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The River Ecological Sustainable Yield Model (RESYM)

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Abstract: Balancing the competing demands for water from consumptive users and the needs of the environment is the goal of sustainable water resource planning in Western Australia (WA). In the south west of WA, irrigated agriculture accounts for approximately 70% of total water use. To support water planning, estimates of consumptive demands for agriculture have been based on licensed entitlements, or where this information is not available, combinations of GIS-based land use mapping and published estimates of crop demand. Numerical models of the yield and reliability of large reservoirs supplying consumptive users have been available for some time.

A range of approaches have been used in Australia to estimate the environmental flow (EF) requirements of rivers. The methods used in Australia (and elsewhere) over the past two decades differ in detail but are essentially habitat approaches that identify flows that achieve a required water depth in important aquatic and riparian habitats. These threshold flows are then used to 'construct' an EF regime. Ecologically important flow thresholds include those that provide access to spawning habitats, or maintain river pools and riffles. High winter flows inundate the river channel and maintain river channel morphology. Other flows drown out barriers and allow upstream breeding migration of native fish. High winter flows inundate riparian vegetation and fill wetlands on the river floodplain.

There has been no standard way however, to create an EF regime that approximates the natural seasonal pattern, frequency and duration of spells above ecologically important thresholds. Nor has there been a standard way to use the results of ecological studies to quantify the ecologically sustainable yields (ESYs) from surface waters and inter-annual variation in these yields. Previously in WA, researchers have used flow gauging records to calculate the historic frequency and duration of spells above ecologically important thresholds, and used these calculations to construct average annual and seasonal EF regimes.

Recent water resource planning in south west WA has clearly showed that statistical analysis of historic time-series is by itself inadequate when identifying the EF regime needed to maintain the ecological health of rivers. These analyses have generated static estimates of EF requirements, which have been used by water managers to set environmental release rules for large water storages. The same volumes of environmental releases are made every year or month according to an agreed invariant schedule, with little regard to inter-annual variation in rainfall and flows. This approach essentially ignores the importance flow regime variation has in maintaining the evolutionary and future adaptive capacity of river ecology, and the impact of constant environmental releases on reservoir levels during drought periods.

A better approach was needed for modelling the desired EF regimes of rivers in south west WA, and for optimising the operating rules of large water storages. To address this problem, the authors developed the River Ecological Sustainable Yield Model (or RESYM). RESYM is a FORTRAN program with a Windows based graphical user interface, which uses a water balance of inflows, storage attributes and operating rules to estimate the volume of water that can be harvested given a specified set of environmental releases. Time-series of natural and impacted flows can then be used to assess changes in the frequency and duration of flows above ecologically important thresholds. Time-series of abstractions from the storage can be used to assess operational aspects of dam management and water supply, such as the frequency and duration of restrictions on consumptive use. RESYM is designed to be used in an iterative fashion by expert panels in a workshop setting to construct non-static EF regimes. This paper discusses the development of RESYM, and its use in determining the ESY and environmental release rules of large reservoirs in south west WA.

Keywords: *Water resource planning, environmental flow requirements, ecologically sustainable yields, environmental water management*

1. INTRODUCTION

Estimates of a river's ESY are a primary consideration in water resource management and planning in WA. Increasingly, water planners in WA are attempting to place limits on total water allocation that reflect the magnitude and variability of the ESY. Consequently, ecologists are being asked to provide quantitative and defensible data on the ESY of rivers, and to provide these figures over time-scales that can support decisions regarding the volume, timing and duration of environmental releases from large water storages, and the volume that can be intercepted (by farm dams for example) or pumped from rivers to off-stream storage.

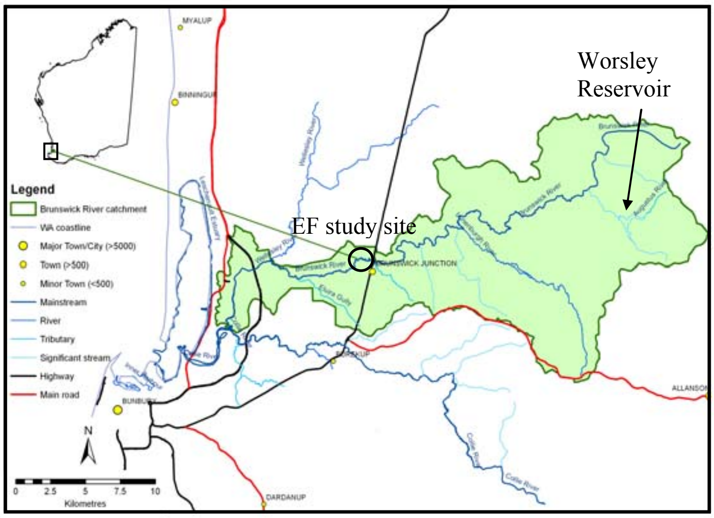

Figure 1. Location of the Worsley Reservoir and EF study site near Brunswick Junction

This paper describes the use of a model called RESYM (**R**iver **E**cological **S**ustainable **Y**ield **M**odel) which has been developed by the authors to help estimate a river's ESY. RESYM does this by simulating how potential EF regimes translate to the water available for consumptive use and the frequency and duration of ecologically important flows. Using case studies from the Brunswick River catchment to the south west of Western Australia (Figure 1), this paper describes how RESYM is used to:

- model environmental release strategies for large reservoirs, and
- determine the ESY of unregulated rivers.

2. ESTIMATING THE ECOLOGICALLY SUSTAINABLE YIELD OF RIVERS

In the last decade a number of approaches have been used to estimate the environmental flows needed to maintain the health of rivers, including the Building Block Method (Davies and Creagh, 2000) and more recently the Flow Events Method (WRM, 2005; Stewardson and Cottingham, 2002). These methods, and others used in Australia, are essentially 'threshold' approaches that identify flow rates and water depths that achieve a specific ecological outcome. Such outcomes include the maintenance of an important habitat type, water quality in river pools, the seasonal inundation of spawning habitat or the maintenance of channel morphology (Figure 2).

Ecological flow thresholds are used by ecologists to construct an EF regime, which is comprised of recommended spell frequencies and durations above these thresholds. Usually these spell recommendations are derived from analyses of historic flow records. In WA these types of analyses have generally resulted in an annual invariant EF regime which has been used to develop environmental release rules for large reservoirs. These rules are volume-based (usually monthly) and result in the same volume of water being released seasonally in most years, with little regard given to the antecedent rainfall, regional patterns of river flow and the role of flow variation in maintaining the evolutionary capacity of river ecosystems (Poff *et al*., 1996).

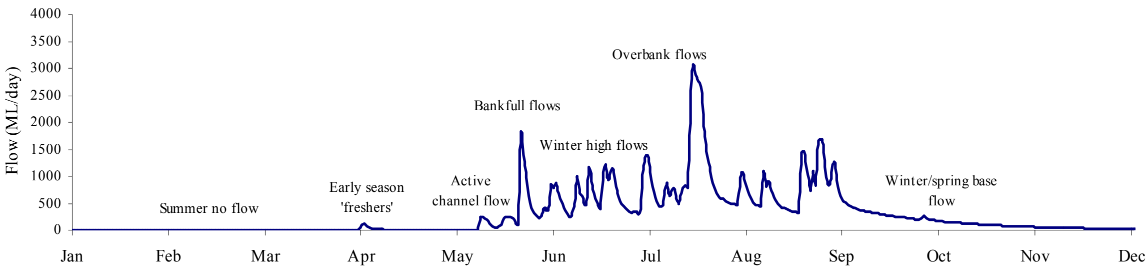

Figure 2. Ecologically functional flows considered in EF studies

Table 1. RESYM parameters for modelling environmental releases from Worsley Reservoir.

Draw from storage

Month	Draw (ML/day)
Jan	7.1
Feb	7.1
Mar	7.1
Apr	7.1
May	7.1
Jun	7.1
Jul	7.1
Aug	7.1
Sep	7.1
Oct	7.1
Nov	7.1
Dec	7.1

Pan evaporation factor	0.9
Storage capacity (GL)	6.2
Initial stored volume (GL)	6.2

Environmental release rules

Flow range (ML/day)	% of inflow released
≤ 0.5	100
> 0.5 ≤ 5	80
> 5 ≤ 18	50
>18 ≤ 40	30
> 40	60

3. RESYM

RESYM is a FORTRAN program with a Windows based graphical user interface, which uses a water balance of inflows, storage attributes and operating rules to estimate the volume of water that can be harvested given a specified set of environmental releases. Time-series of natural and impacted flows are used to assess changes in the frequency and duration of flows above ecologically important thresholds, while time-series of abstracted flows can be used to assess the frequency and duration of restrictions on consumptive users.

RESYM was developed by the authors to be used within EF studies to model potential EF regimes for rivers. In particular, RESYM was designed to enable a panel of ecologists to develop an EF regime and ESY in a workshop setting using data collected in EF studies (e.g. see Donohue *et. al*., 2009a). RESYM is also designed to be used by water resource planners to simulate the environmental impacts of alternative water allocation scenarios.

4. CASE STUDY 1: ENVIRONMENTAL RELEASES FROM STORAGES

Losses of water from reservoirs include evaporation, draw and seepage. Seepage losses are not explicitly modelled in RESYM, but can be implicitly included in the draw from storage parameters. Table 1 shows the user-defined draw from storage for Worsley Reservoir. The consumptive use entitlement of 2.6 GL/annum is modelled as a uniform draw of 7.1 ML per day per month to reflect the uniform pattern of the industrial demands serviced by Worsley Reservoir. For a reservoir supporting an irrigation scheme, the daily draw would vary by month to reflect the seasonal demand of irrigated crops. Below a storage volume of 1 GL, water quality in the reservoir makes it unsuitable for consumptive use and no water is abstracted.

This case study describes the use of RESYM to develop a new (proposed) environmental release strategy for the Worsley Reservoir. The Worsley Reservoir is located on the Augustus River, a small upland tributary of the Brunswick River in the south west of WA (Figure 1). Annual flow in the Augustus River averaged 5 GL/year and ranged from 1 to 11 GL/year between 1975 and 2003. Flow in the Augustus River is naturally ephemeral and highly seasonal with 70% of annual flow occurring between June and October. An EF study was carried out in the Augustus River in 2004 with the aim of identifying environmental release rules for the Worsley Reservoir (WRM, 2005). For this study, the licensed entitlement and required reliability of supply was known *a priori* so the modelling objective was to maximise environmental releases, while providing for the license entitlement with a high level of reliability.

4.1. Parameterisation

To model the impact of environmental release rules on storage behaviour and downstream ecology, data inputs to RESYM include daily rainfall (mm), daily evaporation (mm), daily inflow (ML) and a limiting variable such as salinity (mg/L). The limiting variable allows a user-defined threshold above which no water is harvested into storage. The Worsley Dam is constructed on-channel and is modelled in RESYM in 'On-stream' mode. The storage has a maximum capacity of 6.2 GL and the license is for an annual entitlement of 2.6 GL/annum (Table 1).

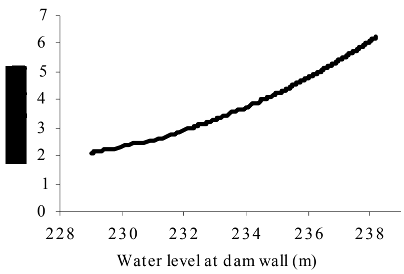

Figure 3. Storage versus elevation for the Worsley Reservoir.

In RESYM the evaporative losses are calculated from pan evaporation and the surface area of the reservoir, which is interpolated from a table of storage-elevation points. Figure 3 shows this relationship for Worsley Reservoir.

Table 2. Flow thresholds for the Augustus River downstream of the Worsley Dam. From WRM (2005).

Threshold (ML/day)	Ecological function
1	Flow to maintain quality of summer habitat
8	Inundated sandy runs and riffle habitat
13	Allow upstream migrations of native fish
35	Flood lower channel benches
70	Flows that inundate active channel.

Environmental releases are modelled in RESYM as a proportion of the daily inflow to the reservoir. The proportion of inflow released from the reservoir is user-defined and can be varied with the magnitude of inflow. When the storage capacity is exceeded the environmental release is calculated as the sum of releases from storage plus spills. The water balance model in RESYM assumes that all water in excess of storage capacity is spilled from storage within a single day.

Table 1 includes the final modelled release strategy for the Worsley Reservoir. These show that below an inflow of 0.5 ML/day, 100% of the daily inflow will be released from storage. The threshold of 0.5 ML comes from the minimum summer flow identified as being required to maintain river pools and flow permanency (WRM, 2005). In the inflow range between 18 ML/day and 40 ML/day, 30% of inflow is released, and 60% of inflows above 40 ML/day are released.

4.2. Model Evaluation

The parameter set shown in Table 1 was arrived at through a process of iteration. For each trialled parameterisation, the panel evaluated the output, and noted where the modelled releases either compromised the annual licensed entitlement or did not achieve any of the five flow thresholds identified during the EF study (Table 2). Where needed, adjustments were made to the proportion of water released in the appropriate inflow range. This process continued until the panel agreed that the environmental release rules achieved a reasonable balance between reliability of supply to the license-holder and the ideal downstream EF regime.

The modelling results from each parameter set are evaluated in RESYM using a combination of data and graphic outputs. For example, Figure 4 shows a time-series plot comparing reservoir inflow with the environmental releases for the period 1990 to 1992. The plot shows a difference between the two traces in the early part and latter parts of 1990, which occurs when the sum of releases and draw is higher than the inflow, meaning the storage is drawn down and downstream flow is comprised solely of releases from storage. Environmental releases increase substantially when the reservoir is full and spills are included in the environmental release volume (e.g. from August to September in 1991, and from July in 1992).

The upper plot in Figure 5 may be of most interest to dam operators. It shows the draw and change in storage volume over the modelling period. The final environmental release strategy for the Worsley Reservoir is expected to result in the full annual licensed entitlement being delivered in 80% of years. The plot shows the reservoir storage is drawn down below 1 GL after a number of low flow years.

Figure 5 also has an example of the bar charts available in RESYM, which are used by ecologists to evaluate the frequency and duration of ecologically significant flows in the inflow time-series versus the environmental release time-series. As an example, the lower plot in Figure 5 shows the duration of flows above the fish passage flow identified by WRM (2005). Notice that the duration of flows above 13 ML/day vary significantly between the inflow (natural) and the modelled environmental release time-series. After each model run, bar charts for each ecological flow threshold may be viewed. Where the frequency and

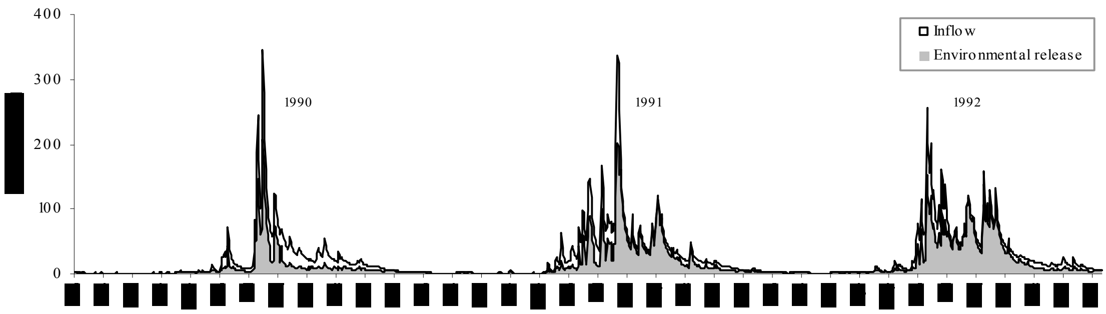

Figure 4. Inflow to the Worsley Reservoir compared to the modelled environmental releases using the rules in Table 1.

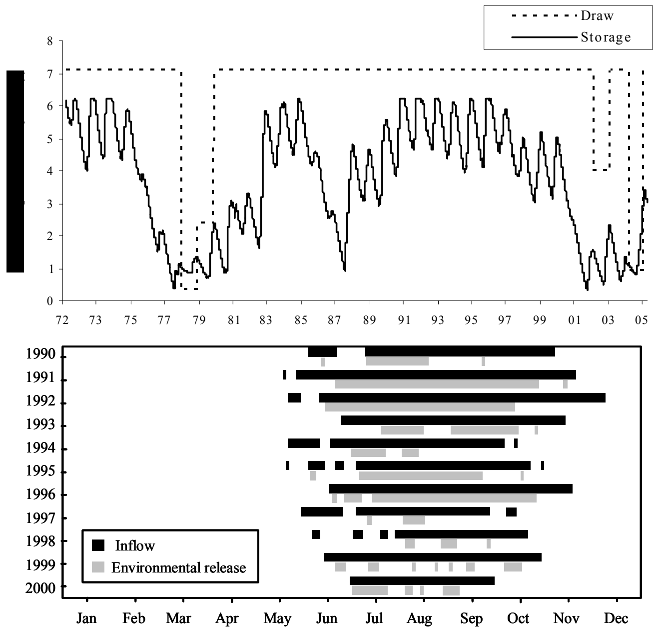

Figure 5. The upper plot shows daily draw and storage in the Worsley Reservoir for the modelling period of 1972 to 2005 which result from the release rules in Table 1. The lower plot is an example of a bar chart from RESYM showing frequency and duration of flow spells greater than the fish passage flow of 13 ML/day in the period 1990 to 2000.

duration of ecologically important flows in the release time-series deviate significantly from that in the inflow time-series, adjustments may be made to the environmental release strategy to achieve a better environmental outcome.

There was some concern among panel ecologists that environmental releases did not provide adequately for upstream migration of native fish (lower plot in Figure 5). However, increasing releases in the flow ranges that controlled depth across barriers to migration was found to compromise supply reliability and delay spilling of the reservoir at the start of the following flow year. The panel concluded therefore that the parameters in Table 1 resulted in a responsible balance between consumptive use and environmental risk. As noted earlier, the primary constraint with developing an agreed environmental release strategy for the Worsley Reservoir was providing for the licensed entitlement with an acceptable reliability of supply.

5. CASE STUDY 2: ESTIMATING THE ESY OF THE BRUNSWICK RIVER

This case study describes how RESYM was used to estimate the ESY of the middle reaches of the Brunswick River. RESYM modelling of the river's ESY was based on the results of an EF study of the Brunswick River (Donohue *et al*., 2009b) (Figure 1). Table 3 shows the ecologically important flow thresholds identified during this study. Annual flow in this part of the catchment averaged approximately 60 GL/year in the period between 1975 and 2003, and varied between 20 and 130 GL/year.

5.1. Data Requirements

The EF regime of rivers can be modelled in RESYM using a 'no dam' mode. This mode requires as input a daily flow time-series covering a period that represents the variation found in the natural flow regime. To estimate the ESY of the Brunswick River, a daily flow record covering the period 1975 to 2003 was used.

To model an EF regime and the ESY of the Brunswick River an iterative approach was also used. In this case, the modelling was concerned only with determining the maximum volume of water that may be extracted from the 'natural' flow time-series while meeting the ecological flow thresholds with appropriate frequency and duration. There were a total of eight flow thresholds for the Brunswick River available to guide the panel during the parameterisation process (Table 3).

Table 3. Flow thresholds for Brunswick River (from Donohue *et. al*., 2009b).

Threshold (ML/day)	Ecological function
2	Minimum summer flow that maintains permanency, depth and quality of river pools
4	Inundates invertebrate habitat in summer
15	Allows for upstream migration of small native fish
30	Allows for upstream migration of large native fish
120	Inundates fish spawning habitat
180	Scours low flow channel
530	Inundate channel benches and vegetation
2220	Inundates river floodplain and maintains floodplain habitats such as wetlands

A water quality time-series may also be included as a constraint on the periods when water can be abstracted for consumptive use (e.g. a maximum salinity level for potable water). This approach is needed for south west rivers in which salinity level may be seasonally high. The Brunswick River is fresh year round and this constraint was not needed.

In RESYM, potential EF regimes for the Brunswick River were simulated by removing a user-defined proportion from an observed daily flow (Table 4). The proportion of daily flow retained as EF was varied within flow ranges. The number and size of the flow ranges can be varied in RESYM depending on system characteristics and the underlying structure of the data set, and the need to target particular spells to achieve ecological objectives in the modelling process

Table 4: Abstraction rules developed by the panel to model the EF and ESY of the Brunswick River.

Flow range	Proportion abstracted per day
≤ 1.3	0%
>1.3 ≤ 2.5	35%
>2.5 ≤ 140	30%
>140 ≤ 920	40%
>920 ≤ 2526	10%
> 2526	10%

5.2. Model Evaluation

The final set of parameters selected for the Brunswick River is shown in Table 4. As with the previous case study, the final parameters were arrived at iteratively through a process of trial and error. The model output from each set of rules was evaluated by ecologists using the data and graphic output of RESYM.

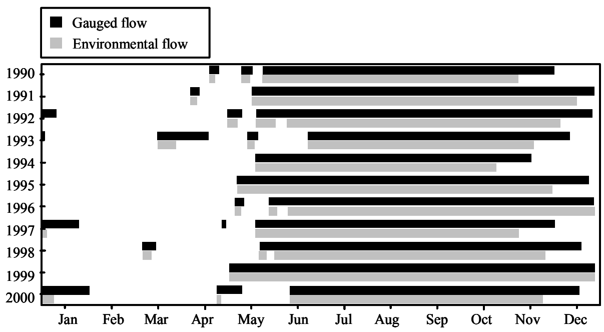

Figure 6. Frequency and duration of flows above 15 ML/day in the middle reaches of Brunswick River.

The panel may view time-series plots, data or bar charts showing the frequency and duration of flow spells above ecological thresholds such as those identified for the Brunswick River (Table 3). Figure 6 for example is a bar chart generated in RESYM that compares the frequency and duration of flows above 15 ML/day in the gauged 'natural' flow and the modelled EF regime. This threshold is the flow rate needed to flood out barriers (rock bars, weirs, logs) in the river channel to a depth of at least 10cm thus allowing upstream migration by native fish. Based on this plot, the ecological panel decided that the abstraction model in Table 4 produced an EF regime with flow of sufficient frequency and duration to allow for upstream breeding migrations of native fish. Based on similar plots for all the ecological threshold flows in Table 3, it was concluded that the abstraction rules (Table 4) produced an acceptable EF regime.

RESYM produces an EF for every year of record used in the modelling process. Figure 7 shows a detail of the EF compared to the gauged 'natural' flow for the year 2000. The plot shows that modelling an EF using the proportional abstraction approach in RESYM produces an EF regime that retains the seasonal pattern and overall variability of the natural flow.

5.3. The Ecologically Sustainable Yield

RESYM is used to progressively remove water from the gauged flow until the frequency and duration of spells above important flow thresholds in the modelled EF deviate unacceptably from that in the gauged 'natural' flow. Based on the EF study and in the opinion of ecologists, this volume of water can be removed from the river without unacceptable risk to river ecology. The volume abstracted is therefore considered the river system's ESY. The plot in Figure 7 shows the ESY volume as the black area between the gauged 'natural' flow and the modelled EF (the area shaded in grey). In the Brunswick River it was estimated that between 1975 and 2003, the annual ESY averaged 20 GL/ year and varied between a minimum of 6 GL (2001) and a maximum of 43 GL (1988).

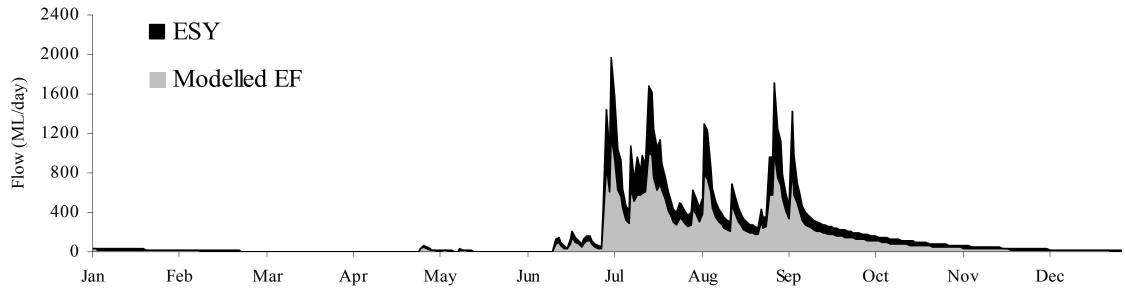

Figure 7. Daily flow in the Brunswick River for the year 2000, showing the EF and the ESY components as modelled by RESYM using the parameters in Table 4. Note that the 'natural' flow is the sum of the ESY and the modelled EF.

6. DISCUSSION

While RESYM uses a relatively simple water balance model to assess potential environmental release strategies and EF regimes for rivers, it has proven to be a valuable tool in the consideration of water allocation options. RESYM presents information to decision-makers and stakeholders in a way that is relevant to their particular interest. Water storage managers for example, are interested in how environmental releases may affect storage levels. Ecologists on the other hand are more interested in the ecological benefits of releases from storage and the risk to ecosystems that result from increased abstraction.

RESYM allows stakeholders to model how changes in water abstractions and specified environmental releases may help achieve an acceptable balance between security of supply and environmental risk. Consequently, the authors have found that using RESYM in a workshop setting has helped guide discussions and significantly improve group understanding of specific management problems. This has proved particularly useful for water planners, who need to make decisions that balance the competing demands of consumptive users and the environment.

A major benefit of using RESYM to assess the merit of potential EF regimes is that the modelling parameters shown in Tables 1 and 4 can be used as a basis for developing rules governing the magnitude and timing of environmental releases from reservoirs, or as abstraction rules limiting daily pumping rates from rivers. These rules may be used to underpin resource sharing management arrangements that account for inter-annual variation in flows, and changes in flows over time (Donohue *et al*., 2009b).

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