Low Flows 2000: a national water resources assessment and decision support tool

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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. However, many decisions are made within catchments for which there are no measured flow data. To meet this challenge, a suite of modelling techniques to assist in the estimation of natural and artificially influenced river-flows at ungauged sites has been developed. This paper summarises these models and how they are incorporated within the GIS framework of the Low Flows 2000 software package. The paper will also describe the implementation of Low Flows 2000 within England and Wales by the Environment Agency, and the use of the system in supporting the implementation of the Environment Agency's Catchment Abstraction Management Strategy. This strategy is focused on the delivery of sustainable abstraction licensing and will contribute to the implementation of the Water Framework Directive within England and Wales.

Keywords Flow duration curves; flows regimes; ungauged catchments; water resources

Introduction

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 characteristics of a catchment. River flow regimes are also affected directly and indirectly by human activities. For water management purposes, it is essential to differentiate between the natural and artificial components of stream flow. The artificial component is the influence of water use within the catchment. Common influences include surface and groundwater abstractions, discharges from sewage treatment plants and industrial sources, canals and impounding reservoirs. This separation of flow components enables practitioners to assess the natural reliable yield of the catchment, from the climatically driven variability of the natural stream flow. The impacts of actual and planned water use scenarios are then subsequently superimposed upon the natural flow regime. This enables the reliable yield to be assessed under both the current water use and/or scenarios of future water use and also enables the environmental impacts of that water use to be assessed.

A review of over 1600 United Kingdom (UK) gauging stations has identified that less than 20% of gauged catchments within the UK can be regarded as being natural (Gustard *et al.*, 1992). The high degree of water use within the UK (and variability in current and future usage) coupled with the complex patterns of natural flow variability has made the task of the environmental authorities charged with managing water-resources and river-quality very difficult to perform. Furthermore, the majority of assessments are required for small catchments with little or no measured flow data.

This paper describes a software system, Low Flows 2000, which has been developed to meet this challenge. This system is used to implement a set of regionalised models to assist in the estimation of natural and artificially influenced river-flows, as represented by flow duration statistics, at ungauged sites. The paper also summarises the implementation of Low Flows 2000 within England and Wales, and the use of the system in supporting the implementation of the Environment Agency's Catchment Abstraction Management Strategies (CAMS). These strategies are focused on the delivery of sustainable abstraction licensing and will contribute to the implementation of the Water Framework Directive within England and Wales.

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 hydrogeology 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 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 and 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 *MS Visual Basic* that uses *MS Access* for databasing and *ESRI MapObjects* 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, analysis, and evaluation of natural and influenced flow regimes, 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.

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 200 m 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 and Heerdegen, 1988; Morris and 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 a shaded polygon.

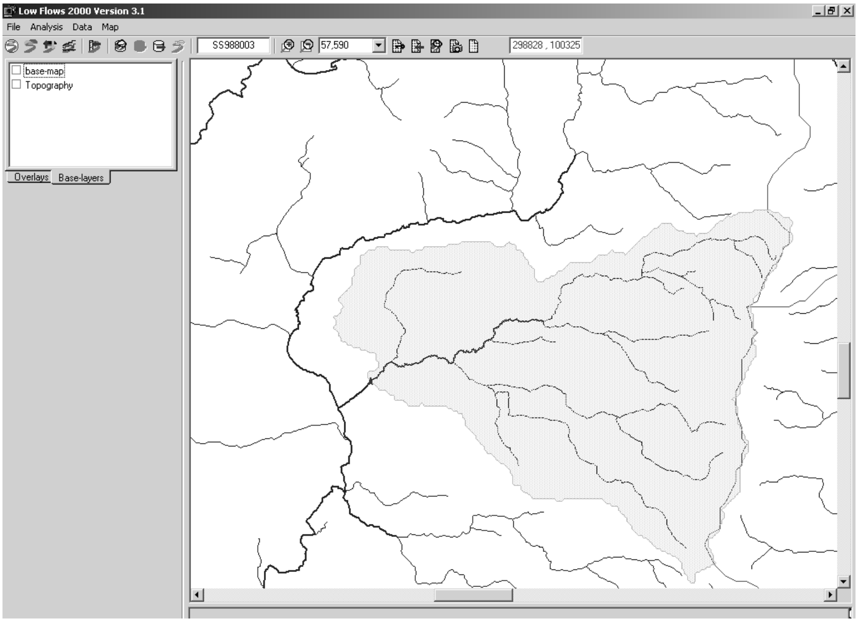

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Figure 1 Example of catchment boundary definition using the Digital Terrain Model

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 permeable catchments where the groundwater boundary might not coincide with the topographic boundary and in karst geologies where subterranean drainage plays a significant role in water movement. By an appropriate use of constraining boundaries, the analogue method can be used to resolve many of these problems.

Catchment analysis

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 Runoff, ARRO (61–90) (Holmes *et al.*, 2002b) and the fractional extents of the 30 class Hydrology Of Soil Types (HOST) soils classification (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 hydrogeological classification of the UK, although 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 the 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 local database. The estimated natural flow statistics 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.

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 reservoired 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 reservoired sub-catchment(s) and any influences (including further impounding reservoirs) that might lie within the reservoired 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 versions of a chosen key flow statistic are plotted against an axis 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

The performance of the hydrological models within Low Flows 2000, evaluated over more than 550 UK catchments, was found to be superior to the Micro LOW FLOWS models for estimating natural flow statistics. This is due to a combination of the revised scientific techniques employed, improved climatic spatial data sets and the refined catchment area estimation methods. Consequently, Low Flow 2000 replaces 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 has involved users assessing results from the system in a framework based on the approach described by Woesnner (1990). The "input data" are validated (for example, checking catchment areas), suitable verification 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 verified 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 for a wide range of purposes, or alternatively, be subject to restrictions and only suitable for use in some clearly defined situations.

Like its predecessor, Micro LOW FLOWS, 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. The system also has an important role in supporting the production of the Environment Agency's CAMS. CAMS aim to make information on water resources availability and abstraction licensing more publicly available and to provide a more consistent and structured approach to water resources management (Environment Agency, 2001). The Resource Assessment and Management (RAM) framework was established as part of CAMS to deliver a consistent, objective means of setting environmental river flows and to determine the status of water resources within each catchment. Within this framework, water available for abstraction is calculated from a naturalised flow duration curve. This flow duration curve may be calculated for gauged sites by decomposition, a process of adding abstractions and discharges from a time series of gauged flows, or at ungauged sites using Low Flows 2000 and the regional low flow estimation methods described above.

While Low Flows 2000 was not developed specifically for RAM 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.

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 have 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 managers.

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.

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