirs, however, the monthly profiles represent a combination of estimates of spill volumes and compensation/regulation releases for each month. Due to these complexities the user is required to supply a bespoke profile for reservoirs.

For abstractions from groundwater, an estimate of the impact of the monthly abstraction profile on the nearest river reach is derived. This is derived using an algorithm based upon the Jenkins superposition method (Jenkins, 1970), applied to the Theis analytical solution for predicting the impact of a groundwater abstraction from a phreatic aquifer (Theis, 1941). This algorithm requires the user to define values for aquifer transmissivity and storativity. The distance of the abstraction site from the nearest stream is calculated automatically using the grid reference of the site in conjunction with the digital river network.

When estimating the flow regime at a site the software uses the catchment boundary and river network to identify all upstream influence feature sites, discounting those that lie above impounding reservoirs. The individual monthly profiles for each upstream influence are then accumulated into a total monthly influence profile for each influence feature type. Initially, considering just abstractions and discharges, the total monthly profile for discharge sites is then added to the estimated natural long term monthly mean flows and the total monthly influence profile for abstractions is subtracted from the natural monthly mean flows to derive influenced monthly mean flow estimates. These influenced estimates are then used to scale the appropriate monthly flow duration curves, which are subsequently combined to yield an influenced long term flow duration curve.

The most complex step within this process relates to the exclusion of the catchment above impoundments. The software identifies the location of all impounding reservoirs immediately upstream of the ungauged site. The system then estimates, and discounts the impounded sub-catchment(s) and any influences (including further impounding reservoirs) that might lie within the sub-catchments. The influenced flow statistics for the ungauged residual catchment are estimated by recalculating the set of natural flow duration statistics for the residual catchment alone and incorporating the influences located within the residual catchment, including the addition of release profiles for the reservoirs, as described above.

The balance between the estimated natural and artificial components of a flow regime along a length of river, represented by a set of stretches, can also be investigated in the Low Flows 2000 residual flow diagram option by repeating the steps described above for consecutive points along a river. The variation of the natural and artificially-influenced estimates of a chosen key flow statistic is plotted as a function of distance along the river, allowing a visual comparison to be made between the two. By evaluating the difference between them, the net influence for the given flow-condition may also be visualised along the course of the river.

IMPLEMENTATION WITHIN ENGLAND AND WALES

Following extensive evaluation and comparison Low Flow 2000 has replaced Micro LOW FLOWS as the Environment Agency's standard tool for estimating flow statistics at ungauged sites and has been implemented in all eight Agency Regions within England and Wales.

The implementation of Low Flows 2000 involved users assessing results from the system in a framework based on the approach described by Woesnner and Anderson (1990) and summarised in Figure 2.

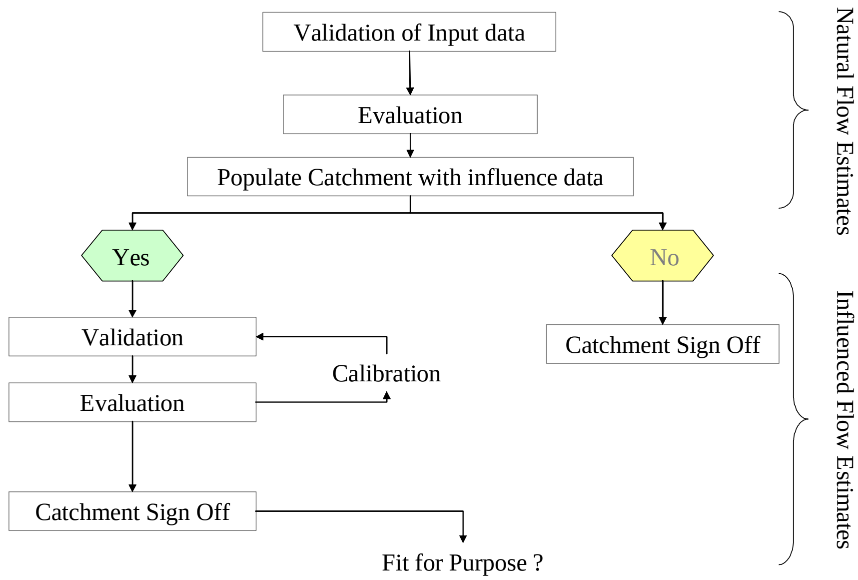

Figure 2: Low Flows 2000 implementation framework.

In this approach, the 'input data' are validated (for example, checking catchment areas), suitable verification, or evaluation, targets are chosen for the key flow statistics (for example, mean flow estimates to within ± 10% of observed) and results from Low Flows 2000 are evaluated by comparison with any available independent data. Depending on the results of the acceptance testing, natural and artificially influenced flow estimates from the system may then be used by Agency staff for a wide range of purposes or, alternatively, be subject to restrictions and only suitable for use in some clearly defined situations.

Some results from the Agency's populated version of Low Flows 2000 for the River Exe, Devon are presented to illustrate some of the outputs of this implementation process. The river Exe has a catchment area of approximately 1200 km^2, it is a relatively rural catchment the catchment geology is predominately Devonian sandstones and carboniferous Culm Measures with subordinate Permian sandstones in the east. The land use is predominately moorland, forestry and a range of agricultural uses. The water use in the catchment is hence primarily associated with agriculture, water supply and effluent returns. There is a regulating reservoir in the headwaters, Wimbleball, which is used to provide regulating releases for downstream abstraction for water supply. This reservoir has a significant influence on low flows within the main river channel.

A comparison of Low Flows 2000 estimates of selected flow statistics and gauged flow statistics for the catchment above the gauging station at Thorverton is presented in Table 1. Thorverton is the lowest gauged location on the Exe and is used in the management of releases from the Wimbleball scheme.

Table 1: Comparison of Low Flows 2000 influenced flow statistics and gauged flow statistic for the River Exe at Thorverton.

	Mean Flow (m^3s^{-1})	Q95 (m^3s^{-1})	Q80 (m^3s^{-1})	Q50 (m^3s^{-1})	Q10 (m^3s^{-1})
LF2000 Estimate (LF2K)	14.7	1.3	3.3	8.9	35.1
Gauged Estimate (GE)	15.9	1.8	3.4	8.7	37.4
(GE-LF2K)/GE (%)	8	29	3	-2	6

The natural and influenced flow duration curves estimated by Low Flows 2000 are presented within Figure 3 for the Thorverton together with the estimated catchment boundary, the digital river network and the location of influence features within the catchment.

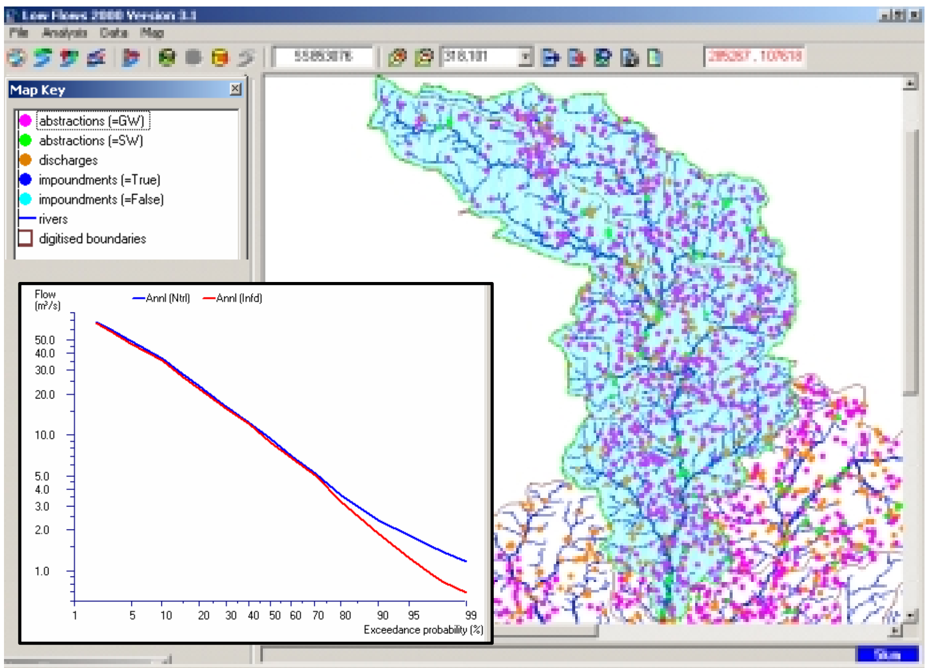

Figure 3: Low Flows 2000 Flow Duration Curves for the River Exe at Thorverton

Low Flows 2000 is an important source of consistent natural and influenced flow statistics for routine abstraction licensing and discharge consenting activities undertaken by the Environment Agency and, as discussed, the system also has an important role in supporting the production of Environment Agency's CAMS through the Resource Assessment and Management (RAM) framework.

Resource assessments in the first CAMS catchments are due to be completed in 2003 and, as Low Flows 2000 is an important supporting tool, a national programme of populating catchments with artificial influence data is currently underway. Data has been loaded and verified in a number of CAMS catchments and Low Flows 2000 estimates of natural and influence flow regimes are now available to water resource practitioners.

In addition to supporting CAMS, Low Flows 2000 flow estimates will be incorporated in the Environment Agency's Restoring Sustainable Abstraction (RSA) Programme. The RSA programme was set up in 1999 to catalogue the number of rivers and wetland sites suspected of being affected by over abstraction in England and Wales and to establish a strategy for their investigation and resolution. Low Flow 2000 can be used to rapidly assess the individual and cumulative impact of abstractions and to identify catchments requiring more detailed investigation.

CONCLUSIONS

This paper has summarised the development of models for estimating flow statistics and described the way in which these have been implemented within a modelling system, founded on a complex and comprehensive data-model and coupled with a GIS tool set. The resulting system, Low Flows 2000, provides the basis for the realisation of a complex and functionally-rich suite of software that has been implemented as a fully operational system by the Environment Agency in England and Wales. Low Flows 2000 has a fundamental role in supporting the Environment Agency's current CAMS and RSA programmes and will also, in the future, contribute to the implementation of the Water Framework Directive within England and Wales.

ACKNOWLEDGEMENTS

The research described in this paper was carried out at CEH-Wallingford (formerly the Institute of Hydrology) under funding from the National Environment Research Council and the Environment Agency (Research and Development Project W6-057, Project Manager Dr. Robert Grew).
Corresponding author:
Dr. Andrew R. Young
Head, River Regimes Section
CEH Wallingford
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB

Tel: 01491 692347
e-mail: ary@ceh.ac.uk

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.* Institute of Hydrology Report 126., Institute of Hydrology, Wallingford, UK.

Bullock, A., Gustard, A., Irving, K.M., Sekulin A. and Young, A.R. (1994). *Low flow estimation in artificially influenced catchments.* National Rivers Authority. R&D Report No. 274.

Burn, D.H. (1990). An appraisal of the "region of influence" approach to flood frequency analysis. *Hydrological Sciences Journal*. **35**(24), 149-165.

Burn, D.H. and Goel, N.K. (2000). The formation of groups for regional flood frequency estimation. *Hydrological Sciences Journal*. **45**(1), 97–112.

Environment Agency. (2001) *Managing Water Abstraction: the Catchment Abstraction Management Strategy Process*: Environment Agency, Bristol, UK.

Grindley, J. 1970 Estimation of mapping of evaporation. *Symposium on World Water-Balance, No. 92 IASH-UNESCO*,**1,** 200-213.

Gustard A, Bullock, A. and Dixon, J.M. (1992*). Low Flow Estimation in the United Kingdom.* Institute of Hydrology Report 108. Wallingford, UK.

Holmes, M.G.R., Young, A.R., Gustard, A.G. and Grew, R. (2002a). (in press). A region of influence approach to predicting flow duration curves in ungauged catchments. *Hydrology and Earth System Sciences*. **6**(4)

Holmes, M.G.R., Young, A.R., Gustard, A.G. and Grew, R. (2002b). (in press). A new approach to estimating mean flow in the UK. *Hydrology and Earth System Sciences*. **6**(4)

Jenkins, C.T. (1970). *Computation of rate and volume of stream depletion by wells*. Techniques of Water Resources Investigations of the USGS. Book 4. Hydrologist Analysis and Interpretation. US Govt. Printing Officer. Washington DC.

Moore, R.V. (1997). The Logical and Physical Design of the LOIS Database. *LOIS Special Volume - Sci. Tot. Environ.,* **194/195**,137-146.

Morris, D. and Flavin, R. 1990. A digital terrain model for hydrology. *Proc. 4th International Symposium on Spatial Data Handling, Zurich*, **1**, 250-262.

Morris, D. and Heerdegen, R. (1988). Automatically derived catchment boundaries and channel networks and their hydrological applications. *Geomorphology*,**1**, 131-141.

Robson, A. and Reed, D.W. 1999. Statistical Procedures for Flow Frequency Estimation. Flood Estimation Handbook Vol.3. Institute of Hydrology, Wallingford.

Sekulin, A.E., Bullock, A. and Gustard, A. (1992). Rapid calculation of catchment boundaries using an automated river network overlay technique. *Wat. Resources. Res.* **28**(8), 2101-2109.

Smakhtin, V. U. (2001). Low flow hydrology: A review. *Journal of Hydrology*. **240**, 147-186.

Spackman, E. (1993). *Calculation and Mapping of Rainfall Averages for 1961-90*. British Hydrology Society Meeting on Areal Rainfall Estimation, 15th Dec. 1993, University of Salford, Manchester.

Theis, C.V. (1941). The effects of a well on a nearby stream. *EOS Trans. AGU*, **22**, 734-738.

Williams, K. (2001). The Impact of the Water Framework Directive of catchment-management planning in the British Isles (Abridged). *J. Instn. Wat & Envir. Mangt.* **15**, 97-102.

Woessner, W W and Anderson, M P. (1990). Setting calibration targets and assessing model calibration-room for improvement: an example from North America. In: Kovar, (ed. by Karel) Proc. Calibration and reliability in groundwater modelling : ModelCARE 90. 279 – 288. IAHS Publication no. 195. IAHS, Washington DC.

Young, A.R., Gustard, A., Bullock, A., Sekulin, A.E. and Croker, K.M. (2000). A river network based hydrological model for predicting natural and influenced flow statistics at ungauged sites, *LOIS Special Volume - Sci. Tot. Environ*. **251/252**, 293-304