Title: ***Procedural Manual for the Water Resources Simulation Model (WRSM)***

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Procedural Manual for the Water Resources Simulation Model (WRSM)

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APPENDICES

LIST OF ABBREVIATIONS

B&P	**Board-and-Pillar**
DSL	**(Reservoir) Dead Storage Level**
DTM	**Digital Terrain Model**
DWAF	**Department of Water Affairs and Forestry**
FSL	**(Reservoir) Full Supply Level**
GIS	**Geographical Information System**
GWSWI	**Groundwater-Surface Water Interaction**
HE	**High Extraction**
HFY	**Historical Firm Yield**
HRU	**Hydrological Research Unit**
IFR	**In-stream Flow Requirement**
LHDP	**Lesotho Highlands Development Project**
MSL	**Mean Sea Level**
PCD	**Pollution Control Dam**
SFR	**Streamflow Reduction**
STOMSA	**Monthly Multi-site Stochastic Streamflow Model of South Africa**
UseSys	**Online User Support System**
WAA	**Water Availability Assessment**
WCDM	**Water Conservation and Demand Management**
WQS	**Water Quality and Sulphates Model**
WR2005	**Water Resources of South Africa, 2005**
WRIMS	**Water Resources Information Management System**
WRPM	**Water Resources Planning Model**
WRSM	**Water Resources Simulation Model**
WRYM	**Water Resources Yield Model**
YRC	**Yield-Reliability Characteristics**

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1. INTRODUCTION

1.1 The water resources planning process

The effective management of water resources is of great importance to ensure the supply of water resources to support changing water requirements over a selected planning horizon and in a sustainable and cost-effective way. Essentially, the purpose of the water resources planning process is to balance the available water resources in a system with the water requirements and losses to which the system is subjected. The process involves a number of aspects, and these are briefly discussed below.

The first aspect involves the assessment of the water resource capability of the system in question, the associated assurance of supply, current and projected water requirements, user priorities and acceptable risks of non-supply, as well as various water quality criteria. The second considers the way in which a system is operated since this directly influences its resource capability and includes aspects such as detailed operating rules for reservoirs and inter-basin transfer schemes, the prioritisation of water sources and supplies, special operating rules associated with the blending of water for the purpose of meeting special water quality criteria, operational cost savings and system maintenance schedules. The third aspect involves the scheduling of interventions that may be required in to ensure that the future balance of water resources and water requirements in a system are maintained. Such interventions may involve, on the one hand, increasing the available resources through infrastructure development and, on the other, lowering requirements through water conservation and demand management (WCDM) initiatives, water reuse, the reallocation of resources to high priority users and catchment management. Finally, an important aspect of the water resources planning process requires the careful monitoring of the various components of the system in order to evaluate the accuracy of predictions and the degree to which implemented measures have succeeded.

1.2 Modelling water resources systems

The modelling of water resources systems represents an essential component of the water resources planning process since it provides a testing environment for assessing the behaviour of a system under any number of selected scenarios prior to actual experience. Models therefore provide an important basis for testing the possible impacts of implementing planned infrastructure developments, management and operational options and other measures and thereby provide a reliable basis for making important decisions in this regard.

A great number of water resources modelling tools are applied across the world and most were developed based on the application of complex analytical techniques and computer programs (software) that simulate the behaviour of water resource systems with mathematical principals. However, due to their very nature, all of these models have certain limitations which may include some or all of the following:

- Models are inherently a simplification of the real world;
- Models are assumption-dependent;
- The reliability of the results are largely data-dependent;
- It is often difficult to select an appropriate model or to standardise on a specific modelling approach;
- The modelling software generally requires expert configuration and interpretation, extensive checking and testing and is applied by relatively small user groups.

1.3 Role of the model

The *Water Resources Simulation Model* (WRSM) was developed for the purpose of modelling complex water resource systems and is used together with other simulation models, pre-processors and utilities for the integrated management of water resources. Essentially, the model provides as a decision support system with the ability to evaluate the capability of existing and proposed water resource systems through simulation of the physical, statistical, operational and water quality aspects that influence the capability of such systems.

The structure of the WRSM was designed with the purpose of maintaining versatility and general applicability. The major strength of the model therefore lies in the fact that it enables the user to configure most water resource system networks using basic *building blocks*, which means that the configuration of a system network and the relationships between its elements are defined by means of input data, rather than by fixed algorithms embedded in the complex source code of the model.

Once the WRSM has been configured for a particular water resource system, the model may be used for undertaking two distinct analysis types depending on the purpose of the study in question. These are **yield analyses** and **planning analyses** and more information in this regard is provided below.

a) Yield analysis

The purpose of a yield analysis is to assess the total long- and short-term resource capability (or *yield*) at a particular point in a water resource system at a fixed selected development level and set of system operating rules. The yield of a system can be determined based either on a historical yield analysis, in which case the yield is typically expressed as a historical firm yield, or based on a stochastic yield analysis, in which case assurance of supply (or risk of non-supply) may be determined for a variety of yields. More information on historical and stochastic yield analyses is provided in **Section 2.4** and the procedure involved with determining system yields using the WRSM in **Section 9**. The yield of a water resource system may also be defined in terms of its hydropower generation potential and more information in this regard is provided in **Section 12.1**.

b) Planning analysis

In general the purpose of undertaking planning analyses is to analytically quantify the capability of dynamic changing water resource systems, determine operating rules and schedule the implementation of development options using network simulation procedures and practical allocation strategy. This involves determining the ability of a water resource system to satisfy water requirements which are distributed geographically and change with time. The water requirements consist of two components, volumetric and reliability of supply requirements, while two additional variables are also modelled, water quality in the form of total dissolved solids (TDS) and sulphates, as well as hydropower generation capabilities. The curtailment strategy is a procedure that was developed to restrict water use during periods of drought in order to protect the resources of high priority users. The implementation of restrictions is a fundamental management principal embedded in the operating rules of the major water resource systems in South Africa.

Over time, changes may also occur in the water resources system itself, with reservoirs and transfer conduits that may be activated or deactivated to mimic the commissioning or decommission of water resource infrastructure. The impoundment and delivery dates of planned reservoirs, as well as the delivery pattern over time, represent the implementation requirement of development options. This schedule of dates is determined with the objective to postpone any implementation as far as possible without exceeding the acceptable risk of curtailments as dictated by predefined criteria.

Furthermore, within the framework of optimal long-term inter-reservoir and inter-sub-system operating rules are simulated by the model with the objective of achieving a balanced utilisation of inter-dependent water resources. Operating rules may also include water quality-related rules, i.e. by imposing TDS concentration limits, which are achieved through blending and/or dilution.

In order to elaborate on the purpose of the model the processes of *development planning* and *operational planning* are described below.

Development planning

Development planning refers to the process carried out to determine the need and timing of interventions in a water resource system. Intervention in this context refers to any measure that could be implemented to improve the balance between water supply and projected requirements which could consists of water demand management options and/or infrastructure developments.

Continuous and increasing deficits in supply may require long-term measures that would probability consists of a series of options to be implemented, while short-term deficit problems, that disappear over time, due to for example increased return flows, require the implementation of interim measures only. Finally, an implementation schedule of proposed intervention measures may be developed. In general the measures with the lowest unit costs will be implemented first to postpone the more expensive solutions.

The model links all water resource systems which are dependant on one another, implements the selected allocation strategy, accounts for growing water requirements, introduces chances to the physical system at specific points in time and simulates salinity dilution or blending rules if required. Analysing the system in this way ensures all relevant aspects are considered in and integrated manner and the results, therefore, reflect the interdependency of all relevant aspects.

Operational planning

Operational planning involves the analytical determination of the optimal operating rule for a water resource system through simulation and scenario analyses. The process consists of the following components:

- Inter-reservoir operating rule optimisation within sub-systems;
- Evaluation of inter-sub-system transfer operating rules;
- Water quality blending operating rules;
- Annual operating analyses to determine short-term operating rules taking into consideration reservoir levels at a given point in time;
- Combined operation of water resource systems with hydropower and water supply as competing users;
- Assessments are usually based on scenarios analyses where the objectives are to:

- Maximise yield or extend the requirement of further intervention as for into the future as possible;
- Reduce operating costs (pumping energy) during periods of full system storage levels by deviating from the long-term operating rule. This can only be considered if the long-term reliability of supply in not jeopardised;
- Optimise the system operation with respect to water quality (salinity) criteria. A balance between water quality and supply reliability has to be achieved;
- Maximising hydropower generation without jeopardising the reliability of water supply, or vice versa.

1.4 Model development and user support

The WRSM is currently under development by the South African Department of Water Affairs and Forestry (DWAF) and combines the functionalities of three established water resources models that have been used for over 20 years for managing the country's water resources. These are:

- The *Water Resources Yield Model* (WRYM) which is used for undertaking yield analyses;
- The *Water Resources Planning Model* (WRPM) which is used for undertaking planning analyses;
- The *Water Quality and Sulphates Model* (WQS) which is used for modelling the concentration of total dissolved solids (TDS) and sulphates in the water resource system.

Also, the *Water Resources Information Management System* (WRIMS) was recently developed to improve the performance and ease of use of the model by providing a database to manage WRSM data sets, as well as an interface which allows for system configuration and run result interpretation within a Microsoft Windows environment.

The DWAF, Directorate: Water Resource Planning Systems is the custodian of the model and is responsible for its ongoing updating and refinement within a development framework which involves the maintenance of all hydrological and systems software systems used by the Department and its service providers. The development process involves a number of steps which include:

- Business process analyses;
- The development of detailed requirement specifications;
- Software development and testing;
- Roll-out;
- Software maintenance and updating.

Furthermore, the Department provides support to model users through an online help system (called *UseSys*), as well as a help desk, which provide:

- Existing model releases and documentation;
- Model updates and documentation;
- A sharable database of queries, comments, requests and feedback;
- Information of training and other events.

1.5 Purpose and structure of document

The *Procedural Manual for the WRSM* aims to describe the way in which the WRSM is configured for the purpose of undertaking yield and planning analyses on a water resource system network. The contents of the document are structured to focus on the building blocks or elements that make up a system model and the data required to configure each element. This gives the reader the opportunity to understand the inter-dependencies between related input parameters rather than focusing on the complex storage structure in the model's database.

However, it is important to note that the procedures described in the *Procedural Manual* are of a general nature, as it would be impossible to deal with all the intricacies of complex water resource systems. In order therefore to ensure effective use of the manual, the user should have a basic understanding of and some experience in system modelling. Furthermore, the information in the *Procedural Manual* should be considered as an elaboration on the parameter and file descriptions provided in other model documentation. Users that are unfamiliar with the function of particular variables should therefore consult the following documents to obtain a comprehensive understanding of the model feature in question:

- *Water Resources Yield Model (WRYM) User Guide – Release 7.5.6.2* (DWAF, 2008);
- *Water Resource Planning Model: User Guide* (DWAF, 2000);
- *Water Quality Modelling – Volume A: water Quality Calibration Model* (DWAF, 1988).

Information is provided in separate sections and sub-sections, each of which deals with the procedure involved with a specific step in the process of configuring the model, undertaking model runs and obtaining run results. These are:

- Managing model runs (**Section 2**);
- Developing a representative system network (**Section 3**);
- Modelling incremental sub-catchments (**Section 4**);
- Creating a variety of standard system features (**Sections 5** to **8**);
- Special modelling features (**Sections 9** to **13**);
- Run result output options (**Section 14**);

- Lists of abbreviations, tables and figures are provided at the beginning of the document and references and appendices may be found at the end.

Each section or sub-section provides an overview of the procedure in question, together with a table, or set of tables, that lists and describes the WRSM input parameters that must be defined as part of the procedure, including detailed references to related parameters and/or sections in the document, as well as any specific conditions that may apply. Furthermore, parameters are highlighted that that are only required if either a yield analysis or a planning analysis is being undertaken, while other parameters are required for both analysis types.

Finally it should be noted that the WRSM modelling capabilities described here include that of **Version 7.5.6.2** of the WRYM and **Version 1.9** of the WRPM. Furthermore, the WRSM also provides all the features of the WQS for modelling water quality in water resource systems, including the concentration of total dissolved solids (TDS) and sulphates, as well as a variety of other features. However, WQS features are not addressed in this version of the Procedural Manual and will only be incorporated at a later stage. References to such features are however provided throughout the document.

2. UNDERTAKING MODEL RUNS

General information must be provided on the way in which a system is to be analysed for a particular model run. Aspects such as a *run description*, *data file location*, *analysis period* and *run type options* are selected here. More information in this regard is provided in the remainder of this section.

2.1 Run description

The run description-facility allows for information to be provided on a WRSM model run and is essential as a means of managing the configuration, output and metadata related to undertaking water resource scenario analyses and ensures that the replication of results is possible. The run description includes three title lines which are written by the model as a header to the appropriate places in the WRSM data output files. The title line-facility also serves as a means of identification and reference between the input and output data sets and its integrity (relevance and reference between input and output data) has to be maintained by the user.

A unique *file name prefix* is selected by the user (of up to five digits), which enables the identification of the WRSM model data input and output files associated with a particular run. The prefix is used by the WRSM in the naming of these files as they are written by the model onto the hard-drive of the computer. For example, if an analysis of the Vaal River system is being undertaken, a prefix “VAAL” might be selected, which means that the *F01.DAT-file will be called *VAAL*F01.DAT, the *F02.DAT-file *VAALF02*.DAT, the *SUM.OUT *VAAL*SUM.OUT and so on (see **Sections 2.3.2** and **14.1** for more information on these data files).

Table 2-1: Run description parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	RCODE	System identification code (≤ 5 characters, which generally provides reference to system name, e.g. “VAAL” for Vaal River System)	1	WRYM.DAT, WRPM.DAT
2	RUNTITLE	General run title and description	3 lines	*F01.DAT
Related parameters and interdependencies:				
-	-	Run code (RCODE) is assigned to data input and output file names (e.g. VAALF01.DAT and VAALSUM.OUT)	-	Selected files
-	-	General run title and description (RUNTITLE) written as headers to appropriate data output files	-	Selected files
-	-	Scenario number used as reference	-	Document

Finally, it should be noted that, in addition to the title line- and file name prefix features shown above, the *Water Resources Information Management System* (WRIMS, as discussed in **Section 1.4**) provides robust information management and metadata capabilities for managing scenarios and related data sets. These are:

- The *study* under which the run is being defined, as well as related information such as the study client, consultant, date and general description;
- The *sub-area* within which the analysed system lies, as well as a general description for the sub-area in question;
- The *scenario* being analysed, including a unique name, number and detailed description.

Finally, the WRIMS also allows for a wide range of metadata particular to the scenario currently selected. This includes descriptions of the source of the hydrology time-series data, a study description, pertinent study results, proposed infrastructure changes, study reports, demand projections, the scenario strategy, development option sequences, study stakeholders, the operating rule strategy, etc.

2.2 Data file location

The location (directory path) of the WRSM data input and output files must be selected and are used by the model to store information on the hard drive of the computer in text-file format. This includes the standard configuration data input files (*F01.DAT, *F02.DAT, etc.), result output files (*SUM.OUT, *PLT.OUT, etc) and the statistical parameter file (PARAM.DAT, as discussed in **Section 2.4 (b)**). The PARAM.DAT-file is also used for specifying the location of the historical hydrology time-series data files (one set of *.INC, *.RAN, *.IRR and *.AFF-files for each incremental sub-catchment modelled in the system, as described in **Section 4.1**).

Finally, it should be noted that the location of configuration input and result output files are used as a means of managing scenarios and related data sets when undertaking WRSM analyses. However, since the development of the *Water Resources Information Management System* (WRIMS, as discussed in **Section 1.4**), with its robust database and metadata capabilities, these files and their locations are managed by the system and will eventually be entirely hidden from the user.

Table 2-2: Data file location parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	DIRI	Directory where data input files are located	1	WRYM.DAT, WRPM.DAT
2	DIRO	Directory to which data output files must be written	1	WRYM.DAT, WRPM.DAT
3	PARMFN	Name and directory of the stochastic parameter file (PARAM.DAT, as described in **Section 2.4 (b)**)	1	*F01.DAT
Related parameters and interdependencies:				
-	-	Data output files are written to directory DIRO	-	Selected files

Conditions associated with defining data file locations are summarised in the table below.

Table 2-3: Conditions for defining the data file location

Condition	Associated parameter/s	Reference
Data input files (i.e. *F01.DAT, etc.) must exist and must be located in specified directory	DIRI	This section
Directory specified for data output files must exist	DIRO	This section

2.3 Analysis period

The period to be analysed must be specified by the model user, including:

- The start year in the Gregorian calendar system (e.g. 1920);
- The start year in another selected calendar system (this value is generally set equal to one);
- The number of years to analyse (e.g. 75);
- The start month number for the analysis, which is usually defined as “1” to coincide with October, the first month of the standard hydrological year;
- The year to analyse first (e.g. 1920).

For historical analyses, the Gregorian start year usually coincides with that of the hydrological time-series data sets (as provided in the *.INC-files, as described in **Section 4.1**). In this case, the total period of analysis should never exceed that of the available data in the shortest hydrological record. Note that a summary of the record length for each incremental catchment may be found in the statistical parameter file (PARAM.DAT, as discussed in **Section 2.4 (b)**).

Table 2-4: Analysis period parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	INTMAX	Number of months to analyse	1	*F01.DAT
2	TIMYR	Number of years to analyse	1	*F01.DAT
3	STYRG	Start year, Gregorian calendar (usually = start of hydrological time-series data, e.g. 1920)	1	*F01.DAT
4	STYRO	Start year, other calendar (usually = 1)	1	*F01.DAT
5	NHYSEQ	Year to analyse first (number, corresponding to STYRG, usually = 1)	1	*F01.DAT
6	TPERD	Month names (≤ 6 characters, start with October if standard hydrological year is used)	12	*F01.DAT
7	DAYS	Number of days in each month (corresponding to TPERD)	12	*F01.DAT
8	MONST	Start month (number, with 1 = first month in list TPERD = October, generally)	1	*F01.DAT
*Parameter 9 must only be defined if a **planning analysis** is being undertaken:*				
9	MONYR	Month which coincides with the beginning of the calendar year (number, with 1 = first month in list TPERD)	1	*F01.DAT
Related parameters and interdependencies:				
-	-	Record length of hydrological time-series data	-	PARAM.DAT
-	-	Start year of hydrological time-series data	-	*.INC, *.RAN, *.IRR, *.AFF
-	-	TPERD written as column headers to appropriate data output file tables	Output	*SUM.OUT

Conditions associated with defining the analysis period are summarised in the table below.

Table 2-5: Conditions for defining the analysis period

Condition	Associated parameter/s	Reference
For historical analyses, period length should not exceed that of catchment with shortest record	INTMAX, TIMYR	This section
Number of months usually = 12 x number of years	INTMAX, TIMYR	This section
Start year should coincide with start year of hydrological time-series data	STYRO	This section.
For historical analyses, parameter NHYSEQ represents year to analyse first. However, for stochastic analyses, NHYSEQ is used to select the specific sequences to be analysed	NHYSEQ	This section and **2.3**

Finally, the user must also provide the *names* and *duration* (in days) of each month of the year, which, for the hydrological year would be as shown below. Note that for February the number of days is usually specified as “28.25”, to avoid leap year calculations in the model.

Table 2-6: Description of months for the standard hydrological year

No.	Name	Number of days in month
1	October	31
2	November	30
3	December	31
4	January	31
5	February	28.25
6	March	31
7	April	30
8	May	31
9	June	30
10	July	31
11	August	31
12	September	30

2.4 Run type and stochastic analysis options

The user must specify whether a *historical* or a *stochastic* run is to be undertaken. More information in this regard is provided below:

a) Historical analysis

If the *historical run-type* is selected, the network model is simply analysed using the historical streamflow, diffuse requirement and runoff reduction sequences contained in the monthly hydrological time-series data files (one set of *.INC, *.RAN, *.IRR and *.AFF for each incremental sub-catchment modelled in the system, as described in **Section 4**). However, in the case of stochastic runs, the model generates streamflow sequences stochastically (synthetically), as well as appropriate monthly target flows for diffuse water requirements and streamflow reductions (SFRs). The latter is achieved by means of methodology which involves the selection of data values from the historical data files (*.IRR and *.AFF), based on the relationship between the historical and the stochastically generated annual flow values for the year in question.

b) Stochastic analysis

Results obtained from undertaking yield or planning analyses based on a single historic streamflow sequence are often very misleading since it depends, to a large extent, on the period of record analysed and the severity of dry periods that the sequence may contain. This can easily be illustrated by analysing a simple water resources system for a variety of period lengths, in which case the historical firm yield (as described in **Section 1.3 (a)**) may drop significantly as the analysed period increases, depending on the location of the most critical dry period on record. Even in cases where the analysed streamflow sequence is long or contains the worst drought in memory, it is not possible to determine the reliability of supply associated with the historical firm yield without undertaking additional analyses.

In order to address the above shortcoming of historical firm yield analyses, stochastic yield analyses are undertaken which allow for the assurance of supply (or risk of non-supply) associated with specific yield values to be determined. The stochastic yield analysis is undertaken in the same way as a historical yield analysis, however, instead of applying the historical monthly hydrological time-series data (as for the historical yield analysis described earlier) stochastically generated (or synthetic) sequences are used. Generally, the process of generating stochastic streamflow sequences is based on the statistical parameters provided in a WRSM data input file referred to as the PARAM.DAT-file. The PARAM.DAT is a complex data file compiled externally to the WRSM using a separate stochastic modelling utility called the *Monthly Multi-site Stochastic Streamflow Model of South Africa* (STOMSA), which is described in the publication *STOMSA User Guide* (WRC, 2003).

Stochastic analyses are undertaken in the WRSM by selecting the *stochastic run-type*, in which case sequences of stochastic monthly hydrological time-series data are generated by the WRSM at run-time, based on information provided in the PARAM.DAT-file.

Table 2-7: Run type and stochastic analysis option parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	HISTO	Run type option: historical or stochastic (H or S)	1	*F01.DAT
2	IFLAG	Stochastic generation options: start randomly, start with historical or bootstrap stochastic method (0, 1 or 2)	1	*F01.DAT
3	RANOPT	Standard random number generator option: no or yes (0 or 1, note: feature not operational, standard random number generator used for all stochastic runs)	1	*F01.DAT
4	MNOSEQ	Number of sequences to analyse	1	*F01.DAT
If number of sequences to analyse (MNOSEQ) ≤ 10, parameter 5 (NHYSEQ) must be defined as follows:				
5	NHYSEQ	List of sequences to analyse (numbers, note: feature is used to analyse specific sequences out of sequence)	MNOSEQ	*F01.DAT
If number of sequences to analyse (MNOSEQ) > 10, parameter 5 (NHYSEQ) must be defined as follows:				
5	NHYSEQ	Sequence to analyse first (number, note: must be defined as selected sequence – 1, e.g. to analyse sequence 1 first, set NHYSEQ = 0; subsequent sequences analysed in sequence)	1	*F01.DAT
*Parameters 6 to 9 are only required if a **yield analysis** is being undertaken:*				
6	OPTFL	Reduce number of sequences option: no or yes (0 or 1)	1	*F01.DAT
7	OPTLIM	Limit option: no or yes (0 or 1)	1	*F01.DAT

No.	Name	Description	Number of inputs	Associated data file/s
8	OPTEPY	Option to calculate stochastic yields based on the "nominal annual yield" (NAY) method: no or yes (0 or 1)	1	*F01.DAT
9	MILPL	Multiple period lengths option: no or yes (0 or 1)	1	*F01.DAT
*Parameters 10 and 11 must be defined if a **planning analysis** is being undertaken and if MNOSEQ = 1 and NHYSEQ = 0. In this case a "manual" analysis option is activated. The user is prompted interactively to select whether a historical or stochastic sequence is to be analysed, in which case either one of NHQ or NSQ is applied.*				
10	NHQ	Number of years, from beginning of hydrological time-series data, at which manual planning analysis must commence (note: user prompted interactively to select which one of five specified values should be used)	5	*F01.DAT
11	NSQ	Sequence to be applied in manual planning analysis (note: user prompted interactively to select which one of five specified values should be used)	5	*F01.DAT
Related parameters and interdependencies:				
-	PARMFN	Name and directory of the PARAM.DAT-file	1	*F01.DAT
-	-	Various statistical parameters used for stochastic streamflow sequence generation	-.	PARAM.DAT

Conditions associated with selecting the run type and stochastic analysis options are summarised in the table below.

Table 2-8: Conditions for selecting run type and stochastic analysis options

Condition	Associated parameter/s	Reference
For historical run, number of sequences to analyse must = 1	MNOSEQ	This section
If option is selected to reduce number of sequences (OPTFL = 1), pairs of target and maximum water requirements must be specified in descending order	YIELD, YLDMAX	This section and **9.2**
PARAM.DAT-file must exist	PARMFN	This section and **4.2**

If a stochastic yield analysis is being undertaken, the user may further customise the analysis by selecting from a number of *stochastic run options*. These are discussed below and relate to aspects such as the sequences to analyse, stochastic streamflow generation, the automatic determination of stochastic yields, as well as further options for short-term stochastic yield analyses.

a) Sequences to analyse

The user must specify the number of stochastic streamflow sequences to be analysed in the model run, as well as select the sequence to be analysed first. Generally, the sequence analysed first is number "1" and the number of sequences analysed is as shown below:

- 201 for long-term stochastic yield analyses;
- 501 for short-term stochastic analyses;
- 1 000 for planning analyses.

b) Stochastic streamflow generation options

As discussed earlier, sequences of stochastic monthly hydrological time-series data are generated by the WRSM based on the statistical parameters provided in the PARAM.DAT-file. However, since each stochastically generated annual streamflow value correlates in some way to the value of the preceding year, this poses a problem for the determination of statistical parameters to be used in the generation of data for the first year of the analysis. In order to address this problem, therefore, values for the first year are generally generated on a random basis. However, the user is provided with three alternative options in this regard and these are:

- For the Start randomly-option, values for the first year are generated on a random basis, as mentioned above. This option should be selected for most stochastic yield and planning analyses.
- For the Start with historical-option, parameters derived from the last year of the historical streamflow sequence (*.INC-file) are used.
- For the Bootstrap stochastic method-option, the parameters in the PARAM.DAT-file are not used at all in the generation process. Instead, the historical streamflow sequences are used to generate stochastic streamflow data, by applying a technique of "random selection with replacement".

The Bootstrap method has been found to perform well in very arid areas such as Namibia where the standard stochastic generation techniques may, in certain instances, produce unrealistic results. Note, however, that this option need not only be used in arid areas and can also produce acceptable results for preliminary analyses where time or budget constraints do not permit the application of the more rigorous approach. For example, analyses were undertaken for catchments in the KwaZulu-Natal province of South Africa and the two methods were shown to produce very similar results. However, the Bootstrap method should be used with great caution and the results considered as first estimates only.

c) Reduce number of sequences option

The purpose of this option is to save computer execution time during stochastic yield analyses. The principal applied is based on the fact that if a sequence is analysed for a specific target draft and no failure occurs, that the sequence in question will not fail if a lower target draft is applied. In the analysis of lower target drafts, non-failing sequences may therefore be excluded, resulting in a reduction in the number of sequences that have to be analysed.

However, it should be noted that for this option to be used effectively, target draft values are sorted in *descending* order (see **Section 9.2**). The model will analyse all sequences for the first target draft and, as the analysis of each target draft is completed, compile (and update) a list of the non-failing sequences. This list is used to selectively analyse only the sequences which failed from the previous analysis. In this regard it is important to note that, since all sequences are not analysed for all the target drafts when this option is selected, the model output for channel flows and reservoir levels will not be complete. This consideration is important in cases where box-plots for specific reservoirs or channels are to be generated from the output.

d) Limit option

In some cases problems may arise in the interpretation of results if a failure occurs during the first year of the analysis. This is particularly relevant when undertaking short-term stochastic analyses when the likelihood of a failure during the first year is high. If the limit option is not selected, the model will calculate failure for the year over the full 12 month period. If the option is selected, however, the failure is calculated on the actual failure period if it occurs during the first year. For example if a failure occurs during month 2 in the first year, the failure will be calculated only from the start of the run up to the second month. In this manner, the possibility is reduced that the failure will decrease as a result of a higher demand.

e) Multiple period lengths option

As part of a short-term stochastic analysis, the system analyst must make an important decision regarding the appropriate period length to select in the generation of short-term yield-reliability curves, for application in planning analyses (as described in **Section 11.2.2**) as a basis for making water resource allocation decisions. The objective of this selection process is to obtain, for each of the reservoir starting storage conditions analysed, the most conservative curve. This is achieved by plotting yield-reliability curves for the different period lengths (1 year, up to the total number analysed, usually 5 years), all on a common plotting plane (usually 5 years), and selecting the curve that exhibits the lowest yield characteristics. In general, shorter period lengths produce more conservative yield-reliability characteristics in the case of low reservoir starting storages conditions.

The above methodology is based on investigations undertaken into the application of short-term yield reliability curves, which revealed that by using only the 5-year period length, the projected short-term yield characteristics is generally over-estimated at low reservoir starting storage levels. The problem is particularly evident during the first two years after a low system storage event. Curtailment level projections produced in planning analyses showed that very severe curtailments at unacceptably high probabilities are implemented in the two to three years following a low system storage situation. It was argued that a more severe curtailment in the first year will decrease the magnitude and probability of restrictions in subsequent years to acceptable levels. This is achieved by adopting yield-reliability curves based on shorter period lengths for low starting storage conditions.

In order to facilitate the selection of the period length for the most conservative yield-reliability curve, a *multiple period lengths*-option is available to calculate the results required to produce curves for various period lengths. Since the yield data associated with the one-year, two-year etc. period lengths are already contained in the five-year (or other period length) analysis, it is not necessary to undertake any additional analyses for this purpose. It should be noted that a maximum analysis period of 10 years has been set in cases where the multiple period length-option has been selected, in order to prevent such calculations being undertaken for long-term stochastic yield analyses.

3. DEVELOPING A REPRESENTATIVE SYSTEM NETWORK

Developing a representative network model for a water resource system involves a process whereby the modeller creates a synthetic representation of the system by drawing a schematic diagram. This is achieved by using a standard set of symbols to indicate the connectivity between and nature of the various components that make up the system in question. This process of synthesis, however, always implies a trade-off between the need to simulate the behaviour of individual system components at a sufficient level of detail, on the one hand, and practical modelling limitations on the other.

The process of developing a representative system network model includes a number of aspects and these are discussed in the following sections.

3.1 Identifying main physical system features

The starting point in the process of developing a representative water resource system network model is usually a geographical map showing the physical features of the system in question. The map should denote rivers, catchment boundaries, reservoirs, abstraction works, water discharge infrastructure, water transfer conduits (canals, tunnels or pipelines), the location of water users, etc. The catchment delineations, required for defining the way in which net runoff from incremental sub-catchments enter the system network, are determined from the map. The selection of incremental sub-catchment boundaries within the system is dictated by the spatial resolution to which modelling needs to be undertaken, position of existing infrastructure, as well as the location of potential new water resource development options that have to be assessed.

3.2 Aggregating and lumping system components

Individual components in water resource systems are often combined (or “lumped”) and represented in the system network as a single element. This approach is inevitable since water resource systems are generally complex and consist of vast amounts of components and it would be impractical to simulate the behaviour of each component individually. The selection of the appropriate resolution for the representative network model depends on the purpose of the study being undertaken and the intended application of the modelled results. For example, water abstractions of the same type that has access to the same surface flow may be grouped and be represented by a single abstraction channel. Small dams located in tributary catchment may be combined to form a dummy dam. Generally, however, larger key dams are modelled individually, especially if they are used to supply primary water users for domestic purposes.

Earlier yield and planning analysis studies generally focused on the overall behaviour of water resource systems and allowed for the definition of relatively large sub-catchments and the lumping together of many elements to form a single system component. Recent studies, however, require a far greater resolution, for example the five *Water Availability Assessment* (WAA) studies recently commissioned by the DWAF, Directorate: National Water Resource Planning (NWRP) on the Mhlathuze, Inkomati, Berg, Crocodile (West) and Olifants river systems in support of the compulsory licensing process. The focus of these studies was on simulating local catchments and tributaries in order to reflect the impacts water users (or groups of water users) have of one another and the system models therefore had to be configured at a sufficient resolution to be able to identify problem areas (over-allocation) in river systems as well as areas where there is surplus water available. As a result, the criteria for deciding on the modelling resolution for the WAA studies included the following:

- The resolution should be dictated by system specific layout and pre-defined modelling should not be followed;
- As a minimum, each quaternary catchment should be represented by a node in the network system;
- Users receiving water from tributaries and from the main stream of a river should be analysed separately in order to evaluate local availability;
- Differences in hydrological and climatic conditions;
- The location of small dams and water use abstractions;
- The resolution should allow for assessment of the downstream impacts of one group of water users on another.

3.3 Drawing a representative schematic diagram

Based on the identified physical features of the water resource system, a representative schematic diagram is created by indicating the connectivity between and nature of the various components that make up the system in question. As mentioned in **Section 1.3**, the WRSM enables the user to configure most water resource system networks using basic *building blocks*. These are listed below and their configuration and application in the WRSM are discussed in **Sections 5**, **6**, **7** and **8**, respectively:

- Reservoirs;
- Junction nodes;
- Flow channels;

- Other system features, which are configured by means of special combinations of the others.

The standard symbols used for the various components of a water resource system on a WRSM system network diagram are shown below.

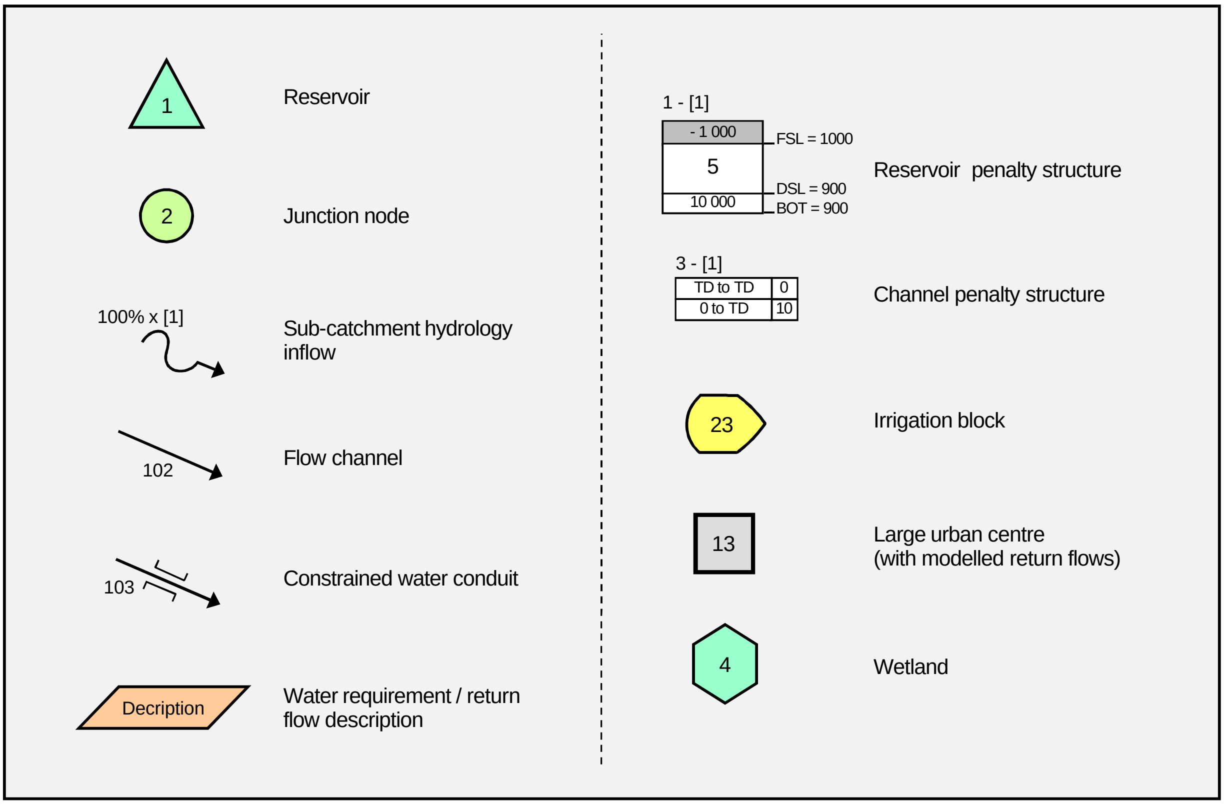


Figure 3-1: Standard symbols for showing water resource system components on a system network diagram

An example of a simple system network diagram is shown in **Appendix A**.

3.4 Selecting and implementing system operating rules

System operating rules are defined to address aspects like the supply priority amongst water users, prioritisation of the use of water sources, inter-reservoir and inter-sub-system support rules, as well as reservoir operational levels and drawdown rules. The selection of operating rules is of great importance because they have a very direct impact on the capability, assurance and sustainability of a system's water resources, as well as the costs associated with its operation. The standard procedure for developing operating rules involves a number of steps, which represents an iterative process that can be repeated as many times as required. Note that typically the objective when following this procedure is to achieve the maximum utilisation of the available resources, while minimising or limiting the associated operational costs. The steps include:

- Selection of an initial set of operating rules based on chosen objectives with regard to the behaviour of the system. This step is probably the most difficult and relies greatly on the intuition and experience of the water resource system analyst.
- Implementation of the selected operating rules in the network model and undertaking of a model run.
- Evaluation of the level of achievement of selected objectives based on the behaviour of the system as exhibited in the simulation results.
- Usually, selection of an alternative set of operating rules followed by repetition of the above steps.

The operating rules selected for a water resource system network model is implemented in the WRSM based on a mechanism called "penalties". This approach is in line with the basic modelling methodology adopted in the WRSM that the configuration of a system network and the relationships between its elements are defined by means of input data, rather than by fixed algorithms embedded in the model's source code.

Penalties are dimensionless values and are used by the WRSM as the basis for flow routing solutions. This is achieved by comparing the overall penalties of one flow routing option with that of another, with the objective of minimising the overall penalty which is incurred. In the case of channel routes, a penalty is assigning to every unit of flow through each channel arc. Penalties are also assigned to every unit of water impounded in reservoirs. These reservoir penalties represent a benefit (or in some cases dis-benefit) of having that unit of water available in the reservoir in question. The model interprets the reservoir penalty by comparing the benefit of having water in one reservoir with the benefit of having it in another, while also considering the penalty that might be incurred if the water is transported or if certain water users in the system are not supplied. It is essential to understand that penalties are not related to monetary units, but rather a dimensionless value that is interpreted by comparison of the relative size of penalties assigned to different system elements. When finding a flow routing solution for a system, the model will always select the option which will result in the lowest overall dis-benefit being incurred. This is calculated for a particular solution by adding up flows multiplied by penalties for all elements in the system.

The process involved with defining reservoir penalties is discussed in **Section 5.2** and that of channels in **Section 7.2**.

4. MODELLING INCREMENTAL SUB-CATCHMENTS

4.1 Hydrological analyses

Detailed hydrological analyses provide the foundation of any assessment aimed at determining the capability of a water resource system and the level of confidence that can be placed on the results of such assessments is largely dependent on the quality of the data available. Typical hydrological analyses consist of a number of aspects and these are summarised below:

- An assessment of the historical developments inside the catchment area under consideration and the impact of those developments of streamflow. These may include the water use and return flows related to urban and industrial areas, irrigation, streamflow reductions (SFRs) and mining, as well as the impacts of physical catchment features, such as water bodies, transfer schemes, streamflow diversions and wetlands.
- The hydro-meteorological data analysis, including the selection, collation, assessment, and correction of historical rainfall, evaporation and streamflow data;
- Modelling of the dynamic relationship between rainfall and runoff;
- The extension of available historical streamflow data and the generation of time-series of natural monthly historical streamflows for defined sub-catchments inside the area under consideration (as discussed in **Section 4.2**);

A summary is provided below of the application of hydro-meteorological data in the WRSM.

a) Rainfall data

Rainfall data are used for calculating, on a monthly basis the:

- Impact of rainfall on catchment developments, such as irrigation water requirements and return flows from large urban areas;
- Rainfall directly on the surface area of water bodies in the catchment, including major dams, small dams, weirs, gravel pits, wetlands and the pollution control dams (PCDs) used in coal mining activities.

b) Evaporation data

Evaporation data are used for calculating, on a monthly basis the:

- Evaporative losses (through evapo-transpiration and other mechanisms) from catchment developments and physical catchment features such as irrigated crops, wetlands and coal mining activities;

- Losses through evaporation directly from the surface area of impoundments in the catchment, including major dams, small dams, weirs, gravel pits, wetlands and PCDs.

c) Streamflow data

Streamflow data are used in the WRSM as a basis for:

- Determining the historical sequence of monthly inflows to reservoirs and other nodal points within the water resources system under consideration and thereby allow for the behaviour of the system to be simulated;
- The stochastic hydrology analysis and subsequent generation of stochastic (or synthetic) streamflow sequences for application in stochastic yield and planning analyses (as discussed in **Section 2.4**).

4.2 Definition of incremental sub-catchment areas

In order to achieve the appropriate modelling resolution in the WRSM (as discussed in **Section 3.2**), the study area is generally divided into a number of smaller sub-catchments. This subdivision is based, firstly, on the topography of the study area and, secondly, on its physical layout, including aspects such as the locality of the main and tributary river catchments, flow gauging stations, water use and return flow centres and water bodies. The exact boundaries of defined sub-catchment can be determined in various ways, including the manual analysis of contour lines on 1:50 000 topographical maps or by using digital terrain models (DTMs) and geographical information systems (GIS).

The defined incremental sub-catchments ultimately form the basic structure of the representative system network model (as discussed in **Section 3.3**) and determine, most importantly, the location within the water resources system at which hydrology inflows to reservoirs and other nodal points occur. More information in this regard is provided in **Section 4.4**. The name of each incremental sub-catchment in the system is defined in the statistical parameter file, PARAM.DAT (as discussed in **Section 2.4 (b)**). For example, if an analysis of the Mgeni River system is being undertaken, incremental sub-catchments may be defined for the Midmar, Albert Falls, Nagle and Inanda Dam catchments, in which case the corresponding catchment names in the PARAM.DAT-file may be *MID*, *ALB*, *NAG* and *INA*.

Furthermore, the total catchment area each incremental sub-catchment in the system (in units of km^2) is also defined in the PARAM.DAT-file, as shown below. This variable is used internally by the model for the purpose of calculating natural runoffs from the natural portion of each sub-catchment after having accounted for the combined extent of areas under irrigation, streamflow reduction catchment portion areas and coal mining activities (as described in **Sections 8.2.4**, **8.2.5** and **8.3.5**, respectively).

Table 4-1: Parameter for defining incremental sub-catchment areas

No.	Name	Description	Number of inputs	Associated data file/s
For each incremental sub-catchment listed in the PARAM.DAT-file (NOFIL, as described below), parameter 1 must be defined:				
1	CATHAR	Catchment area of incremental sub-catchment (km^2)	1	PARAM.DAT
Related parameters and interdependencies:				
-	NOFIL	Number of incremental sub-catchments listed in the PARAM.DAT-file	-	PARAM.DAT

Finally, it should be noted that, since incremental sub-catchments provide the mechanism for defining hydrology inflows to reservoirs and nodes in the system and the catchments are defined in the PARAM.DAT-file, this file must be provided for all WRSM system configurations, even stochastic yield or planning analyses (as discussed in **Section 2.4**) will not be undertaken. This condition is shown in the table below.

Table 4-2: Conditions for defining incremental sub-catchment areas

Condition	Associated parameter/s	Reference
Stochastic parameter file (PARAM.DAT) must exist	-	This section, **2.4 (b)**

4.3 Hydro-meteorological and diffuse water use time-series data files

Hydro-meteorological and data and diffuse water use are defined in the WRSM by means of a set of five time-series data files for each of the defined incremental sub-catchments located inside the water resource system (as discussed in **Section 4.2**). These are the:

- ***.INC-file**, which contains monthly naturalised or natural simulated incremental runoff for the sub-catchment in question (in units of million m^3);
- ***.RAN-file**, which contains monthly rainfall at some point located inside or at the outlet of the sub-catchment (in units of mm);
- ***.IRR-file**, which contains monthly diffuse water requirements inside the catchment (in units of million m^3);
- ***.AFF-file**, which contains monthly streamflow reductions (SFRs) due to commercial forestry and other dry-land crops located inside the catchment (in units of million m^3);

- ***.URB-file**, which contains monthly increases in runoff due to large urban areas located inside the sub-catchment (in units of million m^3).

The names of these files consist of a standard extension and a unique name selected by the modeller. For example, if an analysis of the Mgeni River system is being undertaken, incremental sub-catchments may be defined for the Midmar, Albert Falls, Nagle and Inanda Dam catchments, in which case the corresponding *.INC-files may be called *MID*.INC, *ALB*.INC, *NAG*.INC and *INA*.INC, while the *.RAN may be called *MID*.RAN, *ALB*.RAN, *NAG*.RAN and *INA*.RAN and so on. Also, each file must follow the standard HRU-format for streamflow time-series data files, which starts in the hydrological year (i.e. from October to September).

Furthermore, it is important to note that a complete set of the above five time-series data files must be provided for each of the defined incremental sub-catchments in the water resource system (the *.URB-file is only if a planning analysis is being undertaken). This implies that, even if, say, no streamflow reductions occur in a particular sub-catchment, a *.AFF-file must still be provided, but may be populated with 0-values which means that no streamflow reduction impacts will be modelled. This is of great importance, especially in the light of recent model developments that have been undertaken in support of the five *Water Availability Assessment* (WAA) studies recently commissioned by the DWAF, Directorate: NWRP (as discussed in **Section 3.2**), involving new methodologies for the modelling of, in particular, irrigation and streamflow reductions, which means that the functionality provided by the *.IRR and *.AFF-files have now been largely superseded. More information in this regard is provided in **Sections 8.2.4** and **8.2.5**.

Finally, as discussed in **Section 2.4 (b)**, if stochastic analyses are undertaken in the WRSM by selecting the *stochastic run-type*, data provided in the *.INC, *.RAN, *.IRR, *.AFF and *.URB-files are not applied in the analysis and, instead, sequences of natural incremental runoffs are generated by the model at run-time, based on information provided in the PARAM.DAT-file. The model also generates appropriate monthly target flows for diffuse water requirements and streamflow reductions based on a methodology which involves the selection of data values from the historical data files (i.e. *.IRR and *.AFF), based on the relationship between the historical and the stochastically generated annual flow values.

4.4 Linking hydrology data with system network model

Each of the defined incremental sub-catchments located inside the water resource system (as discussed in **Section 4.2**) is linked to any number of selected junction nodes and/or reservoirs in the system network model by means of a reference number which is assigned based on the sequential order in which the sub-catchments are defined in the PARAM.DAT-file (as discussed in **Section 4.2**). Flow and water use volumes contained in the *.INC, *.IRR, *.AFF and *.URB-files are then apportioned to the selected junction nodes and/or reservoirs by means of four scaling factors, DRAINA, IRRFAC, AFFFAC and DRAINU for the above file respectively. The net flows entering a particular system node is then calculated, on a monthly basis, as follows:

Flow = DRAINA(*.INC-file value) – IRRFAC*(*.IRR-file value)* (Eq. 4-1)
– AFFFAC(*.AFF-file value) + DRAINU*(*.URB-file value)*

Furthermore, the volumes in the *.IRR, *.AFF and *.URB-files can be varied over time when undertaking a planning analysis, by defining associated annual projection data.

Finally, a rainfall-runoff coefficient is used to account for situations where the full supply area of a reservoir covers a significant percentage of its total catchment area (more than, say, 20 %). In most analyses, the catchment area of a reservoir is accepted as the area contributing to the full supply boundary of the reservoir. If the reservoir drops below full supply level, however, an additional intermediate area is exposed which is not taken into account in the natural inflow calculations. In most cases the ratio of the full supply area to the total catchment area is so small that the influence of runoff from the intermediate area is not significant. Sometimes, however, runoff from the intermediate area can be significant and must therefore be taken into account. In such cases the rainfall-runoff coefficient is used to estimate the additional runoff as a proportion of rainfall. If, for example, the average runoff from the catchment is 10 % of the mean annual precipitation, then a value of 0.1 would be assigned to the coefficient. In most cases, however, the full supply surface area of the reservoir is small relative to the catchment area and the value may simply be set equal to zero.

Table 4-3: Parameters for linking hydrology data with system network model

No.	Name	Description	Number of inputs	Associated data file/s
1	FLCODE	Selection of units for hydrological time-series data files *.INC, *.IRR, *.AFF and *.URB: million m^3/a or m^3/s (MCM or CMS)	1	*F02.DAT
*For each reservoir, as well as each junction node with incremental sub-catchment hydrology inflows in the system (MNRES, as described in **Sections 5.1** and **6**), the following must be defined:*				
2	CATCH	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	1	*F02.DAT
3	DRAINA	Scaling factor for natural runoff (proportion of *.INC-file)	1	*F02.DAT
4	IRRFAC (DFIRR)	Scaling factor for diffuse irrigation water use (proportion of *.IRR-file)	1	*F02.DAT
5	AFFFAC (DFAFF)	Scaling factor for streamflow reductions (proportion of *.AFF-file)	1	*F02.DAT
6	ROFFC	Rainfall-runoff coefficient (in sub-catchments with no reservoir, or where the surface area of reservoir at full supply level, RFAREA, is small relative to that catchment area, ROFFC is set = 0)	1	*F02.DAT
*Parameters 7 to 14 must be defined if a **planning analysis** is being undertaken:*				
7	NATCH	Channel number for incremental sub-catchment hydrology inflows	1	*F02.DAT
8	NATTYP	Penalty structure type associated with channel for incremental sub-catchment hydrology inflows, NATCH (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
9	DRAINU	Scaling factor for increased runoff due to large urban areas (proportion of *.URB-file)	1	*F02.DAT
10	MNYP	Number of planning years for which projection information is provided for diffuse water use as provided in the *.AFF, *.IRR and *.URB data files	1	*GTH.DAT
For each incremental sub-catchment listed in the PARAM.DAT-file (NOFIL, as described earlier in this section), parameters 11 to 14 must be defined:				
11	NG	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	1	*GTH.DAT
12	AFFGTH	Annual projection factors for streamflow reductions (applied to *.AFF-file, projected value = base value x (1 + AFFGTH), therefore AFFGTH = 0 implies no change)	MNYP	*GTH.DAT
13	IRRGTH	Annual projection factors for diffuse irrigation use (applied to *.IRR-file, projected value = base value x (1 + IRRGTH))	MNYP	*GTH.DAT
14	URBGTH	Annual projection factors for increased runoff due to large urban areas (applied to *.URB-file, projected value = base value x (1 + URBGTH))	MNYP	*GTH.DAT

Conditions associated with defining incremental sub-catchment hydrology inflows are summarised in the table below.

Table 4-4: Conditions for defining incremental sub-catchment hydrology inflows

Condition	Associated parameter/s	Reference
Set of monthly hydrological time-series data files must exist, i.e. *.INC, *.RAN, *.IRR, *.AFF and *.URB (the latter only if a planning analysis is being undertaken) for each of the incremental sub-catchments in the system	-	**4.3**
Stochastic parameter file (PARAM.DAT) must exist	-	**2.4 (b)**, **4.2**
Catchment reference number ≤ number of catchments appearing in PARAM.DAT	CATCH	This section
For nodes and/or reservoirs located inside the same incremental sub-catchment (i.e. same reference number, CATCH), sum of respective scaling factors generally ≤ 1	CATCH, DRAINA, AFFFAC, IRRFAC, DRAINU	This section
For incremental sub-catchments with no reservoir (i.e. at a junction node with incremental sub-catchment hydrology inflows), or where surface area of reservoir is small relative to the catchment area, rainfall-runoff coefficient (ROFCC) can be set = 0	RFAREA, ROFFC	This section

5. CREATING RESERVOIRS

Reservoirs have the capability of retaining water over time and are modelled in the WRSM using of a special reservoir node-type. Variables required to define a reservoir include those relating to its physical characteristics, storage zones, rule curve and penalty structures (which control the way in which the reservoir is operated) and these are discussed in the following sections. The simulation of reservoir behaviour in the WRSM involves a simple calculation relating to the volume of stored water in the reservoir at the end of each month in the simulation. If the storage volume in the reservoir is known at the beginning of the simulation period, then the storage at the end of the first month can be calculated based on the change in storage that has occurred. The latter is calculated based on a simple mass balance principle, which can be represented as follows:

Change in storage = Inflows – Outflows (Eq. 5-1)

A second principle is applied in order to provide a link between the state of storage in the first and second months. The principle states that the storage in the reservoir at the beginning of any month must be equal to the storage in the reservoir at the end of the preceding month. This is shown below. By applying this principle, the start storage for the second month may be determined.

End storage month(x) = start storage month(x+1) (Eq. 5-2)

Similarly, the applying both these principle, in turn, to every month in the simulation period, the storage in the reservoir may be determined at any point in time.

5.1 Physical characteristics

The variables required to define the physical characteristics of a reservoir are discussed below:

- A unique name, such as *Vaal Dam*, or *Dummy Dam*.
- A status indicator which is used to define whether a reservoir exists or not. This is a useful option when undertaking scenarios where a system is modelled with and without certain reservoirs, since it does not require major changes to the system configuration. It is generally convenient to include all possible reservoirs when a system is initially configured and simply, say, excluding proposed reservoirs for a base scenario, by toggling the status indicator.

- Three fixed reservoir levels: the full supply level (FSL), the dead storage level (DSL) and bottom level (which signifies zero storage), all of which are defined in units of metres above mean sea level (MSL). Often, the bottom of a reservoir is defined at the same elevation as that of the DSL, in cases where the reservoir in question has no dead storage zone (e.g. in the case of farm dams). Mostly, however, the sill of the reservoir outlet structure is located above the bottom level, in which case it is not possible to abstract water below the lowest draw-off. The result is a dead storage zone, which may only be depleted through evaporation.
- A defined relationship between elevation (in metres above MSL), storage capacity (in units of million m^3) and surface area (in units of km^2), with three sets of corresponding data points.
- Lake evaporation values (in mm), defined for each month of the year, starting in October. Note that the net evaporation from the reservoir will be calculated for a particular month as the difference between the defined lake evaporation value and monthly point rainfall. The latter is defined in the *.RAN hydrological data file associated with the incremental catchment in question (as discussed in **Section 4.3**).

Table 5-1: Reservoir physical characteristics parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNRES	Number of reservoirs (as well as nodes with incremental sub-catchment hydrology inflows, as described in **Section 6**) in the system	1	*F02.DAT
For each reservoir in the system (MNRES, excluding nodes with incremental sub-system hydrology inflows), parameters 2 to 16 must be defined:				
2	RESNUM	Reservoir node number	1	*F02.DAT
3	RESNAM	Reservoir name	1	*F02.DAT
4	NSTAT	Reservoir status option: does not or does exist (0 or 1)	1	*F05.DAT
5	FSL	Full supply level of reservoir (m above MSL)	1	*F05.DAT
6	DEAD	Dead storage level of reservoir (m above MSL)	1	*F05.DAT
7	BOT	Bottom level of reservoir (m above MSL, signifies zero storage)	1	*F05.DAT
8	RFAREA	Surface area of reservoir at full supply level (km^2)	1	*F02.DAT
9	MM	Number of reference elevation levels for which storage capacities and surface areas are defined (3 ≤ MM ≤ 15)	1	*F02.DAT
10	SURFEL	Range of reference elevation levels (m)	MM	*F02.DAT
11	SURFVL	Storage capacities (million m^3, corresponding to SURFEL)	MM	*F02.DAT
12	SURFAR (EVAREA)	Surface areas (km^2, corresponding to SURFEL)	MM	*F02.DAT
13	ATOP	Storage level taken as full for allocation procedure (m above MSL, assumed = FSL if set = 0)	1	*F05.DAT

No.	Name	Description	Number of inputs	Associated data file/s
14	COEVAP	Monthly lake evaporation (mm, start in first month of list TPERD, as described in **Section 2.3**)	12	*F02.DAT
15	NUM	Number of hydropower channels downstream of reservoir, along path of normal routing	1	*F02.DAT
16	PDR	Channel numbers of hydropower channels downstream of reservoir, along path of normal routing	NUM	*F02.DAT
Related parameters and interdependencies:				
-	CATCH	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	-	*F02.DAT

Conditions associated with defining the physical characteristics of a reservoir are summarised in the table below.

Table 5-2: Conditions for defining the physical characteristics of a reservoir

Condition	Associated parameter/s	Reference
For all reservoirs, including those without incremental sub-catchment hydrology inflows, a catchment reference number (CATCH) must be assigned	MNRES, CATCH	This section
Storage capacity expected to increase “monotonically” (i.e. at each reference elevation point the storage capacity divided by the surface area is greater than for the preceding point)	SURFEL, SURFVL, SURFAR	This section
Parameters for economic and tariff calculations associated with reservoirs must be defined. Even if an economic analysis is not being undertaken, parameters must still be populated with dummy values	Various	**13**

5.2 Storage zones, rule curves and penalty structures

As discussed in **Section 3.4**, operating rules selected for a water resource system network model is implemented in the WRSM based on a mechanism called "penalties", which are dimensionless values used by the model as the basis for flow routing solutions. In the case of reservoirs, penalties are defined by means of storage zones, rule curves and penalty structures and are assigned to a particular zone in a reservoir in order to signify the benefit (or in some cases dis-benefit) associated with having water in storage, while the storage volume in the reservoir falls within the zone in question. More information in this regard is provided below.

a) Storage zones

A reservoir can be divided into different storage zones for the purpose of controlling the way in which it is drawn down. In general, the first zone in a reservoir lies above the full supply level

(FSL), while the last zone is defined by the dead storage level (DSL) and bottom level. The remaining zones are defined by specifying the elevation of each lower zone boundary. For example, in the case of a reservoir with 7 zones, the user must define 4 sets of lower zone boundaries. It should be noted that in most cases the lower zone boundaries (and therefore the reservoir storage zones) remain constant over the 12 months of the year. However, the facility is provided for varying these definitions from one month to the next.

b) Rule curves

Certain reservoirs in a water resource system may be modelled with a flood attenuation zone, which is a zone reserved for flood events. When water enters such a zone, it does so at a dis-benefit, since ideally the zone in question should be kept empty. Conversely, there may be a storage zone in a reservoir from which water is only used in emergencies. Having water in such a zone signifies a benefit and will only be used when all other water that is assigned a lower benefit has been depleted. The concept of dis-benefit and benefit therefore depends on whether the zone in question is above or below the ideal level. This ideal level is referred to in the WRSM as the rule curve level.

The rule curve level is defined in the WRSM by selecting the reservoir zone with which the rule curve is association. The rule curve will consequently be implemented at the elevation of the lower boundary for the selected zone. It should be noted that in most cases, reservoirs are used primarily for water supply, which means that the rule curve level would typically be defined at the full supply level (i.e. at the elevation of the lower boundary for the spill zone).

c) Reservoir penalty structures

Reservoir penalties are defined using the WRSM penalty structure feature. This involves the definition of a number of standard penalty structure types and a selection is then made of the appropriate penalty structure type which is to be associated with each of the modelled reservoirs in the system. This approach is followed so that the utilisation of a single penalty structure type may be used in the definition of more than one reservoir.

d) Multi-reservoir balancing strategy

Finally, the model allows for the selection of a multi-reservoir balancing strategy to be used when modelling complex systems, based on a set of special policy variables. Reservoirs are assigned to separate priority groups so that, at any one time, water is drawn down evenly from all the reservoirs in a particular group, implying that the same penalty structure is used for all the group's reservoirs. Such balancing strategies are however rarely used and systems are mostly modelled purely on the drawdown rules defined by the penalty structures of individual reservoirs. Standard users are therefore not encouraged to use this facility.

Table 5-3: Reservoir storage zone, rule curve and penalty structure parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	NZOTYP	Number of reservoir penalty structure types	1	*F05.DAT
2	MNSZON	Number of storage zones in a reservoir	1	*F05.DAT
3	RLCZON	Storage zone number with rule curve as lower boundary	1	*F05.DAT
For each storage zone (MNSZON), parameters 4 to 8 must be defined:				
4	ZONNAM	Name of storage zone	1	*F05.DAT
5	ZONCST	Penalty for storage zone, associated with each penalty structure type	NZOTYP	*F05.DAT
6	POLICY(1)	Balancing strategy option: 1, 2 or 3	1	*F05.DAT
7	POLICY(2)	Balancing variable option: elevation or volume (1 or 2)	1	*F05.DAT
8	POLICY(3)	Balancing reference option: 1, 2 or 3	1	*F05.DAT
*For each reservoir in the system (MNRES, excluding nodes with incremental sub-system hydrology inflows, as described in **Section 5.1**), parameters 9 to 13 must be defined:*				
9	NRES	Reservoir node number (same as RESNUM, as described in **Section 5.1**)	1	*F05.DAT
10	ZONTYP	Penalty structure type associated with reservoir, assigned based on the sequential order in which it is defined (under parameters 1 to 8 above)	1	*F02.DAT
11	PRI	Selection of reservoir priority for balancing strategy	1	*F05.DAT
*For each storage zone in a reservoir that does not have the full supply, dead storage or bottom level (FSL, DEAD and BOT, as described in **Section 5.1**) as its lower boundary, parameters 12 and 13 must be defined (i.e. MNSZON – 3 times):*				
12	NRES	Reservoir node number (same as NRES above)	1	*F05.DAT
13	RLC	Monthly elevation levels that define the lower zone boundaries (m above MSL)	12	*F05.DAT

Conditions associated with defining the reservoir storage zones, rule curves and penalty structures are summarised in the table below.

Table 5-4: Conditions for defining reservoir storage zones, rule curves and penalty structures

Condition	Associated parameter/s	Reference
Penalty structure type assigned to reservoir must exist	ZONTYP, NZOTYP	This section
Rule curve level and penalties must be defined such that water is not stored in zone above full supply level	FSL, RLCZON, ZONTYP, ZONCST	This section
Penalties must be defined such that water cannot be abstracted from zone below dead storage level	DEAD, ZONTYP, ZONCST	This section

5.3 Starting storage levels

The water level in the reservoir at the start of the analysis must be defined (in metres above MSL). Note that this value must be defined for all reservoirs in a system, including those for which the status indicator is set to *does not exist* (as discussed in **Section 5.1**). In cases where only the starting storage volume of a reservoir is known, the corresponding elevation may be calculated from the elevation-storage capacity relationship, discussed earlier.

Table 5-5: Reservoir starting storage level parameters

No.	Name	Description	Number of inputs	Associated data file/s
*For each reservoir in the system (MNRES, excluding nodes with incremental sub-system hydrology inflows, as described in **Section 5.1**), the following must be defined:*				
1	NRS	Reservoir node number (same as RESNUM, as described in **Section 5.1**)	1	*F06.DAT
2	ELEV	Water level in reservoir at the start of the analysis (m above MSL)	1	*F06.DAT

Conditions associated with defining reservoir starting storage levels are summarised in the table below.

Table 5-6: Conditions for defining reservoir starting storage levels

Condition	Associated parameter/s	Reference
Reservoir for which starting storage level is specified must exist	NRS, RESNUM	This section, **5.1**
Specified water level at the start of the analysis must lie within the defined range of reference elevation levels for the reservoir in question, and also lie below its full supply level and above its bottom level	ELEV, SURFEL, FSL, BOT	This section, **5.1**

5.4 Time-related reservoir controls

When undertaking a planning analysis, any reservoir may be commissioned at any time before, during, or after the time period being analysed (as discussed in **Section 2.3**). Similarly, the reservoir may also be decommissioned, or its characteristics replaced by that of another defined reservoir. This special feature may be used, for example, to model the change in storage in a reservoir after it has been raised by replacing the reservoir as defined with its existing characteristics with that of another definition provided for the same reservoir, but with its raised characteristics. It should be noted that in this case, the second definition will be allocated a different system network node number, but that the node number associated with the original definition will always be used to define the connectivity of the reservoir with system channels.

Finally, it should be noted that time-related control parameters must be defined for all reservoirs modelled in a planning analysis.

Table 5-7: Time-related control parameters for reservoirs

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNDAMS	Number of reservoirs in the system (same as MNRES, excluding nodes with incremental sub-system hydrology inflows, as described in **Section 5.1**)	1	*DAM.DAT
For each reservoir in the system (MNDAMS), the following must be defined:				
2	DAMND	Reservoir node number (same as RESNUM, as described in **Section 5.1**)	1	*DAM.DAT
3	DAMNDR	Node number for reservoir that is replaced by the characteristic of this reservoir, at a specified time (number, from RESNUM list, or 0 if none)	1	*DAM.DAT
4	DCYR	Hydrological year in which reservoir becomes active	1	*DAM.DAT
5	DCMTH	Month number, in hydrological year, at the beginning of which reservoir becomes active	1	*DAM.DAT
6	DRYR	Hydrological year in which reservoir becomes inactive	1	*DAM.DAT
7	DRMTH	Month number, in hydrological year, at the end of which reservoir becomes inactive	1	*DAM.DAT

Conditions associated with defining time-related controls for reservoirs are summarised in the table below.

Table 5-8: Conditions for defining time-related controls for reservoirs

Condition	Associated parameter/s	Reference
Reservoir for which time-related control is specified must exist	DAMND, RESNUM	This section, **5.1**

6. CREATING JUNCTION NODES

The primary purpose of junction nodes is to connect channels according to the physical layout of the system network in question. These connection points may be used in a variety of situations, as detailed below:

- Combine the flow from tributary catchments;
- Represent points from where water can be abstracted or diverted, while taking account of the appropriate locality and associated resource availability for a particular water user within the system context;
- Provide the capability of splitting conveyance routes to simulate physical constraints that may differ along a conduit;
- A special node type, referred to as the 0-node, is also used and represents an imaginary point outside of the system being modelled. The zero-node is used as a downstream point (head) for channels that model flows leaving the system (e.g. consumptive water uses, losses, etc.) or as an upstream point (tail) for channels that model flows entering the system from elsewhere (e.g. return flows, inflows from other systems, etc.).

Junction nodes are created implicitly within the system network when the user defines the connectivity of channels and involves, simply, the specification of a channel's upstream and downstream node numbers, as described in later sections.

Some nodes, however, may also serve the additional purpose of providing a point where the hydrology inflows from a particular incremental sub-catchment (or portion thereof) enters the system network. This type of node is called an "inflow node" and the link between these nodes and the hydrology data is defined as described earlier in **Section 4.4**. However, since the WRSM uses the basic structure of reservoirs to model inflow nodes, these nodes are essentially treated like reservoirs with zero storage and must a number of additional reservoir-related parameters be defined in these cases, as shown below.

Table 6-1: Special definition of reservoir-related parameters for junction nodes with sub-catchment hydrology inflows

No.	Name	Description	Number of inputs	Associated data file/s
1	MNRES	Number of nodes with incremental sub-system hydrology inflows (as well as reservoirs, as described in **Section 5.1**) in the system	1	*F02.DAT
For each node with incremental sub-system hydrology inflows in the system (MNRES, excluding reservoirs), the following must be defined:				
2	RESNUM	Node number	1	*F02.DAT
3	RESNAM	Node name	1	*F02.DAT
4	RFAREA	Surface area of reservoir at full supply level (must set = 0)	1	*F02.DAT
5	MM	Number of reference elevation levels for which storage capacities and surface areas are defined (must set = 0)	1	*F02.DAT
6	NUM	Number of hydropower channels downstream of reservoir, along path of normal routing (must set = 0)	1	*F02.DAT
7	ZONTYP	Penalty structure type associated with reservoir (must set = 0)	1	*F02.DAT
Related parameters and interdependencies:				
-	CATCH	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	-	*F02.DAT

Furthermore, conditions associated with defining junction nodes with sub-catchment hydrology inflows are summarised in the table below.

Table 6-2: Conditions for defining junction nodes with sub-catchment hydrology inflows

Condition	Associated parameter/s	Reference
For nodes and/or reservoirs located inside the same incremental sub-catchment (i.e. same reference number, CATCH), sum of respective scaling factors generally ≤ 1	CATCH, DRAINA, AFFFAC, IRRFAC, DRAINU	This section
Catchment reference number ≤ number of catchments appearing in PARAM.DAT	CATCH	This section
For incremental sub-catchments with no reservoir (i.e. at a junction node with incremental sub-catchment hydrology inflows), or where surface area of reservoir is small relative to the catchment area, rainfall-runoff coefficient (ROFCC) can be set = 0	RFAREA, ROFFC	This section

7. CREATING FLOW CHANNELS

Channels represent conduits that convey water between nodes and/or reservoirs within a water resource system network and are used to model a variety of system features (as described in **Section 8**). The basic processes involved with creating channels in the WRSM are discussed in the following sections.

7.1 Basic structure (channel arcs)

The basic building blocks of channels used in the WRSM are called “arcs”. Arcs allow channels to be configured in such a way that particular flows are allowed through them under specific circumstances. This is achieved by defining, for each arc, three data values:

- A lower flow limit;
- An upper flow limit that can not be exceeded under any circumstances;
- A penalty associated with each unit of flow through the arc (see below).

As discussed in **Section 3.4**, operating rules selected for a water resource system network model are implemented in the WRSM based on a mechanism called "penalties", which are dimensionless values used by the model as the basis for flow routing solutions.

Although the use of up to five arcs per channel is allowed by the model, one and two-arc channels are generally sufficient to model most situations encountered in water resource system networks and these are discussed below.

a) One-arc channels

This is the simplest type of channel and is modelled using one arc, with the lower limit equal to zero and the upper limit set to the capacity of the system component that the channel represents. A user-selected penalty is defined which is incurred with every unit of flow through the arc. The choice of penalty would depend on the particular problem under consideration, but it is often set equal to zero. The configuration and standard notation associated with one-arc channels is shown in below.

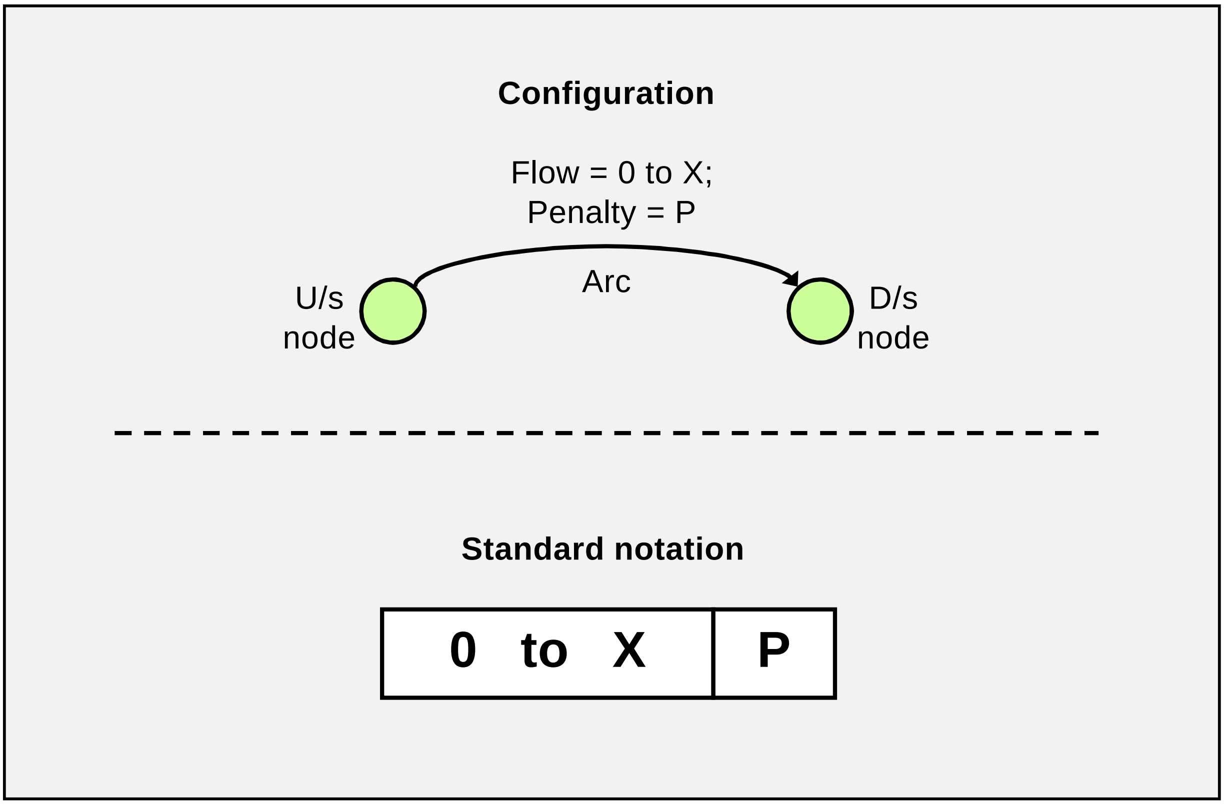


Figure 7-1: Configuration and standard notation associated with one-arc channels

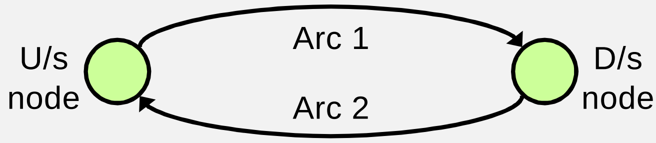
The upper flow limit of a one-arc channel depends on its application. In the case where a channel is required to simulate flow in a river reach, the model structure of the general flow channel is used, in which case the model adopts an upper limit equal to infinity (as discussed in **Section 8.1**). Flow through constrained water conduits like canals and pipelines can be modelled using the one-arc multi-purpose min-max channel structure (as discussed in **Section 8.3.1**). In this case the user sets the upper limit equal to the capacity of the component in question.

b) Two-arc channels

Two-arc channels are generally used to draw (pull) a target flow from one part of the system to another, typically for the purpose of modelling imposed drafts and water requirements, inflows to the system, controlled releases from reservoirs, streamflow diversions and flow-related losses. The configuration and standard notation associated with one-arc channels is shown below.

Configuration

Flow = X to Y (usually Y = X);
Penalty = 0 (usually)



Flow = 0 to X;
Penalty = P

Standard notation

X to Y	**0**
0 to X	**P**

Figure 7-2: Configuration and standard notation associated with two-arc channels

Arc 1 is defined with both the lower and upper limits set equal to the target flow. A penalty with a low value (often zero) is assigned. This implies that when flow through the channel corresponds with the target flow, a small penalty is incurred. The flow direction of this arc follows that of the channel (see following paragraph). Arc 2 represents a relaxation (or deficit) arc and enables flows smaller than the target flow to be simulated. It is defined with a lower limit of zero and an upper limit equal to the target flow. A penalty with a high value is assigned. This implies that when flow through the channel is less than the target flow (i.e. between zero and the target flow), a large penalty is incurred. The flow direction of this arc is opposite to that of the channel (see following paragraph).

The model handles flow through channel arcs in a particular way. if the flow available to the channel at the upstream node is less than the target flow, the full target flow is routed through Arc 1 (incurring the low penalty for every unit of flow) and the deficit is made up by routing the difference back to the upstream node through Arc 2 (incurring the high penalty for every unit of flow). This means that while Arc 1 (the forward arc) follows the flow direction of the channel from the upstream to the downstream node, flow through Arc 2 (the relaxation arc) follows the opposite direction. Therefore the total flow through a channel equals the algebraic sum of flows through each arc.

Target flows are defined for different channel types in different ways. For example, in the case of master control, multi purpose min-max, specified demand and specified inflow channels, monthly target flows are defined by the user (either by means of input parameter data or time-series data files). For all other channels, such as IFR and loss channels, the target flow for a specific month is calculated by the model at run-time based on various user-defined relationships. More information on channel types is provided in **Section 7.3**.

Note that many channel and arc configurations other than those described above are possible and more information in this regard is provided in the *WRYM* and *WRPM User Guides* (DWAF, 2008 and DWAF, 2000).

7.2 Channel penalties

Channel penalties are defined using the WRSM channel penalty structure feature. This involves the definition of a number of standard channel penalty structure types and a selection is then made of the appropriate penalty structure type which is to be associated with each of the modelled channels in the system. This approach is followed so that the utilisation of a single penalty structure type may be used in the definition of more than one channel.

Each penalty structures are defined in terms of the characteristics of channel arcs, including the number of arcs used to model a channel and the penalty associated with every unit of flow in the arc. The number of arcs, as well as the upper and lower flow limits for each arc associated with a particular channel is defined by the user and is dependent on the type of channel in question (e.g. master control, general flow, multi-purpose min-max or IFR).

Table 7-1: Channel penalty structure parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNCTYP	Number of channel penalty structure types	1	*F03.DAT
For each penalty structure type (MNCTYP), the following must be defined:				
2	NTYP	Penalty structure type number	1	*F03.DAT
3	NCHARC	Number of arcs for penalty structure type ($\leq$ 5)	1	*F03.DAT
4	CHNCST	Penalty associated with each unit of flow through arc	NCHARC	*F03.DAT

Conditions associated with defining channel penalty structures are summarised in the table below.

Table 7-2: Conditions for defining channel penalty structures

Condition	Associated parameter/s	Reference
Associated channel type must correspond to defined penalty structure and number of arcs	NCHARC and others, as appropriate	This section, **7.3**
Forward arc representing desired flow range for channel must be allocated lowest penalty	CHNCST	This section
Relaxation arc/s must be allocated higher penalty than forward arc	CHNCST	This section

7.3 Channel types

Water resource system features, such as described later in **Section 8**, are always defined, either by means of a single channel specifically designed for that purpose, or the combination of channels and other system components. A brief summary of the channel types available in the WRSM and their application in the definition of system features, is provided below:

- *General flow channels* are used for modelling river reaches (as described in **Section 8.1**) or other flow routes in a water resource system that do not have a capacity constraint or upper limit;
- *Master control channels* are used in a yield analysis, either for imposing target water requirements on the system network for the purpose of determining the system's yield (see **Section 9**) or imposing target hydropower requirements for determining the system's hydropower generation potential (see **Section 12.1**), or both;
- *Master control channels* are used in a planning analysis for modelling controlled water requirements and return flows that are subject to the allocation of water based on the short-term availability of water from supporting sub-systems (see **Section 8.2.1**). Furthermore, a master control channel may be used in a planning analysis for modelling the allocation of water for hydropower generation, based on the excesses in the short-term availability of water from supporting sub-systems;
- The two-arc *multi-purpose min-max channel* is used for modelling requirements and return flows with fixed monthly distributions (see **Section 8.2.2**) and the one-arc min-max channel for constrained water conduits (see **Section 8.3.1**);
- *Time-series requirement channels* (often referred to as a "specified demand channels") are used for modelling requirements and return flows that vary significantly from one month to the next, as well as from one year to the next, usually due to climatic conditions (see **Section 8.2.3**);
- *Irrigation abstraction and return flow channels* are used to route flows to and from irrigation areas modelled with the Irrigation Block sub-model (see **Section 8.2.4**);

- *In-stream flow requirement (IFR) channels* are used for imposing ecological water requirements, based on a user-defined relationship with runoff into the water resource system network (see **Section 8.2.6**);
- *Urban return flows channels* are used to route return flows from large urban areas back into the system and *reclamation plant loss channels* are used for modelling losses from reclamation plants, both of which are modelled with the Urban Return Flows sub-model (see **Section 8.2.7**);
- *Minimum flow channels* are used to model releases from reservoirs to maintain a minimum level of flow in the downstream river reach (see **Section 8.2.8**);
- *Streamflow diversion channels* are used to model the efficiency of diversion structures to utilise runoff from a river stream, within the context of the monthly time-step used by the WRSM (see **Section 8.3.2**);
- *Wetland inflow and outflow channels* are used to route flows to and from wetlands modelled with the Wetland sub-model (see **Section 8.3.3**);
- *Pumping channel* are used to model the hydraulic characteristics and energy requirements of a pumping station and pipeline;
- *Specified inflow channels* are used to incorporate time-series of direct inflows from another modelled system into the network definition of the current system for separate analysis (see **Section 8.3.7**);
- *Loss channels* are used for simulate flow-related losses based on a percentage of the flow in the main channel or through a user-defined relationship (see **Section 8.4**);
- *Hydropower channels* simulate the power generating characteristics of a hydropower plant (see **Section 12.1.1**).

7.4 Time-related channel controls

When undertaking a planning analysis, channels may be activated at any time before, during, or after the time period being analysed (as discussed in **Section 2.3**). Similarly, the channel may also be deactivated. All channel types can be controlled in this way, but in the case of certain channel types, time-related control parameters must be defined. These are listed below and more information is provided in the following sub-sections:

- Water supply master control channels, used for modelling controlled water requirements (as described in **Section 8.2.1**);
- Pumping channels (as described in **Section 8.3.6**);
- Channels used for modelling reclamation plants (as described in **Section 8.3.9**).

It is important to note that for all of the above channel types, as well as all other time-controlled channels, a set of additional parameters must be defined related to economic analyses (as described in **Section 13**). Even if an economic analysis is not required, those parameters must still be populated with dummy values.

a) Water supply master control channels

The parameters required for defining time-related controls for water supply master control channels are shown below. As mentioned earlier, these parameters must be defined in a planning analysis for all water supply master control channels in the system (as described in **Section 8.2.1**).

Table 7-3: Parameters for defining time-related controls for water supply master control channels

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNYP	Number of years for which time-related control data are provided for water supply master control channels	1	*DBF.DAT
*For each water supply master control channel in the system (MNMCHN, excluding hydropower allocation channels, as described in **Section 8.2.1**), parameters 2 to 6 must be defined:*				
2	DCHN	Water supply master control channel number (same as NCHMC, as described in **Section 8.2.1**)	1	*DBF.DAT
3	DMCYR (N1)	Hydrological year in which channel becomes active	1	*DBF.DAT
4	DMCMTH (N2)	Month number, in hydrological year, at the beginning of which channel becomes active	1	*DBF.DAT
5	DMRYR (N3)	Hydrological year in which channel becomes inactive	1	*DBF.DAT
6	DMRMTH (N4)	Month number, in hydrological year, at the beginning of which channel becomes inactive	1	*DBF.DAT

Conditions associated with defining time-related controls for water supply master control channels are summarised in the table below.

Table 7-4: Conditions for defining time-related controls for water supply master control channels

Condition	Associated parameter/s	Reference
Time-controlled water supply master control channel must exist	DCHN, NCHMC, others	This section, **8.2.1**
Time-related controls must be defined for all water supply master control channels in the system if a planning analysis is undertaken. Also, a set of additional parameters must be defined for an economic analysis. Even if an economic analysis is not required, those parameters must still be populated with dummy values	MNMCHN, others	This section, **8.2.1**, **13**

b) Pumping channels

The parameters required for defining time-related controls for pumping channels are shown below. As mentioned earlier, these parameters must be defined in a planning analysis for all pumping channels in the system (as described in **Section 8.3.6**).

Table 7-5: Parameters for defining time-related controls for pumping channels

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNYP	Number of years for which time-related control data are provided for pumping channels	1	*PMP.DAT
*For each pumping channel in the system (MNPMP, as described in **Section 8.3.6**), parameters 2 to 6 must be defined:*				
2	NOPCH	Pumping channel number (same as NPMPCH, as described in **Section 8.3.6**)	1	*PMP.DAT
3	PCYR	Hydrological year in which channel becomes active	1	*PMP.DAT
4	PCMTH	Month number, in hydrological year, at the beginning of which channel becomes active	1	*PMP.DAT
5	PRYR	Hydrological year in which channel becomes inactive	1	*PMP.DAT
6	PRMTH	Month number, in hydrological year, at the beginning of which channel becomes inactive	1	*PMP.DAT

Conditions associated with defining time-related controls for pumping channels are summarised in the table below.

Table 7-6: Conditions for defining time-related controls for pumping channels

Condition	Associated parameter/s	Reference
Time-controlled pumping channel must exist	NOPCH, NPMPCH, others	This section, **8.3.6**
Time-related controls must be defined for all pumping channels in the system if a planning analysis is undertaken. Also, a set of additional parameters must be defined for an economic analysis. Even if an economic analysis is not required, those parameters must still be populated with dummy values	MNPMP, others	This section, **8.3.6**, **13**

c) Channels used for modelling reclamation plants

The parameters required for defining time-related controls for reclamation plants are shown below. More information on reclamation plants is provided in **Section 8.3.9**.

Table 7-7: Parameters for defining time-related controls for reclamation plants

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNYP	Number of years for which time-related control data are provided for reclamation plants	1	*REC.DAT
2	MNREC	Number of reclamation plants in the system	1	*REC.DAT
For each reclamation plant in the system (MNREC), parameters 2 to 6 must be defined:				
2	RECHN	Channel number associated with reclamation plant (any channel type may be selected)	1	*REC.DAT
3	RCYR	Hydrological year in which reclamation plant becomes active	1	*REC.DAT
4	RCMTH	Month number, in hydrological year, at the beginning of which reclamation plant becomes active	1	*REC.DAT
5	RRYR	Hydrological year in which reclamation plant becomes inactive	1	*REC.DAT
6	RRMTH	Month number, in hydrological year, at the beginning of which reclamation plant becomes inactive	1	*REC.DAT

Conditions associated with defining time-related controls for reclamation plants are summarised in the table below.

Table 7-8: Conditions for defining time-related controls for reclamation plants

Condition	Associated parameter/s	Reference
Channel associated with reclamation plant must exist	RECHN	This section
Time-related controls must be defined for all reclamation plants required for undertaking an economic analysis	Various	This section, **13**

d) Other channels

Any channel, other than those discussed above, may be time-controlled by associating the channel in question with a purification plant (even if such a plant does not actually exist or does not need to be modelled). However, for all such channels a set of additional parameters must for undertaking an economic analysis of the associated reclamation plant (as discussed in **Section 13**). Even if such a plant does not exist, or if an economic analysis is not required, those parameters must still be populated with dummy values.

Table 7-9: Parameters for defining time-related controls for other channel types

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNYP	Number of years for which time-related control data are provided for other channel types (any channel type may be selected)	1	*PUR.DAT
2	MNPUR	Total number of time-controlled channels	1	*PUR.DAT
For each time-controlled channel (MNPUR), parameters 3 to 7 must be defined:				
3	PFCHN	Time-controlled channel number (same as channel number defined in *F03.DAT-file)	1	*PUR.DAT
4	PFCYR	Hydrological year in which channel becomes active	1	*PUR.DAT
5	PFCMTH	Month number, in hydrological year, at the beginning of which channel becomes active	1	*PUR.DAT
6	PFRYR	Hydrological year in which channel becomes inactive	1	*PUR.DAT
7	PFRMTH	Month number, in hydrological year, at the beginning of which channel becomes inactive	1	*PUR.DAT

Conditions associated with defining time-related controls for other channels are summarised in the table below.

Table 7-10: Conditions for defining time-related controls for other channel types

Condition	Associated parameter/s	Reference
Time-controlled channel must exist	PFCHN	This section
If channel is selected for time-control, a set of additional parameters must be defined for the economic analysis of and associated purification plant. Even if such a plant does not exist, or if an economic analysis is not required, those parameters must still be populated with dummy values	Various	**13**

7.5 Reservoir level-related channel controls

The status of channels may also be controlled when undertaking a planning analysis based on the water levels in associated reservoir. This functionality provides an additional means of implementing selected operating rules in the modelled system, over and above the use of penalties, as discussed in **Section 3.4**. For example, a supply channel may only be in use if a reservoir is above a certain level, or supply from a new reservoir may only commence once the reservoir reaches a certain level which signals that its warming-up period is at an end.

Three alternative reservoir level-related channel control types are available:

- Type 1: The channel is active if the water level in the reference reservoir is above the specified level and inactive below the specified level;
- Type 2: The channel is inactive if the water level in the reference reservoir is above the specified level and active below the specified level;
- Type 3: The of the status of the channel changes only once during the analysis period as the water level in the reference reservoir crosses the specified level for the first time, i.e. if the channel is active at the start of the analysis, it will be inactive for the remainder, and vice versa.

Table 7-11: Parameters for reservoir level-related channel controls

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNFSWI	Number of separate sets of reservoir-level related channel control definitions to be applied	1	*DAM.DAT
For each set of reservoir-level related channel control definitions (MNFSWI), parameters 2 to 10 must be defined:				
2	SWIFNM	Name and directory of associated data file (*SW*.DAT, name generally contains system identification code, RCODE as described in **Section 2.3.1**, and unique number, e.g. “VAALSW1.DAT”, “VAALSW2.DAT”, etc.)	1	*DAM.DAT
3	NYRSWI	Hydrological year in which this set of reservoir-level related channel control definitions becomes active	1	*DAM.DAT
4	MTHSWI	Month number, in hydrological year, at the beginning of which this set of reservoir-level related channel control definitions becomes active	1	*DAM.DAT
5	NSWIC	Number of reservoir-controlled channels	1	*SW*.DAT
For each reservoir-controlled channel (NSWIC), parameters 6 to 10 must be defined:				
6	ISTYP	Reservoir-control type option: 1, 2 or 3	1	*SW*.DAT
7	NCSWI	Reservoir-controlled channel number	1	*SW*.DAT
8	NRSWI	Reference reservoir node number (corresponding to RESNUM, as described in **Section 5.1**)	1	*SW*.DAT
9	SWILEV	Water level in reservoir at which the status of channel changes (m above MSL)	1	*SW*.DAT
10	ISWSTU	Status of channel at the start of the analysis: active or inactive (1 or 0)	1	*SW*.DAT

Conditions associated with defining reservoir level-related channel controls are summarised in the table below.

Table 7-12: Conditions for defining reservoir level-related channel controls

Condition	Associated parameter/s	Reference
Reservoir controlled channels must exist	NCSWI	This section
Reference reservoir for defined channel control must exist	NRSWI, RESNUM	This section, **5.1**
Specified level in reservoir at which the status of channel changes must lie below its full supply level and above its bottom level	SWILEV, FSL, BOT	This section, **5.1**

8. CREATING OTHER SYSTEM FEATURES

A variety of system features, other than reservoirs and nodes as discussed in **Sections 5** and **6**, are available when undertaking yield or planning analyses with the WRSM. Most of these are defined in the system model simply by selecting a specific channel type (as outlined in **Section 7.3**). A few examples are general flow channels for modelling river reaches, master control channels for modelling controlled water requirements and return flows in a planning analysis, two-arc multi-purpose min-max channel for requirements and return flows with fixed monthly distributions, one-arc min max channel for constrained water conduits and IFR channels for imposing ecological water requirements the system. In other cases, channels are used in conjunction with other special model components to model the system feature in question. These include irrigation blocks with their associated abstraction and return flow channels, large urban areas with their return flow and reclamation plant loss channels and wetlands with their inflow and outflow channels. The following sections provide detailed descriptions on the procedures for defining the above system features.

8.1 River reaches

Generally, river reaches, which are open water channels with no capacity constraint, are modelled in the WRSM using the *general flow channel type*. General flow channels are modelled as a single arc with an associated penalty for any flow that might occur through the arc. The value of the penalty depends on the particular situation under consideration, but is often set equal to zero. In some cases, however, the penalty may be set at a high value in order to serve as a "plug" in the system, i.e. the channel prevents water users from drawing water from one part of the system to another via the channel in question.

Table 8-1: General flow channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNGFW	Number of general flow channels in the system	1	*F03.DAT
For each general flow channel in the system (MNGFW), the following must be defined:				
2	CHANUM	General flow channel number	1	*F03.DAT
3	RESUP	Upstream reservoir or node number	1	*F03.DAT
4	RESDOW	Downstream reservoir or node number	1	*F03.DAT
5	CHNTYP	Penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT

Conditions associated with defining general flow channels are summarised in the table below.

Table 8-2: Conditions for general channels

Condition	Associated parameter/s	Reference
General flow channels must be single-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with general flow channel must exist	CHNTYP, NTYP	This section, **7.2**

8.2 Water users, requirements and return flows

8.2.1 Controlled water requirements and return flows

As discussed in **Section 1.3 (b)** the purpose of undertaking planning analyses involves determining the ability of a water resource system to satisfy water requirements. Water use may, however, be restricted during periods of drought and the implementation of restrictions is a fundamental management principal embedded in the operating rules of the major water resource systems in South Africa.

The effect of restrictions is modelled in the WRSM by applying “curtailments”. Curtailments imply that the supply of water to certain users in a system may be limited (or curtailed) when the short-term availability of water from supporting sub-systems is insufficient. Low-priority users are curtailed first, followed by higher priority users as the situation deteriorates. In this way an uncontrolled failure of the resource is avoided and the supply of water to high priority users protected. The necessity and severity of curtailments are periodically reviewed by the model on selected decision dates (typically once or twice every year) and implemented as “allocation decisions”. More information in this regard is provided in **Section 11**.

Users that can be restricted in this way are modelled in the WRSM as controlled water users by means of the *water supply master control channel type*, as shown below, including the water requirement (or return flow) for the user in a selected base year and the associated annual projection data which control the change in water requirements and return flows over time. Furthermore, since the supply of water to controlled water users is determined based on an allocation procedure, appropriate volumes must be provided for each month at the beginning of the analysis prior to the first major allocation decision date (as described in **Section 11.1.1**). If the first month of the analysis coincides with a major decision date, however, such information is not required.

Table 8-3: Water supply master control channel parameters for a planning analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNMCHN	Number of master control channels in the system (including water supply and one hydropower allocation, as described in **Section 12.2**)	1	*F03.DAT
2	MNDCEN	Number of master control channels in the system (same as MNMCHN above)	1	*F01.DAT
For each water supply master control channel in the system (MNMCHN, excluding hydropower allocation channels), parameters 3 to 19 must be defined:				
3	NCHMC	Water supply master control channel number	1	*F03.DAT
4	RNAM	Water supply master control channel name	1	*F13.DAT
5	CODE (MASCHC)	Master control channel type option: water or hydropower (W or H, must set = W)	1	*F03.DAT
6	RESUP	Upstream reservoir or node number	1	*F03.DAT
7	RESDOW	Downstream reservoir or node number	1	*F03.DAT
8	NTYP	Penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
9	DMAN	Water supply master control channel number (same as NCHMC above)	1	*F01.DAT
10	DCT	Water supply master control channel type option: water requirement or return flow (D or R)	1	*F01.DAT
11	DEMD	Water requirement (or return flow) for base year (million m^3/a, negative value implies return flow, may not = 0.0, basis for projection factors DMDGTH, as described later in this section)	1	*F01.DAT
12	RATDMD	Water requirement (or return flow) for base year (million m^3/a, same as DEMD above)	1	*FM*.DAT
13	ADEMD	Minimum requirement, which overrides curtailment as based on short-term sub-system yield capability, as described in **Section 11.2** (million m^3/a)	1	*F01.DAT
14	NCH	Water supply master control channel number (same as NCHMC above)	1	*F13.DAT
15	NPAT	Number of alternative patterns of monthly water requirement (or return flow) distribution factors for this channel (assumed = 1.0 if undefined)	1	*F13.DAT
For each alternative pattern of monthly water requirement (or return flow) distribution factors (NPAT), parameters 16 and 17 must be defined:				
16	WDPAT	Monthly water requirement (or return flow) distribution factors	12	*F13.DAT
17	PATLVL	Volume of water in storage below which the pattern is active (fraction of live full supply volume for sub-system within which the channel is located, NSSDMD, as described in **Section 11.2.1**, assumed = 1.0 if NPAT = 0 or undefined)	1	*F13.DAT
18	NCH	Water supply master control channel number (same as NCHMC above)	1	*HST.DAT

No.	Name	Description	Number of inputs	Associated data file/s
19	D	Monthly water supplies prior to first water allocation decision month, as described in **Section 11.1.1** (m^3/s; M = number of values required = number of months from analysis start month, MONST as described in **Section 2.3**, to first major allocation decision date, defined via parameters NMTHDC, MTHDEC and MTHCLS as described in **Section 11.1.1**)	M	*HST.DAT

Table 8-4: Parameters for defining projected water requirements and return flows modelled with master control channels in a planning analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNYP	Number of planning years for which water requirement (or return flow) projection information is provided (same as MNYP, as described in **Sections 4.3**, **8.2.2** and **8.3.1**)	1	*GTH.DAT
For each water supply master control channel in the system (MNMCHN, as described earlier in this section and excluding hydropower allocation channels), parameters 2 to 4 must be defined:				
2	DCHN	Master control channel number (same as NCHMC described earlier in this section)	1	*GTH.DAT
3	DMDGTH	Annual water requirement (or return flow) projection factors (projected value = DEMD x (1 + DMDGTH), therefore DMDGTH = 0 implies no change)	MNYP	*GTH.DAT
4	PERGTH	Projection calculation type option: 1, -1 or 0 (requirement, return flow or none)	1	*FM*.DAT

Conditions associated with defining water supply master control channels are summarised in the table below.

Table 8-5: Conditions for defining water supply master control channels in a planning analysis

Condition	Associated parameter/s	Reference
Water supply master control channels must be two-arc channels	NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with water supply master control channel must exist	NTYP	This section, **7.2**
Water requirement (or return flow) for base year may not = 0.0, since it is multiplied with a factor (1 + DMDGTH) to calculate projected volumes	DEMD, DMDGTH	This section
Time-related controls must be defined for all water supply master control channels in the system. Even if time-related controls are not required for analysis, parameters must still be populated with dummy values (i.e. to cover the full analysis period)	Various	**7.4 (a)**
Parameters for economic and tariff calculations must be defined for all water supply master control channels in the system. Even if an economic analysis is not being undertaken, parameters must still be populated with dummy values	Various	**13**

Finally, as shown in the above table, additional parameters must be defined for the time-related control of all water supply master control channels in the system. More information in this regard is provided in **Section 7.4 (a)**. Furthermore, a set of additional parameters must be defined for each channel, related to economic and tariff calculations, as described in **Section 13**. Even if an economic analysis is not required, those parameters must still be populated with dummy values.

8.2.2 Requirements and return flows with fixed monthly distributions

Requirements and return flows with fixed monthly distributions that are not subject to the allocation decision, as discussed in **Section 8.2.1**, are modelled in the WRSM using the *two-arc multi-purpose min-max channel-type*. This channel type is extremely versatile and can be used for a variety of functions. Min-max channels are defined with anything up to 5 channel arcs, with a set of 12 monthly upper and lower flow limits specified for each arc. In most cases, however, only the one and two-arc configurations are used.

It should be noted that since flows in the two-arc min-max channel are controlled by 12 monthly flow limits, the use of these channels is limited to the modelling of requirements and return flows with fixed monthly distributions (i.e. that stay constant from one year to the next). This means that in cases where annual variations do occur, particularly due to climatic conditions (e.g. for irrigation requirements), the use of this channel type may not be appropriate and must other options be considered, as detailed elsewhere in **Section 8**.

Table 8-6: Two-arc multi-purpose min-max channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNMMX	Number of multi-purpose min-max channels in the system (including one-arc channels, as described in **Section 8.3.1**)	1	*F03.DAT
For each multi-purpose min-max channel in the system (MNMMX), parameters 2 to 8 must be defined:				
2	NMMXCH	Multi-purpose min-max channel number	1	*F03.DAT
3	RNAM	Multi-purpose min-max channel name	1	*F12.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	CHNTYP	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	NCH	Multi-purpose min-max channel number (same as NMMXCH above)	1	*F12.DAT
For each multi purpose min-max channel arc (= 2), parameter 8 must be defined:				

No.	Name	Description	Number of inputs	Associated data file/s
8	CSTMM	Monthly flow limits (m^3/s)	12	*F12.DAT

Growth in requirements and return flows with fixed monthly distributions can be modelled when undertaking a planning analysis, by defining annual projection data for the associated two-arc min-max channels, as shown below.

Table 8-7: Parameters for defining projected water requirements and return flows modelled with two-arc multi-purpose min-max channels

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNYP	Number of planning years for which water requirement (or return flow) projection information is provided (same as MNYP, as described in **Sections 4.3**, **8.2.1** and **8.3.1**)	1	*GTH.DAT
2	NTGCHN	Total number of multi purpose min-max channel arcs for which water requirement (or return flow) projection information is provided (i.e. for all relevant min-max channels)	1	*GTH.DAT
For each multi purpose min-max channel arc for which water requirement (or return flow) projection information is provided (NTGCHN), parameters 3 to 5 must be defined:				
3	NGCHN	Multi-purpose min-max channel number (same as NMMXCH described earlier in this section)	1	*GTH.DAT
4	NGBD	Channel arc number (NCHARC, as described in **Section 7.2**) to which projection factors must be applied	1	*GTH.DAT
5	GFAC	Annual projection factors for monthly flow limits in selected channel arc, NGBD (projected value = CSTMM x (1 + GFAC), therefore GFAC = 0 implies no change)	MNYP	*GTH.DAT

Conditions associated with defining two-arc multi-purpose min-max channels are summarised in the table below.

Table 8-8: Conditions for defining two-arc multi-purpose min-max channels

Condition	Associated parameter/s	Reference
Multi-purpose min-max channels used for modelling water requirements or return flows must be two-arc channels (in some cases up to 5 arcs are used but these are not discussed in this document)	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with multi-purpose min-max channel must exist	CHNTYP, NTYP	This section, **7.2**
Sets of monthly flow limits for each channel arc must be specified in descending order	CSTMM	This section

Condition	Associated parameter/s	Reference
For each channel arc, water requirement (or return flow) projection information must be provided individually, therefore sets of parameters 3 to 5 (as shown in the table above) must be defined twice for each two-arc multi-purpose min-max channel in question	NGCHN, NGBD, GFAC	This section
In channel arcs for which water requirement (or return flow) projection information is provided, monthly maximum flow limits for base year may not = 0.0, since it is multiplied with a factor (1 + GFAC) to calculate projected flow volumes	CSTMM, NGBD, GFAC	This section

8.2.3 Time-series requirements and return flows

Water requirements and return flows defined as a known time-series can be modelled in the WRSM as using the *time-series requirement channel type*. These time-series must be defined in data files that follow the standard HRU-format for streamflow time-series data files (which starts in the hydrological year, i.e. from October to September) and are generated externally to the model, using information from pre-processors and utility programs. Time-series requirements and return flows are not subject to the allocation decision, as discussed in **Section 8.2.1**.

If the user has selected the stochastic run-type (as described in **Section 2.4**), the model generates appropriate monthly time-series values by means of a methodology which involves the selection of data values from the above time-series data file. The selection process is based on the relationship between the historical and the stochastically generated annual streamflow values for the catchment within which the modelled user is located. For this purpose, the user must define a reference to the associated incremental sub-catchment.

Table 8-9: Time-series requirement channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNSDS	Number of time-series requirement channels in the system	1	*F03.DAT
For each time-series requirement channel in the system (MNSDS), parameters 2 to 8 must be defined:				
2	CHANUM	Time-series requirement channel number	1	*F03.DAT
3	RESUP	Upstream reservoir or node number	1	*F03.DAT
4	RESDOW	Downstream reservoir or node number	1	*F03.DAT
5	CHNTYP	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
6	NAMSDS	Name and directory of associated monthly water requirement or return flow time-series data file (in units of million m^3)	1	*F03.DAT

No.	Name	Description	Number of inputs	Associated data file/s
7	SDSTP	Option for applying historical or stochastic water requirements or return flows: (H or S, must correspond to HISTO, as described in **Section 2.4**)	1	*F03.DAT
8	NGCOR	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	1	*F03.DAT

Conditions associated with defining time-series requirement channels are summarised in the table below.

Table 8-10: Conditions for defining time-series requirement channels

Condition	Associated parameter/s	Reference
Time-series requirement channels must be two-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with time-series requirement channel must exist	CHNTYP, NTYP	This section, **7.2**
Associated monthly water requirement or return flow time-series data file must exist and must be located in the specified directory	NAMSDS	This section
Option selected for applying historical or stochastic water requirements or return flows must correspond to selected run type option	HISTO, SDSTP	This section, **2.3.4**
Water user or source of return flows in question should be located within selected incremental sub-catchment, to ensure appropriate generation of stochastic water requirements or return flows	CATCH, NGCOR	This section, **2.3.2**

8.2.4 Irrigation

When undertaking a yield analysis, irrigation water requirements and return flows are modelled in the WRSM using the *Irrigation Block sub-model*. This sub-model was originally developed for the WQS model (mentioned in **Section 1.4**) and has been incorporated into the WRSM to model irrigation water requirements and return flows in the *Water Availability Assessment* (WAA) studies recently commissioned by the DWAF, Directorate: NWRP (as discussed in **Section 3.2**). It should be noted that irrigation blocks can also be defined when undertaking planning analysis by applying the original WQS Irrigation Block sub-model. For this purpose, irrigation block definitions are provided in separate *RR*.DAT-file and linked to the system network by defining the connectivity of the irrigation block abstraction and return flow channels in the WQS *.NET.DAT-file. However, as mentioned in **Section 1.5**, WQS features are not addressed in this version of the Procedural Manual and will only be incorporated at a later stage.

The typical configuration of an irrigation block in the WRSM system network is shown below. The irrigation block is represented by a network node, the number of which is defined through variable IREF. It is linked to the network by means of two channels, the abstraction channel (NRRA) and return flow channel (NRRR). Care must be taken to select appropriate channel penalties ("P_1" and "P_2") in order to ensure that the irrigation water requirements represented by a specific irrigation block are supplied in accordance with the required operation of the system and also that flows through the return flow channel are forced to enter the system at node RRDOW (i.e. a high value must be selected for "P_2").

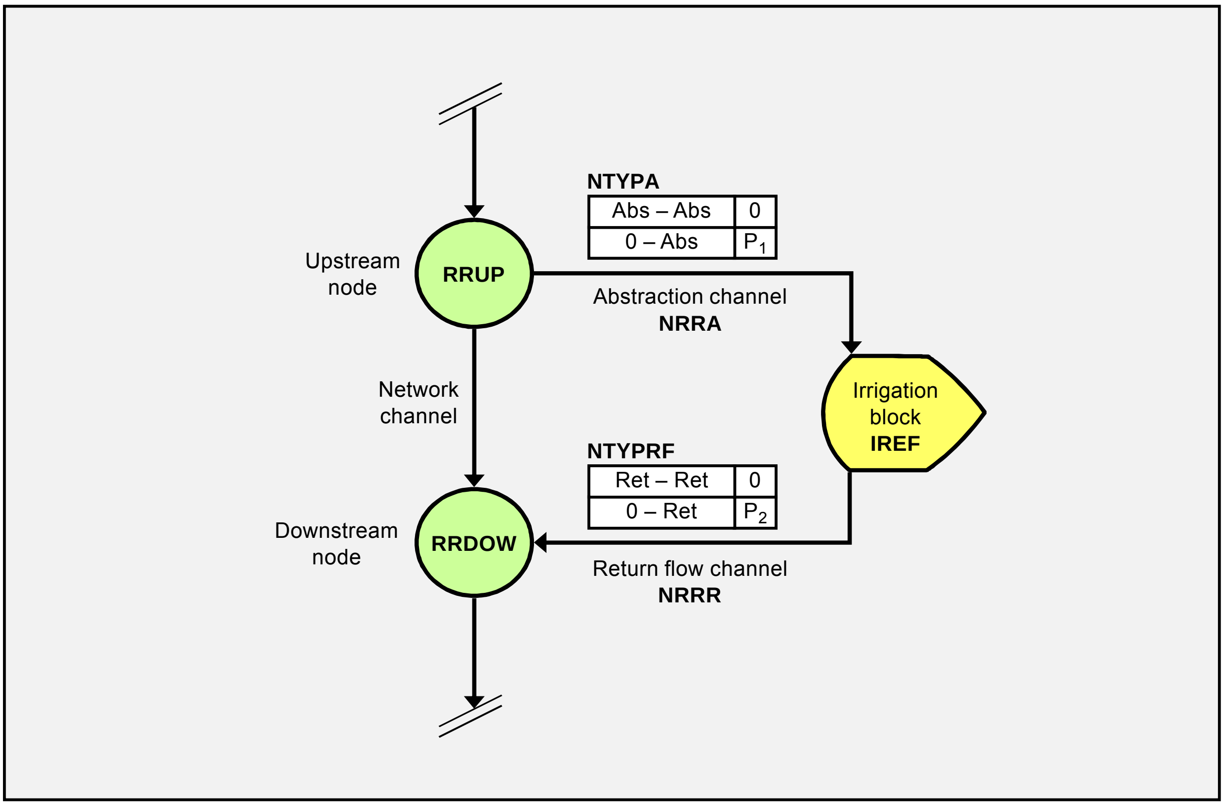


Figure 8-1: Configuration of an irrigation block in the WRSM system network

Table 8-11: Irrigation block parameters applied in a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken:*				
1	NRRBLK	Number of irrigation blocks in the system	1	*F03.DAT
For each irrigation block in the system (NRRBLK), parameters 2 to 32 must be defined:				
2	IREF	Irrigation block network node number	1	*F03.DAT
3	RREN	Irrigation block network node number (same as IREF above)	1	*F17.DAT
4	RRNAM	Irrigation block name	1	*F17.DAT
5	NRRA	Irrigation block abstraction channel number	1	*F03.DAT
6	RRUP	Upstream reservoir or node number for abstraction channel	1	*F03.DAT

No.	Name	Description	Number of inputs	Associated data file/s
7	NTYPA	Penalty structure type associated with abstraction channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
8	NRRR	Irrigation block return flow channel number	1	*F03.DAT
9	RRDOW	Downstream reservoir or node number for return flow channel	1	*F03.DAT
10	NTYPRF	Penalty structure type associated with return flow channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
11	RRAREA	Area under irrigation (km^2)	1	*F17.DAT
12	RRMA	Maximum irrigation allocation (million m^3/a)	1	*F17.DAT
13	RRIE	Irrigation application system efficiency factor	1	*F17.DAT
14	RRDRAPL	Option to activate drought irrigation application reduction-feature: no or yes (0 or 1)	1	*F17.DAT
15	RRSFI	Name and directory of known monthly irrigation abstraction time-series data file, if appropriate (in units of million m^3), set = ‘ ‘ for no file)	1	*F17.DAT
16	RRCFTYP	Crop requirement calculation option: Type 1 (i.e. based on individual crop types) or Type 2 (i.e. based on representative crop) (1 or 2)	1	*F17.DAT
If the Type 1 crop requirement calculation option is selected (RRCFTYP = 1), parameters 17 to 19 must be defined as follows:				
17	RRNCPS	Number of crop types	1	*F17.DAT
For each crop type (RRNCPS), parameters 18 and 19 must be defined:				
18	RRCF	Monthly crop water usage factor, based on selected reference evaporation (i.e. PE x APANF)	12	*F17.DAT
19	RRCPF	Percentage area under crop type	1	*F17.DAT
If the Type 2 crop requirement calculation option is selected (RRCFTYP = 2), parameters 17 to 19 must be defined as follows:				
17	RRNCPS	Number of crop types (must set = 1)	1	*F17.DAT
Parameters 18 and 19 are defined once, for the representative crop:				
18	RRCF	Monthly representative crop evapo-transpiration (mm)	12	*F17.DAT
19	RRCPF	Percentage area under crop type (must set = 100)	1	*F17.DAT
20	PE	Monthly mean pan evaporation (mm, *note: if RRCFTYP = 2 dummy values may be used*)	12	*F17.DAT
21	APANF	Monthly mean pan evaporation-to-reference evaporation conversion factors (i.e. reference evaporation = PE x APANF, e.g. Penman-Monteith, *note: if RRCFTYP = 2 dummy values may be used*)	12	*F17.DAT
22	RRREF	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	1	*F17.DAT
23	RRRNF	Factor for scaling *.RAN-file data (as described in **Section 4.1**) of selected incremental sub-catchment (RRREF) to representative rainfall at irrigated area	1	*F17.DAT
24	RRERF	Monthly effective rainfall factors (*note: if RRCFTYP = 2 dummy values may be used since effective rainfall calculated from crop evapo-transpiration and actual rainfall*)	12	*F17.DAT

No.	Name	Description	Number of inputs	Associated data file/s
25	RRERL1	Rainfall above which effective rainfall factor is equal to specified value (RRERF) (mm)	1	*F17.DAT
26	RRERL2	Rainfall below which effective rainfall factor is equal to 1.0 (mm)	1	*F17.DAT
27	RRHSU	Soil moisture storage capacity for the upper zone (mm)	1	*F17.DAT
28	RRHT	Soil moisture storage target for the upper zone (mm)	1	*F17.DAT
29	RRHI	Initial soil moisture storage (mm)	1	*F17.DAT
30	RRTLPQ	Proportion of flow loss for transport canal from water source	1	*F17.DAT
31	RRTLF	Portion of flow loss from transport canal that contributes to return flows	1	*F17.DAT
32	RRLF	Calibrated return flow factor	1	*F17.DAT

Conditions associated with defining irrigation blocks are summarised in the table below.

Table 8-12: Conditions for defining irrigation blocks

Condition	Associated parameter/s	Reference
Irrigation block abstraction and return flow channels must be two-arc channels	NTYPA, NTYPRF, NTYP, NCHARC	This section, **7.2**
Penalty structure types associated with irrigation block abstraction and return flow channels must exist	NTYPA, NTYPRF	This section, **7.2**
High penalty must be assigned to the second arc of irrigation block return flow channels, to ensure that the channel does not relax (i.e. routes less than the calculated flow volume)	NTYPRF, CHNTYP, CHNCST	This section, **7.2**
Combined extent of areas under irrigation, as well as streamflow reduction catchment portion areas and coal mining activities, may not be greater that the incremental sub-catchment within which they are located	RRAREA, SFRAR, AMINE(1) CATHAR, CATCH, others	This section, **8.2.5**, **8.3.5**, others
Associated known monthly irrigation abstraction time-series data file monthly water requirement or return flow time-series data file, if defined, must exist and must be located in the specified directory	RRSFI	This section
If the Type 1 crop requirement calculation option is selected, monthly crop water usage factors multiplied with selected reference evaporation must result in representative crop evapo-transpiration (in units of mm)	RRCFTYP, RRCF, PE, APANF	This section

Note: (1) AMINE may be calculated from various input parameters related to the definition of coal mining activities (as described in **Section 8.3.5**).

Finally, it should be noted that in earlier versions of the WRSM, irrigation water requirements and return flows were generally modelled as time-series and implemented in the system network either as diffuse water requirements, using the *.IRR data file (described in **Section 4.3**), or using the time-series requirement channel type (as discussed in **Section 8.2.3**). These time-series, however, had to be generated externally to the model with specialist pre-processors and utilities such as SAPWAT. Furthermore, an additional facility is provided for the simplified modelling of irrigation areas based on 12 monthly target irrigation flows specified by the user. This is achieved by defining an irrigation area consisting of three special irrigation channels, together with an associated irrigation area node. More information in this regard may be obtained from the *WRYM User Guide* (DWAF, 2008). These methodologies have now been largely superseded by the Irrigation Block Sub-model.

8.2.5 Streamflow reductions

When undertaking a yield analysis, the impact of streamflow reductions is modelled in the WRSM using the *Streamflow Reduction (SFR) sub-model*, recently developed as part of the five *Water Availability Assessment* (WAA) studies commissioned by the DWAF, Directorate: NWRP (as discussed in **Section 3.2**). The sub-model is based on the principle that a portion of the incremental sub-catchment associated with a node or reservoir in the system network is covered by an SFR land-use type. The SFR sub-model may be applied to any one of the following:

- Commercial forestry;
- Dry-land sugarcane;
- In-catchment alien invasive vegetation (located in mountain catchment areas).

For this purpose, a number of time-series data files are required, as detailed below:

- Monthly unit runoffs (in units of mm), for each SFR catchment portion modelled in the system network. The data in this file will be used for the calculation of the monthly runoff volume for the SFR portion in question.
- Monthly values of total soil moisture (or “S”, in units of mm), for each SFR catchment portion.
- The *.S-file, which contains monthly values of total soil moisture (or “S”, in units of mm), for the natural portion of the sub catchment (i.e. the portion which is not covered by an SFR land cover type).

“S”-time-series are obtained as a direct output from the rainfall-runoff modelling undertaken using the *Water Resources Simulation Model 2000* (WRSM2000). The *.S-file follows a strict file naming convention, where, as is the case with the hydrological and diffuse water use time-series data files (i.e. *.INC, *.IRR, *.AFF and *.URB, as described in **Section 4.3**), the “*” represents the name of the sub-catchment in question. This, however, is not the case with the total soil moisture and unit runoff files for SFR catchment portions and the user will be allowed to use any file name considered appropriate, subject to the DOS-environment limitation of a maximum of eight digits for the file name and three digits for the file extension.

It is important to note that "S"-time-series are only required for incremental sub-catchments in the system network where groundwater-surface water interaction is modelled using the GRA II *Groundwater-Surface Water Interaction* (GWSWI) methodology. However, as discussed in **Section 8.5**, the GRA II methodology will only be implemented in a later version of the WRSM, which means that no "S"-time-series are required for the current version of the model.

Table 8-13: Streamflow reduction parameters

No.	Name	Description	Number of inputs	Associated data file/s
The parameters in this table must be defined if a ***yield analysis*** *is being undertaken:*				
1	MNSFR	Number of streamflow reduction catchment portions in the system	1	*F20.DAT
For each streamflow reduction catchment portion in the system (MNSFR), parameters 2 to 5 must be defined:				
2	SFRNAM	Streamflow reduction catchment portion name	1	*F20.DAT
3	SFRAR	Area of the streamflow reduction catchment portion (km^2)	1	*F20.DAT
4	SFRRN	Reference reservoir or node number with incremental sub-catchment hydrology inflows (i.e. for identifying sub-catchment within which streamflow reduction is located, as described in **Section 4.2**)	1	*F20.DAT
5	SFRRFN	Name and directory of associated monthly unit (reduced) runoff time-series data file for the streamflow reduction catchment portion (in units of mm)	1	*F20.DAT
For each SFR catchment portion located within an incremental sub-catchment for which groundwater-surface water interaction is modelled using the GRA II methodology(1), parameter 6 must be defined:				
6	SFRSFN	Name and directory of associated monthly total soil moisture (S) time-series data file for the streamflow reduction catchment portion (in units of mm)	1	*F20.DAT

Note: (1) The GRA II *Groundwater-Surface Water Interaction* (GWSWI) methodology. This functionality is not available in the current version of the model (as explained earlier).

Conditions associated with defining streamflow reductions are summarised in the table below.

Table 8-14: Conditions for defining streamflow reductions

Condition	Associated parameter/s	Reference
Combined extent of streamflow reduction catchment portion areas, as well as the areas under irrigation and coal mining activities, may not be greater that the incremental sub-catchment within which they are located	SFRAR, RRAREA, AMINE(1) CATHAR, CATCH, others	This section, **8.2.4**, **8.3.5**, others
Reference reservoirs and/or nodes must exist and must have incremental sub-catchment hydrology inflows	SFRRN, others	This section, **4.2**
Associated monthly unit runoff time-series data file for the streamflow reduction catchment portion must exist and must be located in the specified directory	SFRRFN	This section

Condition	Associated parameter/s	Reference
Monthly total soil moisture (S) time-series data file is only required for streamflow reduction catchment portions located within incremental sub-catchments for which groundwater-surface water interaction is modelled using the GRA II methodology(2)	SFRSFN	This section, **3.8.3**

Note: (1) AMINE may be calculated from various input parameters related to the definition of coal mining activities (as described in **Section 8.3.5**).

(2) The GRA II *Groundwater-Surface Water Interaction* (GWSWI) methodology. This functionality is not available in the current version of the model (as explained earlier).

Finally, it should be noted that in earlier versions of the WRSM, the impact of SFRs was generally modelled as time-series of runoff reduction volumes and implemented in the system network either as diffuse water requirements using the *.AFF data file (described in **Section 4.3**). These time-series, however, did not allow for the user to adjust SFR areas and therefore to undertake scenario analyses without the use of pre-processors. The *.AFF has therefore now been largely superseded by the SFR sub-model.

8.2.6 Ecological water requirements

Ecological water requirements are modelled in the WRSM in the form of in-stream flow requirements (IFRs) using the *IFR channel-type*. The structure of the IFR channel is based on that of the two-arc multi-purpose min-max channel (as discussed in **Section 8.2.2**) and are defined in exactly the same way. However, a number of additional parameters are required for the calculation of appropriate IFR volumes by the model at runtime.

Two alternative IFR channel types are available:

- Type 1: IFR volumes are calculated from user-defined relationships between IFR volumes and runoff entering the system at one ore more selected reference nodes and/or reservoirs. Relationships are defined in units of m^3/s, for each month of the hydrological year (i.e. starting in October) and are derived externally to the model using information from pre-processors and utility programs such as the Hughes-model.
- Type 2: The second type was designed to accommodate an entirely different method for modelling the IFR developed for the *Lesotho Highlands Development Project* (LHDP) which requires for monthly IFRs to be modelled based on annual reference flow values and for a range of "IFR classes". More information in this regard may be obtained from the *WRYM User Guide* (DWEAF, 2008).

Furthermore, a selection must be made of whether reference flows used as a basis for calculating IFRs represent “natural” or “developed” flow volumes. In this context, “natural” refers to the flow volumes provided in the hydrological time-series data files containing monthly natural incremental runoff (i.e. from the *.INC, as described in **Section 4.3**). On the other hand, “developed” refers to flows that enter the system network after the impact of diffuse water use (i.e. from the *.IRR, *.AFF). The associated calculation is shown in **Equation 4-1** of **Section 4.4**.

Finally, the WRSM also allows for the user to specify *lag* times of up to 12 months. In cases where a lag time is implemented, the IFR volume for the months at the start of the analysis period is taken to be equal to the target flows defined by the min-max flow limits.

Table 8-15: IFR release control channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNMMX	Number of multi-purpose min-max channels in the system (including IFR release control channels, as described below)	1	*F03.DAT
For each IFR release control channel in the system (MNMMX, excluding other multi-purpose min-max channels), parameters 2 to 25 must be defined:				
2	NMMXCH	IFR release control channel number		*F03.DAT
3	RNAM	IFR release control channel name	1	*F12.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	CHNTYP	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	NCH	IFR release control channel number (same as NMMXCH above)	1	*F12.DAT
For each IFR release control channel arc (= 2), dummy values must be defined for parameter 8:				
8	CSTMM	Monthly flow limits (m^3/s)	12	*F12.DAT
*Parameter 9 is only required if a **yield analysis** is being undertaken:*				
9	IFRNREF	Runoff reference flow option: natural or developed (1 or 2)	1	*F14.DAT
10	NIFRS	Number of Type 1 IFR release control channels (i.e. based on *monthly* runoff reference flow values)	1	*F14.DAT
For each Type 1 IFR release control channel (NIFRS), parameters 11 to 17 must be defined:				
11	IFRCN	IFR release control channel number (same as NMMXCH above)	1	*F14.DAT
12	NIFRRI	Number of reference reservoirs and/or nodes with incremental sub-catchment hydrology inflows (i.e. for calculating runoff reference flows, FIFRIN or RALOWLMT below)	1	*F14.DAT
13	IFRRN	Reference reservoir and/or node number	NIFRRI	*F14.DAT
14	IFRLAG	Lag for monthly runoff reference flows (number of months, from -12 to 12)	1	*F14.DAT

No.	Name	Description	Number of inputs	Associated data file/s
15	NIFRPN	Number of points in the monthly runoff reference flow vs. IFR volume relationships (defined to cover range of possible monthly flow volumes)	1	*F14.DAT
For each point in the monthly runoff reference flow vs. IFR volume relationships (NIFRPN), pairs of monthly values must be defined for parameters 16 and 17:				
16	FIFRIN	Range of monthly runoff reference flows (m^3/s)	12	*F14.DAT
17	FIFRREL	Monthly IFR volumes (m^3/s, corresponding to FIFRIN)	12	*F14.DAT
*Parameters 18 to 25 are only required if a **yield analysis** is being undertaken:*				
18	NAIFRS	Number of Type 2 IFR release control channels (i.e. based on *annual* runoff reference flow values)	1	*F14.DAT
For each Type 2 IFR release control channel (NAIFRS), parameters 19 to 25 must be defined:				
19	IACHNIFR	IFR release control channel number (same as NMMXCH above)	1	*F14.DAT
20	NAREFN	Number of reference reservoirs and/or nodes with incremental sub-catchment hydrology inflows (i.e. for calculating runoff reference flows)	1	*F14.DAT
21	IAREFN	Reference reservoir and/or node number	NAREFN	*F14.DAT
22	RASCALE	IFR volume calculation option: 1 (i.e. based on defined reference flow vs. IFR volume relationships) or 2 (i.e. IFR volume calculated as reference flow x factor RASCALE) (0 or selected factor for option 2)	1	*F14.DAT
23	NACLASS	Number of points in the annual runoff reference flow vs. IFR volume relationships (also referred to as “classes”, defined to cover range of possible annual flow volumes)	1	*F14.DAT
For each point in the annual runoff reference flow vs. IFR volume relationships (NACLASS), parameters 24 and 25 must be defined:				
24	RALOW-LMT	Annual runoff reference flow (million m^3)	1	*F14.DAT
25	RAMONT	Monthly IFR volumes (million m^3)	12	*F14.DAT

Conditions associated with defining IFR release control channels are summarised in the table below.

Table 8-16: Conditions for defining IFR release control channels

Condition	Associated parameter/s	Reference
IFR release control channels must be two-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with IFR release control channel must exist	CHNTYP, NTYP	This section, **7.2**
Reference reservoirs and/or nodes must exist	IFRRN, IAREFN, others	This section
Sets of monthly flow limits for each channel arc are not applied by the model, but must still be populated with dummy values	CSTMM	This section
Annual runoff reference flows must be defined to cover full range of possible volumes	NIFRPN, FIFRIN, NACLASS, RALOWLMT	This section

8.2.7 Return flows from large urban centres

When undertaking a yield analysis, return flows from large urban centres are modelled in the WRSM using the *Urban Return Flows sub-model* (also referred to as the "Demand Centre" sub-model). This sub-model was originally developed for the WQS model (mentioned in **Section 1.4**) and has been incorporated into the WRSM to model return flows in the *Water Availability Assessment* (WAA) studies recently commissioned by the DWAF, Directorate: NWRP (as discussed in **Section 3.2**). Return flows are calculated in the sub-model based on a routing equation developed by Dr WV Pitman (SS&O, 1986), details of which can be found in the document *Detailed Business Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling (Demand Centre Return Flows and Mining)* (WRP, 2007).

The typical configuration of an urban centre in the WRSM system network is shown below.

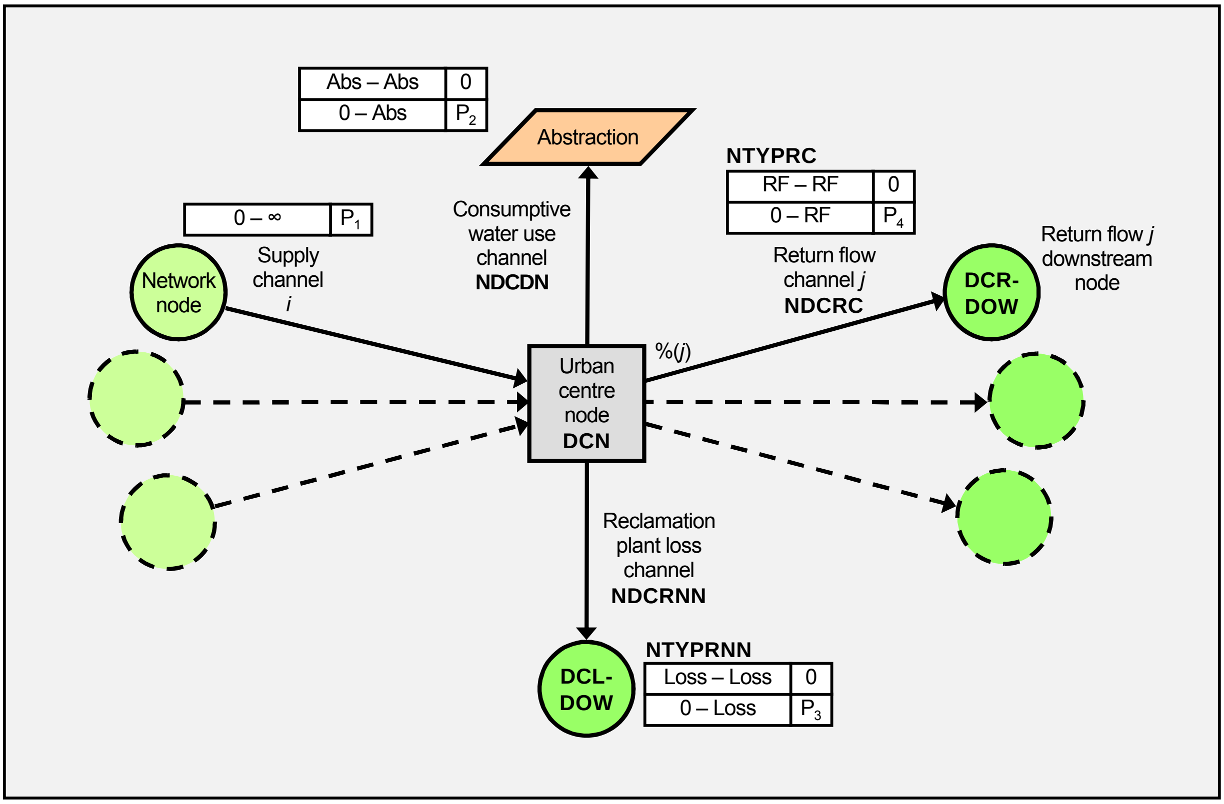


Figure 8-2: Configuration of an urban centre in the WRSM system network

Four sets of system network channels are associated with an urban centre and must be specified by the user. The first is a set of water supply channels which serve to transport water from various sources within the system network to the demand centre in question. For this purpose, the required number of supply channels may be defined, externally to the Urban Centre sub-model, using any one-arc channel (e.g. a general flow channel as described in **Section 8.1** or a one-arc min-max channel as described in **Section 8.3.1**). Generally, a channel penalty of zero is selected ("P1").

The second is the consumptive water use channel, NDCDN. The consumptive water use channel provides a mechanism for imposing the desired water requirement on the system. For this purpose, any appropriate two-arc channel may be defined, externally to the Urban Centre sub-model (e.g. a two-arc min-max channel as described in **Section 8.2.2**). The user must be careful to select appropriate channel penalties ("P2") in order to ensure that the water requirement is supplied in accordance with the required operation of the system.

The third is the set of urban centre return flow channels, NDCRC. In this case, the special two-arc urban centre return flow channel type is used, which provides the mechanism for transporting return flows from the urban centre back to the system network. For this purpose, the user must select appropriate channel penalties to ensure that the full return flow volume enters the system (i.e. by selecting a high value for "P4"). For each return flow channel the portion of the total return flow volume allocated to each return flow channel is defined through variable DCPRC. Return flows are discharged to the system network and may enter the system at any selected system element, such as a reservoir, wetland or junction node.

Part or all of the return flows may be diverted to a reclamation plant for reuse and is calculated based on DCPRA, the portion of flow in each return flow channel which is diverted in this way. Losses from the reclamation plant are calculated as a constant portion of the total volume diverted to the plant, through variable DCPQR and are routed through the special reclamation plant loss channel, NDCRNN. Again, the user must select appropriate channel penalties to ensure that the full loss volume exits the system (i.e. a high value must be selected for "P3").

Finally, variable DCREF represents the reference node number and is used to specify which incremental sub-catchment in the system network, and therefore which rainfall time-series data files (i.e. *.RAN, as described in **Section 4.3**) is associated with the urban centre in question. Rainfall data are applied in the calculation of return flows and the user is also allowed to apply a rainfall scaling factor DCRMF.

Table 8-17: Urban return flow parameters applied in a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken:*				
1	MNDC	Number of large urban centres in the system for which return flows are to be modelled	1	*F03.DAT
2	DCN	Urban centre network node number	1	*F03.DAT
3	DCEN	Urban centre network node number (same as DCN above)	1	*F19.DAT
4	DCNAM	Urban centre name	1	*F19.DAT
5	NDCDN	Channel number of associated channel used for imposing urban centre consumptive water use	1	*F03.DAT
6	MNRL	Number of urban centre reclamation plant loss channels (set = 0 if no reclamation plant)	1	*F03.DAT
For each reclamation plant loss channel (MNRL), parameters 7 to 9 must be defined:				
7	NDCRNN	Reclamation plant loss channel number	1	*F03.DAT
8	DCLDOW	Downstream reservoir or node number for reclamation plant loss channel	1	*F03.DAT
9	NTYPRNN	Penalty structure type associated with reclamation plant loss channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
10	MNRF	Number of urban centre return flow channels	1	*F03.DAT
For each return flow channel (MNRF), parameters 11 to 16 must be defined:				
11	NDCRC	Return flow channel number	1	*F03.DAT
12	DCRDOW	Downstream reservoir or node number for return flow channel	1	*F03.DAT
13	NTYPRC	Penalty structure type associated with return flow channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
14	DCRC	Return flow channel number (same as NDCRC above)	1	*F19.DAT
15	DCPRC	Portion of total return flow from urban centre routed to this return flow channel	1	*F19.DAT
16	DCPRA	Portion of flow in this return flow channel diverted to reclamation plant for reuse	1	*F19.DAT
17	DCPQR	Portion of total flow volume lost from reclamation plant	1	*F19.DAT
18	DCRFA	Long-term monthly average return flow factor	1	*F19.DAT
19	DCSDF	Standard deviation factor	1	*F19.DAT
20	DCRK	Routing constant	1	*F19.DAT
21	DCPET	Monthly potential evapo-transpiration (mm)	12	*F19.DAT
22	DCREF	Reference reservoir or node number with incremental sub-catchment hydrology inflows (i.e. for identifying sub-catchment within which urban centre is located, as described in **Section 4.2**)	1	*F19.DAT
23	DCRMF	Factor for scaling *.RAN-file data (as described in **Section 4.3**) of selected incremental sub-catchment (DCREF) to representative rainfall at urban centre	1	*F19.DAT
24	DCEPA	Long-term monthly average of *evaporation – rainfall*-values (mm)	1	*F19.DAT

It should be noted that return flows from large urban centres can also be defined when undertaking planning analysis by applying the original WQS Demand Centre sub-model. For this purpose, definitions are provided in separate *DC*.DAT-files for each of the urban centres in the system and linked to the system network by defining the connectivity of the water supply, consumptive water use, reclamation plant losses and return flow channels in the WQS *.NET.DAT-file. However, as mentioned in **Section 1.5**, WQS features are not addressed in this version of the Procedural Manual and will only be incorporated at a later stage. Alternatively, an additional set of parameters my be used for defining special return flow algorithms for controlled water requirements (defined using water supply master control channels, as described in **Section 8.2.1**), as shown below. These algorithms also apply a routing equation (as mentioned earlier in this section).

Table 8-18: Parameters for defining special return flow algorithms for master control channels

No.	Name	Description	Number of inputs	Associated data file/s
1	MNRF	Number of special return flow algorithm definitions provided for master control channels in the system	1	*RET.DAT
For each special return flow algorithm definition (MNRF), parameters 2 to 13 must be defined:				
2	RFDC	Master control channel number for which a special return flow algorithm definition is provided	1	*RET.DAT
3	RFRFA	Long-term monthly average return flow factor	1	*RET.DAT
3	RFRMF	Return flow multiplication factor	1	*RET.DAT
4	RFRFK	Calibration factor used in the return flow factor equation	1	*RET.DAT
5	RFCRF	Curtailment factor used in return flow equation	1	*RET.DAT
6	RFRTK	Routing constant for routing equation		*RET.DAT
7	RFEPA	Long-term monthly average of *evaporation – rainfall*-values (mm)	1	*RET.DAT
8	RFGN	Reference number of the incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)		*RET.DAT
9	RFE	Monthly potential evapo-transpiration (mm)	12	*RET.DAT
10	RFN	Number of return flow master control channels associated with water requirement channel RFDC	1	*RET.DAT
For each return flow master control channels associated with water requirement channel (RFN), parameters 11 to 13 must be defined:				
11	RFCN	Return flow master control channel number	1	*RET.DAT
12	RFAN	Return flow reuse channel number (set = 0 if none)	1	*RET.DAT
13	RFF	Assumed return flow factor	1	*RET.DAT

8.2.8 Minimum flow specifications

Specified releases from reservoirs to maintain a minimum level of flow in the downstream river reach are modelled in the WRSM with the minimum flow channel type, based on a set of minimum monthly flow requirements, defined in units of m^3/s.

Table 8-19: Minimum flow channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNSUP	Number of minimum flow channels in the system	1	*F03.DAT
For each minimum flow channel in the system (MNSUP), parameters 2 to 8 must be defined:				
2	NSUPCH	Minimum flow channel number	1	*F03.DAT
3	RNAM	Minimum flow channel name	1	*F11.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	NTYPS	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	NCH	Minimum flow channel number (same as NSUPCH above)	1	*F11.DAT
8	SUPQ	Monthly minimum flows (m^3/s)	12	*F11.DAT

Conditions associated with defining minimum flow channels are summarised in the table below.

Table 8-20: Conditions for defining minimum flow channels

Condition	Associated parameter/s	Reference
Minimum flow channels must be two-arc channels	NTYPS, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with multi-purpose min-max channel must exist	NTYPS, NTYP	This section, **7.2**

8.3 Physical system components

8.3.1 Constrained water conduits

Constrained water conduits with a fixed capacity limit, such as pipelines, canals, tunnels and aqueducts, are modelled in the WRSM using the *one-arc multi-purpose min-max channel-type* as shown below. This channel type is extremely versatile and can be used for a variety of functions. Min-max channels are defined with anything up to 5 channel arcs, with a set of 12 monthly upper and lower flow limits specified for each arc. In most cases, however, only the one and two-arc configurations are used – the latter to model requirements and return flows with fixed monthly distributions (as discussed in **Section 8.2.2**).

Table 8-21: One-arc multi-purpose min-max channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNMMX	Number of multi-purpose min-max channels in the system (including two-arc channels, as described in **Section 8.2.2**)	1	*F03.DAT
For each multi-purpose min-max channel in the system (MNMMX), parameters 2 to 8 must be defined:				
2	NMMXCH	Multi-purpose min-max channel number	1	*F03.DAT
3	RNAM	Multi-purpose min-max channel name	1	*F12.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	CHNTYP	One-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	NCH	Multi-purpose min-max channel number (same as NMMXCH above)	1	*F12.DAT
8	CSTMM	Monthly conduit capacity limits (m^3/s)	12	*F12.DAT

Since multi-purpose min-max channels can also be used to model requirements and return flows, as mentioned above, parameters relating to time-related changes must be defined for all min-max channels in the system when undertaking a planning analysis. This includes one-arc min-max channels, even though the capacity limit of constrained water conduits will typically remain unchanged over the course of the analysis period. Details in this regard are shown below.

Table 8-22: Parameters for defining time-related changes for single-arc multi-purpose min-max channels

No.	Name	Description	Number of inputs	Associated data file/s
The parameters in this table must be defined if a ***planning analysis*** *is being undertaken:*				
1	MNYP	Number of planning years for which time-related change information is provided (same as MNYP, as described in **Sections 4.3**, **8.2.1** and **8.2.2**)	1	*GTH.DAT
2	NTGCHN	Total number of multi purpose min-max channel arcs for which time-related change information is provided (i.e. for all relevant min-max channels)	1	*GTH.DAT
3	NGCHN	Multi-purpose min-max channel number (same as NMMXCH described earlier in this section)	1	*GTH.DAT
4	NGBD	Channel arc number (must set = 1)	1	*GTH.DAT
5	GFAC	Annual projection factors for monthly conduit capacity limits (projected value = CSTMM x (1 + GFAC), therefore GFAC = 0 implies no change)	MNYP	*GTH.DAT

Conditions associated with defining single-arc multi-purpose min-max channels are summarised in the table below.

Table 8-23: Conditions for defining two-arc multi-purpose min-max channels

Condition	Associated parameter/s	Reference
Multi-purpose min-max channels used for modelling constrained water conduits must be single-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with multi-purpose min-max channel must exist	CHNTYP, NTYP	This section, **7.2**

8.3.2 Streamflow diversion structures

The *streamflow diversion channel type* is used in the WRSM to model the efficiency of diversion structures to utilise flow from a river stream within the context of the monthly time-step used by the model. Four diversion channel-types are available in the model, each calculating the magnitude of diverted flows in a particular way. These are:

- Type 1: Monthly target diversion flows are specified, together with a maximum diversion which is expressed as a proportion of available natural runoff entering the upstream node;
- Type 2: Diversion flows are calculated based simply on a user-defined relationship to natural runoff entering the upstream node;
- Type 3: Calculated based on natural runoff entering the upstream node (as for Type 2), as well as the storage level in a specified reference reservoir. In this case, the user must define both the reference reservoir storage levels and natural runoff reference flows which are associated with the range of specified diversion flow values;

- Type 4: This type is used when diverted flows are dependent on both the natural runoff and upstream inflows to a specified reference node.

All of the above diversion flow and natural runoff reference flow values are defined in units of m^3/s (unless otherwise stated). It is important to note that the Type 4 diversion channel differs from the other three in that it takes into account inflows entering a node from upstream nodes. For this reason, Type 4 diversions channels are defined in the WRSM using the structure of a Type 1 loss channel (loss channels can account for inflows from upstream nodes) and details in this regard are provided later in this section. One should bear in mind, however, that the modelling of this type of diversion channel requires an iterative solution procedure and therefore significantly increase the model runtime of a particular system.

Table 8-24: Streamflow diversion channel parameters (for Types 1, 2 and 3)

No.	Name	Description	Number of inputs	Associated data file/s
1	MNDIV	Number of Type 1, 2 and 3 streamflow diversion channels in the system	1	*F03.DAT
For each Type 1, 2 or 3 streamflow diversion channel in the system (MNDIV), parameters 2 to 18 must be defined:				
2	NDIVCH	Streamflow diversion channel number	1	*F03.DAT
3	RNAM	Streamflow diversion channel name	1	*F10.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	NTYPD	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	DIVTYP	Streamflow diversion channel type (1, 2 or 3)	1	*F03.DAT
8	NCH	Streamflow diversion channel number (same as NDIVCH above)	1	*F10.DAT
For each Type 1 diversion channel (DIVTYP = 1), parameters 9 and 10 must be defined:				
9	DIVQ	Monthly target diversion flows (m^3/s)	12	*F10.DAT
10	DIVLMT	Monthly maximum diversion flows (proportion of natural runoff into upstream reservoir or node, RESUP above)	12	*F10.DAT
For each Type 2 diversion channel (DIVTYP = 2), parameters 11 and 12 must be defined:				
11	DIVQ	Range of natural runoff reference flows into upstream reservoir or node, RESUP above (m^3/s)	≤ 12	*F10.DAT
12	DIVLMT	Diversion flows (m^3/s, corresponding to DIVQ)	As for DIVQ	*F10.DAT
For each Type 3 diversion channel (DIVTYP = 3), parameters 13 to 18 must be defined:				
13	DIVRES	Reference reservoir number (i.e. for defining reference storage levels, NRSL below)	1	*F10.DAT
14	NRSL	Number of reference reservoir storage levels for which diversion flows are defined	1	*F10.DAT
15	DIVL	Range of storage levels in reference reservoir (m)	NRSL	*F10.DAT

No.	Name	Description	Number of inputs	Associated data file/s
16	NRQL	Number of natural runoff reference flows into upstream reservoir or node, RESUP above, for which diversion flows are defined	1	*F10.DAT
For each natural runoff reference flow into upstream reservoir or node (NRQL), parameters 17 and 18 must be defined:				
17	DIVF	Natural runoff reference flow value (m^3/s)	1	*F10.DAT
18	DIVP	Diversion flows (as proportion of DIVF, corresponding to DIVL)	NRSL	*F10.DAT

Conditions associated with defining Type 1, 2 or 3 streamflow diversion channels are summarised in the table below.

Table 8-25: Conditions for defining Type 1, 2 or 3 streamflow diversion channels

Condition	Associated parameter/s	Reference
Streamflow diversion channels must be two-arc channels	NTYPD, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with associated streamflow diversion channel must exist	NTYPD, NTYP	This section, **7.2**
Upstream reservoir or node must have incremental sub-catchment hydrology inflows	RESUP, CATCH	This section, **4.2**
Natural runoff reference flows into upstream reservoir or node must cover full range of possible volumes	DIVQ (for Type 2), DIVF (for Type 3)	This section
For Type 3 diversion channels, selected reservoir for defining reference storage levels must exist	DIVRES, others	This section
For Type 3 diversion channels, reference reservoir storage levels for which diversion flows are defined must cover full possible range	DIVRES, NRSL	This section

Table 8-26: Parameters for defining Type 4 streamflow diversion channel parameters (using the Type 1 loss channel structure)

No.	Name	Description	Number of inputs	Associated data file/s
1	MNLOSS	Number of loss channels in the system (including Type 1, which are used for defining Type 4 streamflow diversion channels, as described earlier)	1	*F03.DAT
For each Type 4 streamflow diversion channel in the system (MNLOSS, excluding loss channels other than Type 1), parameters 2 to 11 must be defined:				
2	NLSSCH	Streamflow diversion channel number	1	*F03.DAT
3	RNAM	Streamflow diversion channel name	1	*F11.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	CHNTYP	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT

No.	Name	Description	Number of inputs	Associated data file/s
7	LOSTYP	Loss channel type (must set = 1)	1	*F03.DAT
8	LSREF (LSSREF)	Reference reservoir or node number with incremental sub-catchment hydrology inflows (i.e. for defining reference inflows, PCLOSS below) (0 for upstream reservoir or node, RESUP)	1	*F03.DAT
9	NCH	Streamflow diversion channel number (same as NLSSCH above)	1	*F11.DAT
10	PCLOSS	Range of reference flows into selected reservoir or node, LSREF above (m^3/s, including both natural runoff and inflows from upstream)	≤ 12	*F11.DAT
11	PCLOS1	Diversion flows (m^3/s, corresponding to PCLOSS)	As for PCLOSS	*F11.DAT

Conditions associated with defining Type 4 streamflow diversion channels are summarised in the table below.

Table 8-27: Conditions for defining Type 4 streamflow diversion channels

Condition	Associated parameter/s	Reference
Streamflow diversion channels must be two-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with associated streamflow diversion channel must exist	CHNTYP, NTYP	This section, **7.2**
For Type 4 streamflow diversion channels, loss channel type must be set = 1	LOSTYP	This section, **8.4**
Selected reservoir or node for defining reference flows must exist	LSREF, others	This section
Reference flows into selected reservoir or node must cover full possible range	LSREF, PCLOSS	This section

8.3.3 Wetlands

When undertaking a yield analysis, wetlands are modelled in the WRSM using the *Wetland sub-model* which was which was developed as part of the *Water Resources of South Africa, 2005* (WR2005) study and has been incorporated into the model for application in the *Water Availability Assessment* (WAA) studies recently commissioned by the DWAF, Directorate: NWRP (as discussed in **Section 3.2**). It should be noted that wetlands can also be defined when undertaking planning analysis as part of the original WQS Channel Reach sub-model. For this purpose, wetland definitions are provided in separate *CR*.DAT-file and linked to the system network by defining the connectivity of the wetland to the system network in the WQS *.NET.DAT-file. However, as mentioned in **Section 1.5**, WQS features are not addressed in this version of the Procedural Manual and will only be incorporated at a later stage.

The Wetland sub-model algorithm is based on the assumption that a wetland has a nominal storage capacity and surface area, which can be exceeded. The nominal value refers to the wetland storage below which there is no linkage to the river channel. Flow from wetland to river channel is governed by the storage state of the wetland and is proportional to the storage volume over and above the nominal capacity. Flow from the river channel to the wetland occurs when the river flow is above a prescribed threshold. The surplus flow is then apportioned between the river channel and the wetland inflow channel.

Wetlands are modelled in the WRSM as a special reservoir which must be defined externally to the Wetland sub-model as described in **Section 5**. This includes physical characteristics (the relationship between elevation level, storage capacity and surface area), water levels at the start of the analysis, the net runoff from catchments contributing to local inflows, evaporation from and direct rainfall on water surfaces, as well as the definition of operating rule characteristics (including user-selected storage zones and drawdown rules, as appropriate). However, unlike with standard reservoirs, spillage from wetland to the river system does not commence instantaneously as the wetland reaches a defined full supply capacity. Instead, flows in the wetland outflow channel are governed by the storage state of the wetland and are defined as a proportion of the storage over and above a nominal storage capacity, as explained earlier. Also, only a portion of the flows, above a certain threshold, that occur in the river channel upstream of a wetland, will enter the wetland in question.

The typical configuration of a wetland in the WRSM system network is shown below and the following should be noted:

- The wetland is represented by system network node WLEN, which is a standard WRSM reservoir (as explained earlier) and allows for the modelling of local incremental hydrology inflows;
- Inflows entering the wetland from the river system are passed along the special wetland inflow channel. The magnitude of the modelled flows in this channel (“Inf”) is calculated at runtime, based on the defined algorithms of the Wetland sub model, and imposed by the model on the channel on a monthly basis;
- The wetland node is not configured with a standard open spill channel to the river system (as is generally the case with reservoirs), but rather with a special wetland outflow channel. As with the wetland inflow channel, the magnitude of modelled flows in the outflow channel (“Out”) is calculated and imposed by the model at runtime.

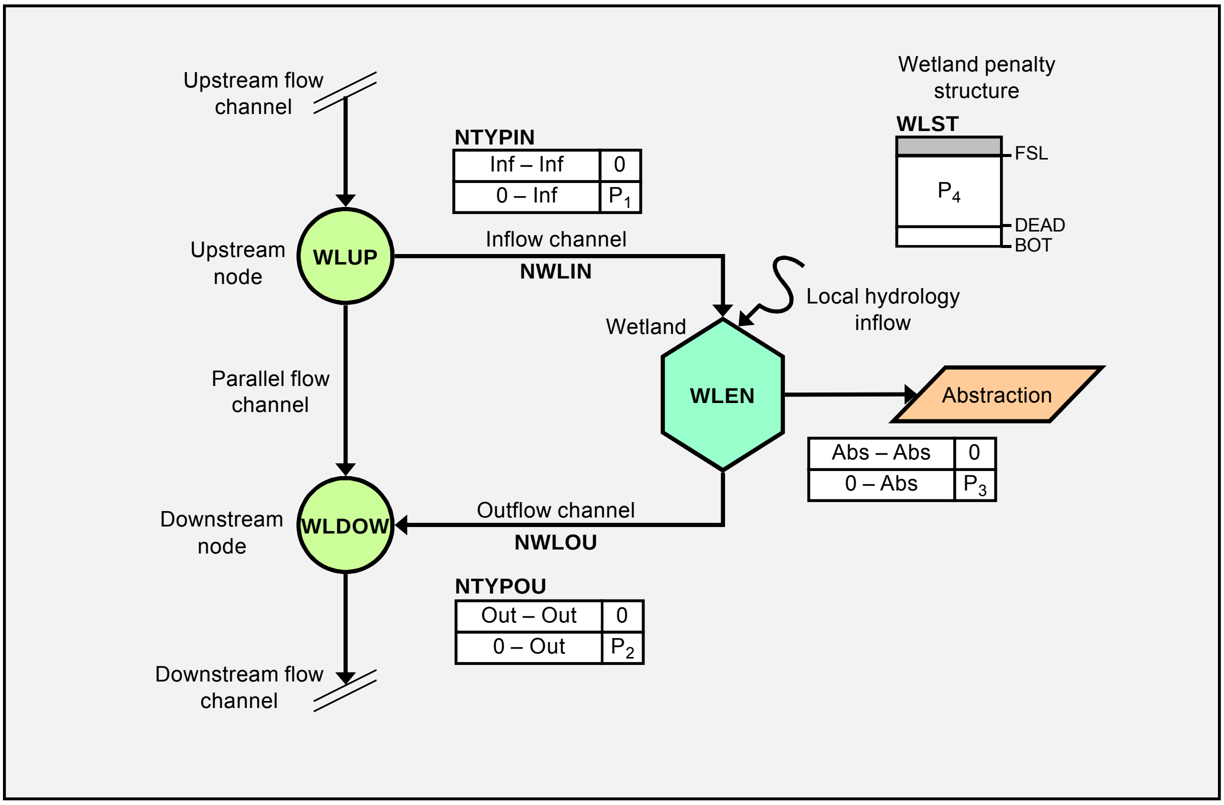


Figure 8-3: Configuration of a wetland in the WRSM system network

- In order to accommodate the above configuration, where no spill channel is modelled, the user should ensure that the physical characteristics of the wetland reservoir are defined such that the wetland will never reach full supply capacity. For this purpose, an arbitrarily large value may be selected for its full supply level (as described in **Section 5.1**);
- In cases where abstractions are modelled on the wetland, the user must be careful to select appropriate reservoir zone penalties (“P4”) and channel penalties (“P3”), in order to ensure that the associated water requirement is supplied in accordance with the required operation of the system.

Table 8-28: Wetland parameters applied in a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken:*				
1	MNWL	Number of wetlands in the system	1	*F03.DAT
For each wetland in the system (MNWL), parameters 2 to 14 must be defined:				
2	WLEN	Wetland node number	1	*F03.DAT
3	WLN	Wetland node number (same as WLEN above)	1	*F18.DAT
4	WLNAM	Wetland name	1	*F18.DAT
5	WLUP	Upstream reservoir or node number for wetland inflow channel	1	*F03.DAT

No.	Name	Description	Number of inputs	Associated data file/s
6	NWLIN	Wetland inflow channel number	1	*F03.DAT
7	NTYPIN	Penalty structure type associated with wetland inflow channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
8	WLDOW	Downstream reservoir or node number for wetland outflow channel	1	*F03.DAT
9	NWLOU	Wetland outflow channel number	1	*F03.DAT
10	NTYPOU	Penalty structure type associated with wetland outflow channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
11	WLUFC	Flow threshold in upstream flow channel above which inflow to wetland occurs (m^3/s)	1	*F18.DAT
12	WLUFP	Proportion of flows above WLUFC that will enter wetland through the wetland inflow channel (0 ≤ WLUFP ≤ 1)	1	*F18.DAT
13	WLNS	Nominal wetland storage volume (million m^3)	1	*F18.DAT
14	WLNSP	Proportion of volume above WLNS that will exit wetland through the wetland outflow channel (0 ≤ WLNSP ≤ 1)	1	*F18.DAT

Conditions associated with defining wetlands are summarised in the table below.

Table 8-29: Conditions for defining wetlands

Condition	Associated parameter/s	Reference
Wetland inflow and outflow channels must be two-arc channels	NTYPIN, NTYPOU, NTYP, NCHARC	This section, **7.2**
Penalty structure types associated with wetland inflow and outflow channels must exist	NTYPIN, NTYPOU	This section, **7.2**
Since wetlands are modelled as a special reservoir type, the wetland must be defined in the system, externally to the Wetland sub-model, as a standard reservoir with the appropriate physical and operation characteristics	Various	**5**
The wetland reservoir must be defined such that it will never reach full supply capacity and spill, by selecting a large value for its full supply level	FSL	**5.1**

8.3.4 Sand aquifers

Sand aquifers can be modelled in the WRSM as a standard reservoir with the appropriate physical and operation characteristics (as described in **Section 5**). However, since the aquifer is located underground and therefore behaves differently to normal reservoirs, the reservoir definition must be adapted to exclude the impacts of incremental runoffs, rainfall directly onto their water surfaces and evaporation (as described in **Section 4.4** and **5.1**)

The flow linkage between a sand aquifer and the system network is modelled in the WRSM by means of a general flow channel type (as discussed in **Section 8.1**) and a special flow control structure Type 11. Flow control structures represent physical flow constraint in a channel and various other flow control structure types are available, as discussed in **Section 8.3.8**. The behaviour of the aquifer channel is based on the principle that flow from the river channel to the aquifer (i.e. aquifer recharge) occurs when the elevation of the water in the aquifer is lower than the flow level in the river. Alternatively, flow from the aquifer back to the river channel occurs when the flow level is lower than the aquifer level. When the levels are equal, the flow is zero.

Aquifer channels are defined by means of two sets of data values, the first of which defines the relationship between:

- The head difference of water in the aquifer and water in the river flow channel;
- The corresponding flow that occurs, either from the aquifer to the river channel or in the opposite direction.

The head difference is defined as the elevation of the water in the aquifer minus the flow level in the river. Therefore, if the level of water in the aquifer is lower than the flow level in the river, the specified head difference would be negative. Furthermore, the corresponding flow values are always defined to be in the direction from the aquifer towards the river channel. Therefore, flows in the opposite direction (i.e. when aquifer recharge occurs) are defined as negative values.

The second set of data values defines the relationship between:

- The water flow level of the water in the river flow channel;
- The corresponding flow that occurs in the river.

Table 8-30: Parameters for defining wetlands using special flow control structure Type 11

No.	Name	Description	Number of inputs	Associated data file/s
1	MNSTRT	Number of sand aquifers in the system (and other special flow control structures, as described in **Section 8.3.8**)	1	*F04.DAT
For each sand aquifer in the system (MNSTRT, excluding other special flow control structures), parameters 2 to 10 must be defined:				
2	ARBCHN	Reference to channel for modelling flow link between aquifer and river channel	1	*F04.DAT
3	IRUP	Upstream reservoir number for channel ARBCHN (representing aquifer)	1	*F04.DAT
4	IRDOW	Downstream node number for channel ARBCHN (representing river channel)	1	*F04.DAT
5	NSTYPE	Control structure type option (must set = 11)	1	*F04.DAT

No.	Name	Description	Number of inputs	Associated data file/s
6	DISCUR	Number of points in aquifer and river flow head differences and flows from aquifer to river relationship, as well as river flow depth and river total flows relationship	1	*F04.DAT
7	DISEL(1)	Range of head differences between aquifer and river flow depth (m above MSL)	DISCUR	*F04.DAT
8	DISCHR(1)	Flows from aquifer to river channel (m^3/s, corresponding to DISEL(1), negative flows represent flows in the apposite direction)	DISCUR	*F04.DAT
9	DISEL(2)	Range of flow depths in river channel (m above MSL)	DISCUR	*F04.DAT
10	DISCHR(2)	Total flows in river channel (i.e. entering downstream node, m^3/s, corresponding to DISEL(2)).	DISCUR	*F04.DAT

Conditions associated with defining wetlands are summarised in the table below.

Table 8-31: Conditions for defining wetlands

Condition	Associated parameter/s	Reference
Channel for modelling flow link between aquifer and river channel must exist and may be defined using a general flow channel type	ARBCHN, others	This section, others
Head differences between aquifer and river flow depth must cover full possible range	DISEL(1)	This section
Flow depths in river channel must cover full possible range	DISEL(2)	This section
Total flows in river channel must cover full possible range	DISCHR(2)	This section

8.3.5 Coal mines

When undertaking a yield analysis, coal mines are modelled in the WRSM using the *Mine sub-model*. The sub-model was developed as part of the *Development of an Integrated Water Resources Model of the Upper Olifants River (Loskop Dam) Catchment* study (BKS, et. al., 2000) and has been incorporated into the model for application in the *Water Availability Assessment* (WAA) studies recently commissioned by the DWAF, Directorate: NWRP (as discussed in **Section 3.2**). It should be noted that coal mines can also be defined when undertaking planning analysis as part of the original WQS Mine sub-model. For this purpose, mine definitions are provided in separate *MM*.DAT-file and linked to the system network by defining the connectivity of the mine to the system network in the WQS *.NET.DAT-file. However, as mentioned in **Section 1.5**, WQS features are not addressed in this version of the Procedural Manual and will only be incorporated at a later stage.

A typical coal mining operation can consist of any of a number of distinct components. These are:

- Opencast mining pit element;
- Underground mine element with its underground storage dam;
- Discard / slurry dump element;
- Central pollution control dam (PCD);
- Coal beneficiation plant.

A schematic diagram of the typical configuration of a coal mine in the WRSM system network is shown below and includes the following mining components:

- The *Mine sub-model element*, which incorporates the underground mining activities, as well as the opencast mining pits and discard / slurry dumps with their associated PCDs.
- The *central PCD*.
- The *underground storage dam*, which is associated with the underground mining activities.

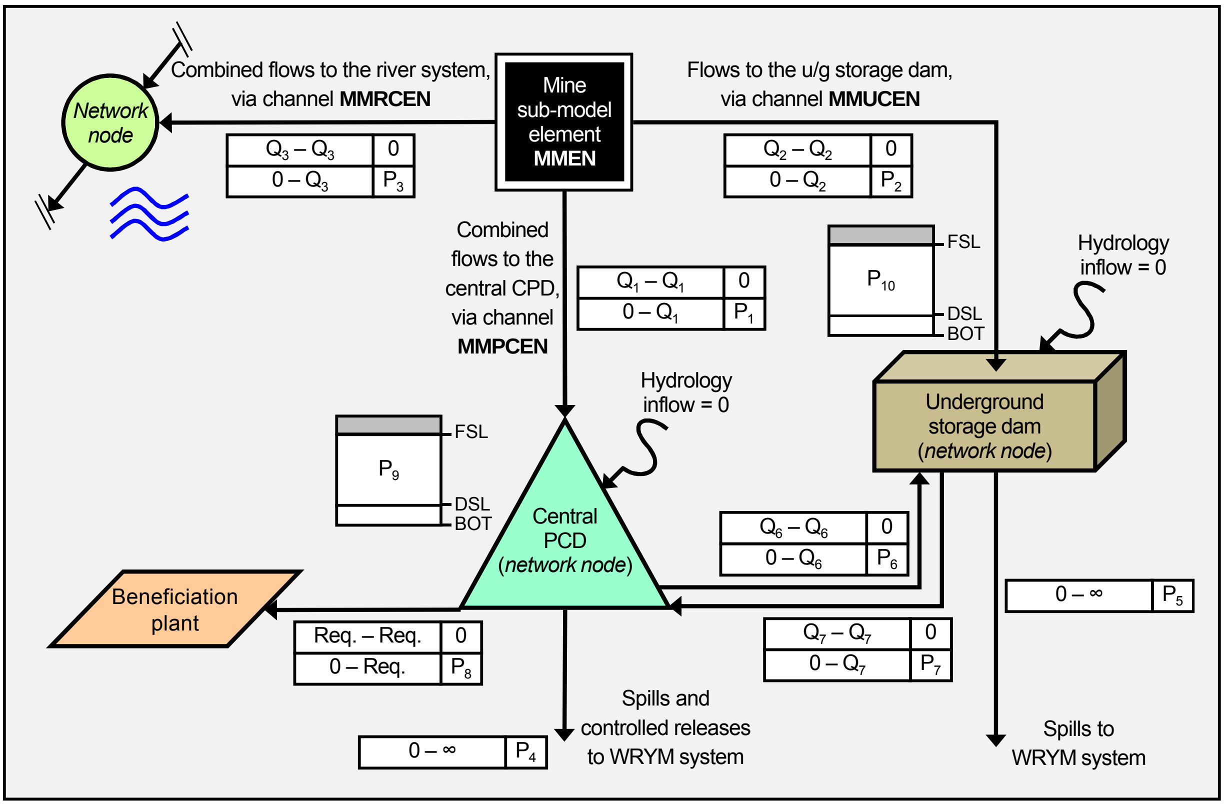


Figure 8-4: Configuration of a coal mine in the WRSM system network

In this regard it is important to note the following:

- The Mine sub-model element lies *outside* of the WRSM network and is therefore not represented by a network node;
- Unlike the PCDs associated with opencast mining pits and discard / slurry dumps, which are associated with the Mine sub-model and therefore lie outside of the WRSM network, both the central PCD and the underground storage dam are modelled in the WRSM as network reservoir nodes. The reason for this approach is that it enables the user to implement appropriate operating rules in the model, such as controlled releases or options where mine water is desalinated and supplied to other users or released back into the river system.

As a result of the above, both the central PCD and the underground storage dam must be defined in the WRSM as standard reservoirs with the appropriate physical and operation characteristics (as described in **Section 5**). However, unlike other reservoirs, inflows to these reservoirs originate from mining activities only and will be calculated by the model at run-time based on outputs from the Mine sub-model. The reservoir definition must be adapted to exclude the impacts of incremental runoffs (as described in **Section 4.4**). Furthermore, since the underground storage dam is located underground, evaporation does not occur from its water surface and the user should therefore also set equal to zero the monthly lake evaporation values associated with this reservoir.

The figure above also shows that the various components of the Mine sub-model are linked together and to the system network by means of a number of channels. The most important are the channels that route water from the Mine sub-model to:

- The river system, which is represented by a node in the system network;
- The central PCD;
- The underground storage dam.

All of the above must be defined externally to the Mine sub-model, by means of two-arc multi-purpose min-max channels (as described in **Section 8.2.2** for the definition of water requirements and return flows with fixed monthly distributions), and referenced in the Mine sub-model, as discussed below.

Variable MMRCEN represents the channel number for the route that conveys the combined outflows from the mine to the river system, including:

- Surface runoff from the undisturbed and disturbed areas of the opencast mining pit, as well as spills from its PCD;
- Surface runoff from the catchment upstream of the undermined areas of an underground mine, as well as runoff from the catchment areas undermined by board-and-pillar (B&P) and high extraction (HE) mining activities;
- A portion of the seepage from a discard / slurry dump.

MMPCEN is the channel number for the route that conveys combined flows from the mine to the central PCD, including:

- Seepage and overflow from the opencast mining pit, in case the pit does not have its own PCD;
- Water pumped from the underground storage dam to the central PCD;
- Spills from the discard / slurry dump PCD;
- Polluted runoff generated at the coal beneficiation plant.

Finally, a reference is provided through variable MMUCEN for the channel that conveys recharge generated as a result of the underground mining activities to the underground storage dam.

It should be noted, however, that unlike standard min-max channels, the monthly maximum flow limits in the above channels are not based on the values defined for variable CSTMM (as described in **Section 8.2.2**). Instead, the flows will be calculated by the model at run-time based on outputs from the Mine sub-model. The user may therefore set the values of variable CSTMM equal to zero.

As mentioned earlier, both the central PCD and the underground storage dam are modelled as network reservoirs. The user will therefore also be required to provide these reservoirs with spill channels. Generally, as shown in the figure above, such channels are modelled by means of the general flow channel-type (see **Section 8.1**).

Finally, the water requirements of the coal beneficiation plant, as shown in the figure above, may be imposed on the central PCD, either as a water requirement with a fixed monthly distribution (i.e. using a two-arc multi-purpose min-max channel, as described in **Section 8.2.2**) or as a time-series requirement (as described in **Section 8.2.3**).

Table 8-32: Coal mine parameters applied in a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken:*				
1	MNMM	Number of mines in the system	1	*F21.DAT
For each mine in the system (MNMM), parameters 2 to 54 must be defined:				
2	MMEN	Mine sub-model element number (note: not a system network node)	1	*F21.DAT
3	MNNAM	Mine name	1	*F21.DAT
4	MMRCEN	Reference to channel defined for conveying combined outflows from mine to river system	1	*F21.DAT
5	MMPCEN	Reference to channel defined for conveying combined flows from mine to central PCD	1	*F21.DAT
6	MMREF	Reference reservoir or node number with incremental sub-catchment hydrology inflows (i.e. for identifying sub-catchment within which mine is located, as described in **Section 4.4**)	1	*F21.DAT
7	MMPEL	Monthly mean pan evaporation (mm)	12	*F21.DAT
8	MMAPF	Monthly mean pan evaporation-to-lake evaporation conversion factors (i.e. lake evaporation = MMPEL x MMAPF)	12	*F21.DAT
9	MMAPNT	Surface area of coal beneficiation plant from which runoff reaches the central PCD (km^2)	1	*F21.DAT
10	MMQFPNT	Portion of coal beneficiation plant area that is impervious	1	*F21.DAT
11	MMMNO	Number of opencast mining pits on the mine	1	*F21.DAT
For each opencast mining pit on the mine (MMMNO), parameters 12 to 29 must be defined:				
12	MMPNAM	Opencast mining pit name	1	*F21.DAT
13	MMARES	Area of coal reserves (km^2)	1	*F21.DAT
14	MMADA	Disturbed area (km^2)	1	*F21.DAT
15	MMQFDA	Runoff factor for disturbed area	1	*F21.DAT
16	MMRFDA	Monthly recharge factors for disturbed area	12	*F21.DAT
17	MMADAW	Disturbed area contributing to workings (km^2)	1	*F21.DAT
18	MM-QFDAW	Runoff factor for disturbed area contributing to workings	1	*F21.DAT
19	MM-RFDAW	Monthly recharge factors for disturbed area contributing to workings	12	*F21.DAT
20	MMAW	Area of workings (km^2)	1	*F21.DAT
21	MMAED	Evaporation area of in-spoils store water surface (km^2)	1	*F21.DAT
22	MMVSDD	Volume of spoils storage at which overflow occurs (million m^3)	1	*F21.DAT
23	MMVSDS	Volume of spoils storage at which seepage through weathered zone occurs (million m^3)	1	*F21.DAT
24	MMIVI	Volume of water in spoils storage at the start of the analysis (million m^3)	1	*F21.DAT
25	MM-SEEPM	Maximum rate of seepage from spoils storage (million m^3/month)	1	*F21.DAT
26	MMEXPS	Exponent of seepage equation for spoils storage	1	*F21.DAT

No.	Name	Description	Number of inputs	Associated data file/s
27	MMAFPC	Surface area of PCD for opencast mining pit (km^2)	1	*F21.DAT
28	MMVFPC	Storage capacity of PCD (million m^3)	1	*F21.DAT
29	MMVPCI	Volume of water in PCD at the start of the analysis (million m^3)	1	*F21.DAT
30	MMMNU	Number of underground mining sections on the mine	1	*F21.DAT
For each underground mining section on the mine (MMMNU), parameters 31 to 40 must be defined:				
31	MMUNAM	Underground mining section name	1	*F21.DAT
32	MMUCEN	Reference to channel defined for conveying recharge from underground mining section to underground storage dam	1	*F21.DAT
33	MMAUM1	Undermined catchment area for board-an-pillar component of mine	1	*F21.DAT
34	MM-RFUM1	Monthly recharge factors for board-and-pillar area	12	*F21.DAT
35	MMAUM2	Undermined catchment area for high extraction component of mine	1	*F21.DAT
36	MM-QFUM2	Runoff factor for high extraction area	1	*F21.DAT
37	MM-RFUM2	Monthly recharge factors for high extraction area	12	*F21.DAT
38	MMAUP	Area of catchment upstream of the undermined area (km^2)	1	*F21.DAT
39	MMRFUP	Monthly values for portion of upstream catchment area runoff that recharges the underground storage dam	12	*F21.DAT
40	MMMNS	Number of discard / slurry dumps on the mine	1	*F21.DAT
For each discard / slurry dump on the mine (MMMNS), parameters 41 to 48 must be defined:				
41	MMSNAM	Discard / slurry dump name	1	*F21.DAT
42	MMADMP	Surface area of discard / slurry dump (km^2)	1	*F21.DAT
43	MMADD	Surface area of PCD for discard / slurry dump (km^2)	1	*F21.DAT
44	MMVFDD	Storage capacity of PCD (million m^3)	1	*F21.DAT
45	MMVDDI	Volume of water in PCD at the start of the analysis (million m^3)	1	*F21.DAT
46	MM-QFDMP	Runoff factor for flow from dump to PCD	1	*F21.DAT
47	MMFDMP	Factor to split seepage from dump to river and PCD	1	*F21.DAT
48	MM-RFDMP	Monthly recharge factors for seepage from dump to PCD or river	12	*F21.DAT
49	MNMMC	Number of incremental sub-catchments in the system for which opencast mining pits or underground mining sections are defined	1	*F21.DAT
For each incremental sub-catchment in the system for which opencast mining pits or underground mining sections are defined (MNMMC), parameters 50 to 54 must be defined:				
50	MM-CATCH	Reference number of the incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.2**)	1	*F21.DAT
51	MMGMB	Monthly minimum groundwater flow volume (million m^3)	12	*F21.DAT
52	MMRDF	Antecedent runoff decay factor	1	*F21.DAT

No.	Name	Description	Number of inputs	Associated data file/s
53	MMPAF	Proportion of antecedent flows	1	*F21.DAT
54	MMGI	Groundwater flow volume at the start of the analysis (million m^3)	1	*F21.DAT

Conditions associated with defining coal mines are summarised in the table below.

Table 8-33: Conditions for defining mines

Condition	Associated parameter/s	Reference
Channel for conveying combined outflows from mine to river system must be defined externally to the Mine sub-model, by means of two-arc multi-purpose min-max channel	MMRCEN, others	This section, **8.2.2**
Channel for conveying combined flows from mine to central PCD must be defined externally to the Mine sub-model, by means of two-arc multi-purpose min-max channel	MMPCEN, others	This section, **8.2.2**
Channel for conveying recharge from underground mining section to underground storage dam must be defined externally to the Mine sub-model, by means of two-arc multi-purpose min-max channel	MMUCEN, others	This section, **8.2.2**
The central PCD and underground storage dam must be defined in the system, externally to the Mine sub-model, as standard reservoirs with the appropriate physical and operation characteristics	Various	**5**
Combined extent of coal mining activities, as well as areas under irrigation and streamflow reduction catchment portion areas, may not be greater that the incremental sub-catchment within which they are located	RRAREA, SFRAR, AMINE(1) CATHAR, CATCH, others	This section, **8.2.4**, **8.2.5**, others

Note: (1) AMINE may be calculated from various input parameters related to the definition of coal mining activities, as show at the end of this section.

The total area of mines in a sub-catchment, AMINE, is determined by adding up all of the mining activity areas for all the mines that are located within the catchment in question, as shown below:

$$AMINE = \sum (ADA_i + ADAW_i + AW_i + AUP_i + AUM1_i + AUM2_i + ADMP_i + APNT_i) \quad \text{(Eq. 8-1)}$$

Where:

AMINE = total area of mines in sub-catchment

ADA_i = opencast mining pit disturbed area for mine *i*

$ADAW_i$ = opencast mining pit disturbed area contributing to workings for mine *i*

AW_i = opencast mining pit area of workings for mine *i*

AUP_i = catchment upstream of the undermined area for mine *i*

$AUM1_i$ = catchment area over the B&P undermined area for mine *i*

$AUM2_i$ = catchment area over the HE undermined area for mine *i*

$ADMP_i$ = surface area of the discard / slurry dump for mine *i*

$APNT_i$ = surface area of beneficiation plant from which runoff reaches the central PCD for mine *i*

(all in units of km^2)

8.3.6 Pumping stations

The hydraulic characteristics and energy requirements of a pumping station and pipeline are modelled in the WRSM using the *pumping channel type*. The structure of the pumping channel is based on that of the two-arc multi-purpose min-max channel (as discussed in **Section 8.2.2**) and are defined in exactly the same way. However, a number of additional parameters are required and these are discussed below.

The pumping head (or static head, in units of metres) is the difference in elevation between the full supply level (FSL) of the supply reservoir and the peak elevation of the delivery pipeline. The total pumping head is equal to the sum of the static head and the drawdown head, where the drawdown head is the difference between the FSL and the actual water level at the supply reservoir for the given time period. The pumping efficiency is a dimensionless factor and it is used to calculate the power requirements of the pumping channel and will usually be in the range 0.75 to 0.95.

Table 8-34: Pumping channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNPMP	Number of pumping channels in the system	1	*F03.DAT
For each pumping channel in the system (MNPMP), parameters 2 to 10 must be defined:				
2	NPMPCH	Pumping channel number	1	*F03.DAT
3	RNAM	Pumping channel name	1	*F12.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	CHNTYP	Penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	PMPHD	Pumping head (m)	1	*F03.DAT
8	PMPEFF	Pumping efficiency (proportion)	1	*F03.DAT
9	NCH	Pumping channel number (same as NPMPCH above)	1	*F12.DAT

No.	Name	Description	Number of inputs	Associated data file/s
For each pumping channel arc (NCHARC for selected penalty structure type, CHNTYP, as described in ***Section 7.2****), parameter 10 must be defined:*				
10	CSTMM	Monthly flow limits (m^3/s)	12	*F12.DAT

Conditions associated with defining pumping channels are summarised in the table below.

Table 8-35: Conditions for defining pumping channels

Condition	Associated parameter/s	Reference
Number of arcs for pumping channels must be ≤ 5	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with pumping channel must exist	CHNTYP, NTYP	This section, **7.2**
Sets of monthly flow limits for each channel arc must be specified in descending order	CSTMM	This section
Time-related controls must be defined for all pumping channels in the system. Even if time-related controls are not required for analysis, parameters must still be populated with dummy values (i.e. to cover the full analysis period)	Various	**7.4 (b)**
Parameters for economic and tariff calculations must be defined for all pumping channels in the system. Even if an economic analysis is not being undertaken, parameters must still be populated with dummy values	Various	**13**

Finally, as shown in the above table, when undertaking a planning analysis additional parameters must be defined for the time-related control of all pumping channels in the system. More information in this regard is provided in **Section 7.4 (b)**. Furthermore, a set of additional parameters must be defined for each pumping channel, related to economic and tariff calculations, as described in **Section 13**. Even if an economic analysis is not required, those parameters must still be populated with dummy values.

8.3.7 Inflows from other modelled systems

The *specified inflow channel type* is used in the WRSM to incorporate time-series of direct inflows from another system into the network definition of the current system for separate analysis. The purpose is to account for the outflows from the first system, in the form of monthly channel flows, without having to analyse both of the systems simultaneously. In the past, specified inflow channels were used to reduce the size of systems (by analysing them separately) and thereby condensing associated model runtimes. Currently however, with the significantly enhanced capability of computer processors, this is rarely necessary and consequently little use is made of this channel type.

For the definition of a specified inflow channel, the downstream node of the channel must always be defined as a reservoir or node with sub-catchment hydrology inflows (as discussed in **Section 4.4**). Also, the user must ensure that the specified time-series data file is named according to the correct convention. This requires that the filename corresponds with that of the sub-catchment in question (i.e. as for the associated hydro-meteorological and diffuse water use time-series data files, as discussed in **Sections 4.2** and **4.3**). For example, if the natural runoff data file is called “VAAL.INC”, the first part of the name must appear in the specified inflow filename as follows: “VAAL*.INF”.

The creation of a time-series data file (*.INF-file) for use with a specified inflow channel in another system, the appropriate output file option must be selected. For this purpose, the option to output detailed system outflow channel results (to the *YLD.OUT-file) must be selected via parameter OPTSAV and more information in this regard is provided in **Section 14.1**.

Table 8-36: Specified inflow channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNQCH	Number of specified inflow channels in the system	1	*F03.DAT
For each specified inflow channel in the system (MNQCH), parameters 2 to 5 must be defined:				
2	CHANUM	Specified inflow channel number	1	*F03.DAT
3	RESUP	Upstream node number (must set = 0)	1	*F03.DAT
4	RESDOW	Downstream reservoir or node number	1	*F03.DAT
5	CHANTYP	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
Related parameters and interdependencies:				
-	-	Specified inflow time-series data file (with name corresponding to catchment name, as described below, and extension *.INF)	-	*.INF.
-	-	Catchment name assigned to associated incremental sub-catchment, CATCH (as used for the naming of the associated set of hydrological time-series data files *.INC, *.IRR, *.AFF and *.URB, as described in **Section 4.2**)	-	-
-	CATCH	Reference number of associated incremental sub-catchment (assigned based on the sequential order in which it appears in the PARAM.DAT-file, as described in **Section 4.4**)	-	*F02.DAT

Conditions associated with defining specified inflow channels are summarised in the table below.

Table 8-37: Conditions for defining specified inflow channels

Condition	Associated parameter/s	Reference
Specified inflow channels must be two-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with specified inflow channels must exist	CHNTYP, NTYP	This section, **7.2**
Specified inflow time-series data file must exist	-	This section
Name of specified inflow time-series data file must correspond to that of associated incremental sub-catchment, with extension *.INF	CATCH	This section, **4.4**

8.3.8 Special flow control structures

Special flow control structures represent *physical flow constraints* in channel. Any channel in a WRSM system network can be constrained in this way, including pumping, general flow and multi-purpose min-max channels. The operation of a control structure is usually dependent on its physical characteristics and in many cases the head of water in a reservoir, for example when a reservoir spills, flow through the associated spill channel might occur over a spillway, through an outlet pipe or through radial sluice gates. In these situations the definition of a control structure in the model would include a relationship between reservoir elevation and flows released into the constrained channel.

Various control structure types are available (Type 2 to 12), depending on the type of constraint and flow release to be modelled. Note however that many of these are designed for specific problems and may not be of use in other systems without modification. Specific information about each type is therefore not provided here and may be found in **Section 3.4.2** of the WRYM *User Guide* (DWAF, 1999). The Type 11 flow control structure is used in the WRSM for modelling sand aquifers and is described in **Section 8.3.4**.

Table 8-38: Special flow control structure parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNSTRT	Number of special flow control structures in the system (including sand aquifers, as described in **Section 8.3.4**)	1	*F04.DAT
For each special flow control structure in the system (MNSTRT), parameters 2 to 23 must be defined:				
2	ARBCHN	Reference to channel constrained by special flow control structure	1	*F04.DAT
3	IRUP	Upstream reservoir or node number (set = 0 if upstream node)	1	*F04.DAT
4	IRDOW	Downstream reservoir or node number (set = 0 if upstream node)	1	*F04.DAT

No.	Name	Description	Number of inputs	Associated data file/s
5	NSTYPE	Control structure type option (2 to 12, note: types 1 and 0 not in use and Type 11 discussed in **Section 8.3.4**)	1	*F04.DAT
For each channel constrained by a special flow control structure of Type (NSTYPE) = 2 or 3, parameters 6 to 9 must be defined:				
6	SILL	Elevation of control structure sill (m)	1	*F04.DAT
7	HOSL	Maximum height of gate or stop logs (m)	1	*F04.DAT
8	COEFF	Coefficient of discharge	1	*F04.DAT
9	LENGTH	Length of control structure (m)	1	*F04.DAT
For each channel constrained by a special flow control structure of Type (NSTYPE) = 4, 5 or 7, parameters 10 to 12 must be defined:				
10	DISCUR	Number of points in the upstream reservoir reference storage level vs. flow release relationship	1	*F04.DAT
11	DISEL	Range of reference storage levels in upstream reservoir (m above MSL)	DISCUR	*F04.DAT
12	DISCHR	Flow releases (m^3/s, corresponding to DISEL)	DISCUR	*F04.DAT
For each channel constrained by a special flow control structure of Type (NSTYPE) = 6, parameter 13 must be defined:				
13	LENGTH	Maximum flow release (m^3/s)	1	*F04.DAT
For each channel constrained by a special flow control structure of Type (NSTYPE) = 8 or 9, parameters 14 to 16 must be defined:				
14	DISCUR	Number of points in reservoir reference storage level difference vs. flow release relationship	1	*F04.DAT
15	DISEL	Range of reference differences in storage levels between upstream and downstream reservoirs (m)	DISCUR	*F04.DAT
16	DISCHR	Flow releases (m^3/s, corresponding to DISEL)	DISCUR	*F04.DAT
For each channel constrained by a special flow control structure of Type (NSTYPE) = 10, parameters 17 to 20 must be defined:				
17	HOSL	Reference elevation (m above MSL)	1	*F04.DAT
18	DISCUR	Number of pipe or channel sections	1	*F04.DAT
19	DISEL	Channel numbers	DISCUR	*F04.DAT
20	DISCHR	Loss factors (corresponding to DISEL)	DISCUR	*F04.DAT
For each channel constrained by a special flow control structure of Type (NSTYPE) = 12, parameters 21 to 23 must be defined:				
21	DIVH	Range of differences in elevation between upstream and downstream reservoir or node (m)	10	*F04.DAT
22	MQAV	Monthly average inflow to upstream reservoir or node (m^3/s)	1	*F04.DAT
23	MQDIV	Monthly average diverted flow (m^3/s, corresponding to DIVH)	10	*F04.DAT

Conditions associated with defining special flow control structure are summarised in the table below.

Table 8-39: Conditions for defining special flow control structure

Condition	Associated parameter/s	Reference
Channels constrained by special flow control structures must exist, including pumping, general flow and multi-purpose min-max channel types	ARBCHN, others	This section, others
Reference reservoir storage levels must cover full possible range	DISEL (for Types 4, 5, 7)	This section
Reference differences in storage levels between upstream and downstream reservoirs must cover full possible range	DISEL (for Types 8 or 9)	This section

8.3.9 Reclamation plants

Reclamation plants are used for the reclamation of return flow water for further distribution. For example, industrial effluent or urban runoff may be re-processed and the treated water diverted to an irrigation project. There is always a percentage of water lost through the reclamation process, which is the major difference between re-using return flows and routing them via a reclamation plant.

When undertaking a planning analysis, reclamation plants can be modelled in the WRSM by associating the plant with a selected channel in the system network and defining associated parameters for its economic analysis, as well as for time-related controls to define the dates on which the plant must be commissioned and decommissioned (as detailed in **Sections 13** and **7.4 (c)**, respectively). Any channel type may be used for this purpose.

The conditions associated with defining reclamation plants are summarised in the table below.

Table 8-40: Conditions for defining reclamation plants

Condition	Associated parameter/s	Reference
Channel associated with reclamation must exist and may be defined using any channel type	RECHN, others	This section
Time-related controls must be defined for all reclamation plants in the system. Even if time-related controls are not required for analysis, parameters must still be populated with dummy values (i.e. to cover the full analysis period)	Various	**7.4 (c)**
Parameters for economic and tariff calculations must be defined for all reclamation plants in the system. Even if an economic analysis is not being undertaken, parameters must still be populated with dummy values	Various	**13**

8.4 System losses

Flow-related losses from a water resource system are modelled in the WRSM using the *loss channel type*. Losses are calculated based on a monthly proportion of inflows (excluding incremental sub-catchment inflows, as described in **Section 4.2** to **4.4***)* to a selected reservoir or node in the system network. It should be noted that two loss channel types are available in the model but that the 0-type should always be selected for modelling system losses. The Type 1 loss channel is used exclusively for the purpose of modelling streamflow diversions and more information in this regard is provided in **Section 8.3.2**.

Finally, when defining loss channels one should always bear in mind that, since the calculation of losses is dependent on the flows entering a node via other channels in the network model, these channels require an iterative solution procedure and therefore significantly increase the model runtime of a particular system.

Table 8-41: Loss channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNLOSS	Number of loss channels in the system (including Type 1, which is used for defining Type 4 streamflow diversion channels, as described in **Section 8.3.2**)	1	*F03.DAT
For each loss channel in the system (MNLOSS, excluding Type 4 streamflow diversion channels), parameters 2 to 10 must be defined:				
2	NLSSCH	Loss channel number	1	*F03.DAT
3	RNAM	Loss channel name	1	*F11.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	CHNTYP	Two-arc penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	LOSTYP	Loss channel type (must set = 0)	1	*F03.DAT
8	LSREF (LSSREF)	Reference reservoir or node number (i.e. for calculating reference inflows, PCLOSS below) (set = 0 for upstream reservoir or node, RESUP)	1	*F03.DAT
9	NCH	Loss channel number (same as NLSSCH above)	1	*F11.DAT
10	PCLOSS	Monthly flow losses (proportion of inflows to reference reservoir or node, LSREF, excluding incremental sub-catchment hydrology inflows)	12	*F11.DAT

Conditions associated with defining loss channels are summarised in the table below.

Table 8-42: Conditions for defining loss channels

Condition	Associated parameter/s	Reference
Loss channels must be two-arc channels	CHNTYP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with associated streamflow diversion channel must exist	CHNTYP, NTYP	This section, **7.2**
Loss channel type must be set = 0	LOSTYP	This section
Selected reservoir or node for calculating reference inflows must exist	LSREF, others	This section

8.5 Groundwater-surface water interaction

The explicit modelling of the interaction between groundwater and surface water resources and the impact of groundwater abstractions on streamflow, is modelled in the WRSM based on the *Groundwater-Surface Water Interaction* (GWSWI) methodology developed by K Sami as part the *Phase II Groundwater Resource Assessment (GRA II)* programme. The GRA II methodology utilises a time-series of the Pitman “S"-variable (i.e. subsurface storage) from the *Water Resource Simulation Model 2000* (WRSM2000) rainfall-runoff model as input, from which a time-series of recharge is generated. Interflow and groundwater base flow are derived independently and used to simulate base flow to the catchment hydrograph.

The methodology can be summarised as shown below and a detailed description of the model may be found in the document *Lake-Groundwater Interaction Sub-model* (Sami, 2006):

- Utilising the catchment total soil moisture (or “S”) time-series generated by WRSM2000 to calculate a time-series of recharge;
- Incrementing a percolating storage by recharge, with any recharge in excess of percolating storage capacity being dumped to aquifer storage;
- Calculating interflow from the percolating storage utilising the Pitman methodology;
- Incrementing groundwater storage from the percolating storage up to a maximum recharge rate, with any recharge in excess of the maximum recharge rate contributing to interflow;
- Depleting groundwater storage by evapo-transpiration and groundwater outflow to other catchments as a function of groundwater storage until static water level conditions are reached;
- Calculating groundwater base flow or transmission losses in a non-linear manner as a function of groundwater storage and runoff volume;
- Depleting groundwater storage and groundwater base flow due to abstraction as a function of aquifer diffusivity, time since pumping started, distance, and recharge.

However, at the time of publication of the Procedural Manual, the implementation of the *GRA II Groundwater-Surface Water Interaction* methodology in the WRSM had not yet been completed. Its features are therefore not addressed in this version of the document and will only be incorporated at a later stage.

9. DETERMINING SYSTEM YIELDS

As explained in **Section 2**, the yield of a water resource system represents the total long- and short-term water resource capability of the system at a particular point, at a fixed development level and for a selected set of operating rules. Yield can be determined based either on a historical or a stochastic yield analysis, as described below. The selection of historical or stochastic run type options is described in **Section 2.3.4**.

In the case of historical (or single-sequence) analyses, the yield of a system is determined by imposing a selected target water requirement (or “target draft”) on the system at the point in question and evaluating the system’s modelled behaviour. The historical firm yield (HFY) of the system is then determined by means of an iterative process, where a range of target drafts are imposed on the system and the yield (or supplied amount) determined for each target draft. The firm yield, associated with a particular modelled sequence of runoffs, is generally taken to be the maximum target draft that can be imposed without causing the system to fail (i.e. yield equals target draft).

For multi-sequence stochastic analyses, the reliability of supply associated with a particular target draft is determined by the model based on the number of analysed sequences for which failures were recorded. The assessment of the reliability characteristics of a system is generally based on the analysis of a range of target drafts and the results are displayed in a table showing target drafts (in units of million m^3/a), together with the associated reliability of supply (as a %) and risk of failure as a recurrence interval (RI, in years).

The procedure for determining system yields involves the defining a water supply master control (yield) channel, imposing target drafts and the utilisation of tools designed for the automation of yield determination. These are discussed in the following sections.

9.1 Defining a water supply master control (yield) channel

When undertaking a yield analysis, target drafts are imposed on the water resource system using the *water supply master control channel type* (also known as the “yield channel”). Only one such channel may be defined in a particular system, in order to determine the yield of that system at a selected point. The yield may be determined based on either a historical, long- or short-term stochastic yield analysis, as discussed earlier. It should be noted that, apart from the water supply master control channel, the user may also define a power supply master control channel for the purpose of determining a system’s hydropower generation potential.

Details in this regard are provided in **Section 12.1**.

Extensive statistics are produced for the water supply master control channel in the yield analysis output results and can be used for detailed for evaluation and analysis purposes.

Table 9-1: Water supply master control channel parameters for a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken:*				
1	MNMCHN	Number of master control channels in the system (one water supply and one power supply type, as discussed in **Section 12.1.2**, or one of each)	1	*F03.DAT
If a water supply master control channel is required, parameters 2 to 7 must be defined:				
2	NCHPC	Water supply master control channel number	1	*F03.DAT
3	RNAM	Water supply master control channel name	1	*F13.DAT
4	CODE	Master control channel supply type option: water or power (W or P, must set = W)	1	*F03.DAT
5	RESUP	Upstream reservoir or node number	1	*F03.DAT
6	RESDOW	Downstream reservoir or node number	1	*F03.DAT
7	NTYP	Penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT

Conditions associated with defining water supply master control channels are summarised in the table below.

Table 9-2: Conditions for defining a water supply master control channel in a yield analysis

Condition	Associated parameter/s	Reference
At least one water supply master control channel or one power supply master control channel or one of each must be defined for the system.	MNMCHN, CODE	This section, **12.1.2**
Upstream node number cannot be zero	RESUP	This section
Water supply master control channels must be two-arc channels	NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with water supply master control channel must exist	NTYP	This section, **7.2**

9.2 Imposing target drafts

Another process that relates to the configuration of water supply master control channels is the definition of annual target requirement (or target draft) values. For each target draft specified, a separate simulation will be undertaken (historical or stochastic), with the target draft imposed on the system through the channel in question. The model allows for up to 10 target draft values to be specified for analysis in a single model run.

The user is also required to specify, for each target draft, an associated maximum system yield. Generally, this value is set equal to the corresponding target draft, which implies that the system yield can not exceed the target draft. In certain cases, however, when the system is spilling, some additional water may be available, resulting in a potential increase in yield. In cases where physical infrastructure is in place to utilise these spills, the maximum system yield may be set to a value higher than that of the target draft (depending on the capacity of the infrastructure in question). The increase in yield is referred to as "secondary yield" and provides an indication of the ability of the system to occasionally supply additional water requirements.

Finally, 12 monthly distribution factors must be defined, which are used by the model to disaggregate annual target water requirements into monthly values. Appropriate values of the monthly distribution factors are calculated externally to the model and are based on the relationship between the required flow rate for a given month and the monthly flow rate which would be obtained (from the annual target requirement specified) if the flow rate were constant over the whole year.

Table 9-3: Parameters for imposing target drafts in a yield analysis using a water supply master control channel

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken and a water supply master control channel is modelled (i.e. CODE = W, as described in **Section 9.1**):*				
1	MNYLD	Number of target drafts to be analysed	1	*F01.DAT
2	YIELD	Target draft (million m^3/a)	MNYLD	*F01.DAT
3	YLDMAX	Maximum water requirement (million m^3/a)	MNYLD	*F01.DAT
4	NCH	Water supply master control channel number (same as NCHPC, as described in **Section 9.1**)	1	*F13.DAT.
5	WATDF	Monthly target draft distribution factors	12	*F13.DAT

Table 9-4: Conditions for defining target drafts in a yield analysis

Condition	Associated parameter/s	Reference
Target water requirement ≤ maximum water requirement	YIELD, YLDMAX	This section
If option is selected to reduce number of sequences when undertaking a stochastic yield analysis (i.e. OPTFL = 1), pairs of target and maximum water requirements must be specified in descending order	YIELD, YLDMAX, OPTFL	This section and **2.4**

9.3 Automated determination of yields

The WRSM provides a useful feature whereby the interactive input from the user is reduced by allowing the model to automatically determine system yields by means of an automated search routine. This feature can be applied when undertaking both historical and stochastic yield analyses and more information in this regard is provided below.

a) Historical yield analysis

When undertaking a historical yield analysis, the model can be used to automatically determine the historical firm yield of the system. For this purpose, the user must define two target drafts, an upper value and a lower value, between which the firm yield is expected to occur. The associated parameters are shown below.

Table 9-5: Parameters for automatically determining the historical firm yield

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken and a water supply master control channel is modelled (i.e. CODE = W, as described in **Section 9.1**):*				
1	OPTFY	Option to determine historical firm yield: no or yes (0 or 1, must set = 1)	1	*F01.DAT
Related parameters and interdependencies:				
-	HISTO	Run type option: historical or stochastic (H or S, must set = H)	1	*F01.DAT
-	MNYLD	Number of target drafts to be analysed (must set = 2)	1	*F01.DAT
-	YIELD	Target draft (million m^3/a)	MNYLD = 2	*F01.DAT
-	YLDMAX	Maximum water requirement (million m^3/a)	MNYLD = 2	*F01.DAT

The following conditions apply when automatically determining the historical firm yield:

Table 9-6: Conditions for automatically determining the historical firm yield

Condition	Associated parameter/s	Reference
One pair of specified target draft and maximum water requirements must be higher than expected firm yield	YIELD, YLDMAX	This section
The other pair of specified target draft and maximum water requirements must be lower than expected firm yield	YIELD, YLDMAX	This section

b) Stochastic yield analysis

Similarly, the model provides a feature to automatically determine the stochastic yield of a system at a selected recurrence interval of failure (RI, in years). For this purpose, the user must define two target draft values, one with an RI expected to be lower and the other higher than the target RI, as shown below.

Table 9-7: Parameters for automatically determining stochastic yields

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken and a water supply master control channel is modelled (i.e. CODE = W, as described in **Section 9.1**):*				
1	OPTFY	Option to determine stochastic yield: no or yes (0 or 2, must set = 2)	1	*F01.DAT
2	TARGRI	Target recurrence interval for stochastic yield (in units of years, e.g. "50" for 1:50, "20" for 1:20, etc.)	1	*F01.DAT
Related parameters and interdependencies:				
-	HISTO	Run type option: historical or stochastic (H or S, must set = S)	1	*F01.DAT
-	MNYLD	Number of target drafts to be analysed (must set = 2)	1	*F01.DAT
-	YIELD	Target water requirement (million m^3/a)	MNYLD (= 2)	*F01.DAT
-	YLDMAX	Maximum water requirement (million m^3/a)	MNYLD (= 2)	*F01.DAT

The following conditions apply when automatically determining a stochastic yield:

Table 9-8: Conditions for automatically determining stochastic yields

Condition	Associated parameter/s	Reference
Pair of lower target draft and maximum water requirements must have a recurrence interval higher than the target recurrence interval	YIELD, YLDMAX, TARGRI	This section
Pair of higher target draft and maximum water requirements must have a recurrence interval lower than the target recurrence interval	YIELD, YLDMAX, TARGRI	This section

10. TOOLS FOR MANAGING WATER REQUIREMENTS IN A YIELD ANALYSIS

As discussed in **Section 11**, when undertaking planning analyses in the WRSM, the effect of restrictions may be modelled by applying "curtailments" to controlled water requirements in the system (modelled using water supply master control channels, as discussed in **Section 8.2.1**). Curtailments imply that the supply of water to the users in question is limited (or curtailed) when the short-term availability of water from supporting sub-systems is insufficient. Similarly, when undertaking a yield analysis, the supply of water to users in the system can be managed based using one of the following three strategies:

- Undertaking a reconciliation analysis;
- Implementing periods with fixed curtailment levels;
- Defining drought restriction rules.

These tools, however, are not as sophisticated as the allocation algorithm available when doing a planning analysis and require manual inputs and scenario analyses by the model user to achieve the desired result. Furthermore, it should be noted the, since the function of the water supply master control channel in a yield analysis is for imposing target water requirements and determining system yields, the above tools are designed for managing water requirements that are modelled in other ways. These include requirements with fixed monthly distributions (modelled using two-arc min-max channels, as discussed in **Section 8.2.2**) and time-series requirements (see **Section 8.2.3**).

A detailed description of each tool is provided in the following sections.

10.1 Reconciliation analyses

The purpose of a reconciliation analysis is to establish the extent to which the supply to a particular water use channel should be curtailed in order to achieve a situation where the resulting number of non-supply events does not violate accepted risk criteria for the channel in question (or other affected channels). The assessment is based on a scenario analysis involving a historical yield analysis and can incorporate any number of water use channels.

Each water user is classified as a particular type and the typed, each of which is subject to a unique combination of risk criteria. NOUTYP represents the number of water user types that will be considered in the analysis. The number of risk criteria levels to be analysed is defined by NOCRIT and applies to all water user types defined. RECURIN represents the acceptable risk of non-supply associated with each risk criteria level and is defined as a recurrence interval (RI, in years). For example, if the value of RECURIN is set equal to “50”, this would represent an RI of 1:50 years, which equates to an annual maximum risk of non-supply of 1/50, or 2.0 %. CRITFAC represents the portion of the total water demand allocated to each risk criteria level. A set of CRITFAC values is defined individually for each water user type in the analysis. NOCHAN is the number of water use channels that are to be included with the reconciliation analysis and the number of each channel is defined by IOCHUM. Note that only two-arc min-max and time-series requirement channel types may be included here. IOCUT is used to classify each channel in the analysis as a particular user type.

The reconciliation of each water user is undertaken on the basis of a scenario analysis. It involves a progressive decrease in the portion of the demand that is supplied from the system until a point is reached where the observed number of failures does not exceed an accepted risk criteria relating to the recurrence interval of non-supply for the channel in question. The process involved is, however, not automated and requires manual interaction from the user in order to define the number of scenarios to be undertaken and the extent to which the channel should be curtailed in each scenario. FINIT represents the portion of the water demand to be imposed on the system under each scenario. A set of FINIT values is defined for each channel.

Table 10-1: Parameters for undertaking reconciliation analyses as part of a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a reconciliation analysis is being undertaken as part of a **yield analysis**:*				
1	NOUTYP	Number of water user types defined for the reconciliation analysis	1	*F16.DAT
2	NOCRIT	Number of risk criteria levels for water users	1	*F16.DAT
3	NOITER	Number of scenarios in reconciliation analysis	1	*F16.DAT
4	RECURIN	Recurrence interval associated with each risk criteria level (number, e.g. 50 = 1:50 years, 20 = 1:20 years, etc)	NOCRIT	*F16.DAT
For each water user type (NOUTYP), parameter 6 must be defined:				
6	CRITFAC	Portion of total water requirement allocated to each risk criteria level	NOCRIT	*F16.DAT
7	NOCHAN	Number of water use channels to be included with the reconciliation analysis	1	*F16.DAT
For each water use channel (NOCHAN), parameters 8 to 10 must be defined				
8	IOCHUM	Reference to associated channel number	1	*F16.DAT

No.	Name	Description	Number of inputs	Associated data file/s
9	IOCUT	Specification of water user type (number, based on the sequential order in which water user type are defined above, ≤ NOUTYP)	1	*F16.DAT
10	FINIT	Portion of total requirement to be imposed on system, under each scenario	NOITER	*F16.DAT

The following conditions apply when undertaking a reconciliation analysis:

Table 10-2: Conditions for undertaking a reconciliation analyses as part of a yield analysis

Condition	Associated parameter/s	Reference
Sum of water requirement portions allocated to each risk criteria level must = 1.0	CRITFAC	This section
Channels included in reconciliation analysis must exist	IOCHUM, others	This section, others
Channels included in reconciliation analysis must be two-arc min-max or time-series requirement channels	IOCHUM, others	This section, **8.2.2**, **8.2.3**
Number for specifying user type must be ≤ number of user types defined	IOCUT, NOUTYP	This section

10.2 Periods with fixed curtailment levels

This feature was developed specifically for application in the yield analysis of the Komati River system to analyse short-term operating scenarios where user-defined curtailments are imposed for selected periods in the analysis.

Variable NCURP represents the number of periods for which curtailments need to be implemented. Each period applies a different allocation or multiplication factor for the channels on which the curtailments are imposed. NSMTHS is the number of the month, from the start of the analysis, which represents the beginning of each of the NCURP curtailment periods. MCCHN is the number of channels on which curtailments will be imposed and NCCHN the respective channel numbers. Any channel type may be selected and the user must ensure that it would be realistic to impose curtailments on the channels specified. Variable CURFAC represents the allocation (or multiplication) factor that is applied to change the arc flow limits by multiplying the upper and lower bounds of each arc by CURFAC.

Table 10-3: Parameters for defining periods with fixed curtailment levels in a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined for modelling fixed curtailment levels in a **yield analysis**:*				
1	NCURP	Number of periods to be modelled with fixed curtailments	1	*F15.DAT
If number of periods to be modelled with fixed curtailments (NCURP) ≥ 1, parameters 2 to 5 must be defined:				
2	NSMTHS	Month number, from the start of the analysis, that indicates the beginning of each curtailment period	NCURP	*F15.DAT
3	MCCHN	Number of water use channels to be curtailed	1	*F15.DAT
For each water use channels to be curtailed (MCCHN), parameters 4 and 5 must be defined:				
4	NCCHN	Reference to associated channel number	1	*F15.DAT
5	CURFAC	Portion of total requirement to be imposed on system for each curtailment period	NCURP	*F15.DAT

The following conditions apply when defining periods with fixed curtailment levels:

Table 10-4: Conditions for defining periods with fixed curtailment levels in a yield analysis

Condition	Associated parameter/s	Reference
Selected channels for curtailment must exist	NCCHN, others	This section, others
Any appropriate water use channel type may be selected for curtailment	NCCHN, others	This section, others

10.3 Drought restriction rules

This feature was developed specifically for application in the yield analysis of the KwaZulu-Natal Middle South Coast system to model drought restrictions imposed based on the storage levels in selected reference reservoirs.

NALO is the number of drought restriction rule sets to be applied. Each rule operates independently, although they may be based on the same reference reservoirs, and it is not advisable to define the same control channel in different drought restriction rule sets. NCALO is used to define the number of channels that are controlled through the drought restriction structure and ICALO the associated channel numbers. NRALO is the number of reference reservoirs used to calculate the reference storage volumes applied in the drought restriction calculation and IRALO the associated reservoir numbers. The storage volumes in the reference reservoirs are accumulated to obtain the total reference storage. RVALCO provides a range of storage volume values which must span the full possible range (i.e. from full to empty) of any combination of total volumes of water in the reservoirs as specified in the IRALO list. ALOF represents the allocation factors associated with each of the storage volume values defined through RVALCO. At the beginning of each month, the total reference storage in the reference reservoirs is calculated and used, together with the defined RVALCO and ALOF data pairs, to determine the appropriate allocation factor to be applied to the selected channels. Linear interpolation is used if the total reference storage value is between two RVALCO data points.

Table 10-5: Parameters for defining drought restriction rules in a yield analysis

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined for modelling drought restriction rules in a **yield analysis**:*				
1	NALO	Number of drought restriction rules defined	1	*F15.DAT
For each drought restriction rule (NALO), parameters 2 to 7 must be defined:				
2	NCALO	Number of channels to be that controlled by the drought restriction rule	1	*F15.DAT
3	ICALO	References to associated channel numbers	NCALO	*F15.DAT
4	NRALO	Number of reference reservoirs number (i.e. for calculating reference storage volumes, IRALO as described below)	1	*F15.DAT
5	IRALO	Reference reservoirs numbers	NRALO	*F15.DAT
6	RVALCO	Range of reference storage volumes (million m^3, must define 10 values)	10	*F15.DAT
7	ALOF	Portions of total requirement to be imposed on system (corresponding to RVALCO)	10	*F15.DAT

The following conditions apply when applying drought restriction rules:

Table 10-6: Conditions for applying drought restriction rules in a yield analysis

Condition	Associated parameter/s	Reference
Selected channels for curtailment must exist	NCCHN, others	This section, others
Any appropriate water use channel type may be selected for curtailment	NCCHN, others	This section, others
Reference reservoir storage levels for calculating drought restrictions must cover full possible range	RVALCO, IRALO, others	This section, **5.1**
Number of reference reservoir storage levels provided must = 10 and must be defined in descending order	RVALCO	This section

11. MANAGING WATER ALLOCATIONS IN A PLANNING ANALYSIS

As discussed in **Section 8.2.1**, the supply of water to certain users in a water resource system may be restricted during periods of drought and the implementation of restrictions is a fundamental management principal embedded in the operating rules of the major water resource systems in South Africa. Users that can be restricted in this way are modelled in the WRSM as controlled water users by means of the water supply master control channel type (see **Section 8.2.1**).

The effect of restrictions is modelled in the WRSM when undertaking planning analyses by applying "curtailments". Curtailments imply that the supply of water to certain users in a system may be limited (or curtailed) when the short-term availability of water from supporting sub-systems is insufficient. Low-priority users are curtailed first, followed by higher priority users as the situation deteriorates. In this way an uncontrolled failure of the resource is avoided and the supply of water to high priority users protected. The necessity and severity of curtailments are periodically reviewed by the model on selected decision dates (typically once or twice every year) and implemented as "allocation decisions". Allocation decisions are taken based on three main aspects and these are summarised below:

- Projected water requirements and return flows for users that are subject to curtailments (the definition of which is discussed in **Section 8.2.1**);
- The volume of water in storage in the sub-system (or sub-systems) that support the users in question and the short-term yield-reliability characteristics of those sub-systems;
- The selected water allocation control definition, which includes a user priority classification and the associated acceptable risks of non-supply, as well as a curtailment definition which controls the levels of curtailment associated with each user priority class.

The implementation of water allocation and sub-system supply definitions is discussed in the following sections.

11.1 Water allocation control definitions

11.1.1 General

General water allocation control definition parameters relate to the activation of the allocation procedure and the selection of the specific months in the year for implementing or reviewing water allocations (as discussed at the beginning of **Section 11**). Parameter PLAN provides three options for the activation of the allocation procedure, as follows:

- Option "P": The allocation procedure is enabled and curtailments may be implemented based on the short-term availability of water from supporting sub-systems. This is the default option when undertaking planning analyses with the WRSM.
- Option "N": The allocation procedure is disabled and the system is analysed simply by imposing the full defined water requirements. This option is useful for observing uncontrolled failures in supply.
- Option "M": This option is used to undertaken allocation decisions interactively (manually), and is seldom used.

Furthermore, the number of separate sets of water allocation control and sub-system supply definitions to be applied must be defined via parameter MNSTY. Each of these definitions is contained in a separate WRSM input data file, referred to as a "family"-file. The name of the file generally follows the format *FM*.DAT and contains the system identification code (RCODE as described in **Section 2.3.1**) and a unique number, e.g. "VAALFM1.DAT", "VAALFM2.DAT", etc. Typically, each file represents the situation for a unique system configuration, e.g. after the commissioning of a new reservoir, and the user must therefore also specify the point in time at which each consecutive file becomes active.

Table 11-1: General water allocation control definition parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	PLAN	Water allocation control option: P, N or M (enabled, disabled, manual)	1	*F01.DAT
2	NMTHDC	Number of decision dates per year for implementing or reviewing water allocations based on available short-term yield	1	*F01.DAT
3	MTHDEC	Months coinciding with allocation decision dates (number, with 1 = first month in list TPERD = October if standard hydrological year is used, as described in **Section 2.3**)	NMTHDC	*F01.DAT
4	MTHCLS	Allocation decision type option: main or relaxation (M or R)	NMTHDC	*F01.DAT
5	MNSTY	Number of separate sets of water allocation control and sub-system supply definitions to be applied	1	*DAM.DAT
For each set of water allocation control and sub-system supply definitions (MNSTY), parameters 6 to 8 must be defined:				
6	STYFNM	Name and directory of associated data file (*FM*.DAT, name generally contains system identification code, RCODE as described in **Section 2.3.1**, and unique number, e.g. "VAALFM1.DAT", "VAALFM2.DAT", etc.)	1	*DAM.DAT
7	NYRSTP	Hydrological year in which this set of water allocation control and sub-system supply definitions becomes active	1	*DAM.DAT
8	MTHSTP	Month number, in hydrological year, at the beginning of which this set of water allocation control and sub-system supply definitions (*FM*.DAT-file) becomes active	1	*DAM.DAT

11.1.2 User priority classification

Users in a water resource system are divided in to different classes according to the associated priority of supply. These may include classes like “High”, “Medium” and “Low” priority users, each of which has specific criteria with regard to the acceptable probability of non-supply. These probabilities are defined through parameter ISG as a recurrence interval of failure (RI) in years, e.g. = “100” for 1:100 years, “50” for 1:50 years and so on. Furthermore, various user groups may be defined, such as “Industrial”, “Domestic” or “Irrigation”, each of which has a unique priority classification profile defined through parameter CLSFAC as a portion of the total requirement (or return flow) allocated to each user priority class.

Details on the definition of user priority classification parameters are provided below and must be repeated for each set of water allocation control and sub-system supply definitions (*FM*.DAT-file) to be applied in the analysis (as described in **Section 11.1.1**). Finally, it should be noted that the current version of the model requires that the user specify one more user priority class that required for the system in question. This “dummy” class will, however, be inactive and no requirements will be assigned to it.

Table 11-2: User priority classification parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken, and must be repeated for each set of water allocation control and sub-system supply definitions to be applied (MNSTY, as described in **Section 11.1.1**):*				
1	NCLS	Number of user priority classes (e.g. = 3 for “High”, “Medium” and “Low”)	1	*FM*.DAT
2	ISG	Risk criteria of non-supply, for each user priority class (as a recurrence interval (RI) of failure in years, e.g. = 100 for 1:100, 50 for 1:50 and 20 for 1:20)	NCLS	*FM*.DAT
3	CLS	Risk criteria labels for run results output purposes (corresponding to ISG, e.g. 1/100Y, 1/50Y and 1:20Y)	NCLS	*FM*.DAT
4	NAG	Number of user groups, each with its own priority classification profile (e.g. 3 for “Industrial”, “Domestic” and “Irrigation”)	1	*FM*.DAT
For each user group defined (NAG), sets of parameter 5 must be defined:				
5	CLSFAC	Portion of total requirement (or return flow) allocated to each user priority class	NCLS	*FM*.DAT

11.1.3 Curtailment definition

When undertaking planning analyses, the severity of curtailments imposed by the WRSM is described in terms of "curtailment levels". For example, a maximum curtailment level of "3" may be applied in which case the implication of applying curtailment levels may be defined as follows:

- Curtailment level "0": No curtailments are applied;
- Curtailment level "1": The full requirement of Low-priority users is curtailed, but non of the other users;
- Curtailment level "2": The full requirement of both Low-priority and Medium-priority users is curtailed, but not the High-priority users;
- Curtailment level "3": The full requirement of all of the users in the system is curtailed.

It should be noted that curtailment levels represent a continuum of possible options up to the maximum defined, such that, if the full requirement of Low-priority users is curtailed and 41 % of the requirement of the Medium priority users this would imply an overall system curtailment level of "1.41" (i.e. 1 + 0.41).

The number of curtailment levels to be applied in system is defined with parameter NAL and the corresponding portion of the requirement supplied if each curtailment level is in force, for each of the defined user priority classes (e.g. for "High", "Medium" and "Low", as described in **Section 11.1.2**) via parameter ALLRES.

Finally it should be noted that this information must be repeated for each set of water allocation control and sub-system supply definitions (*FM*.DAT-file) to be applied in the analysis (as described in **Section 11.1.1**).

Table 11-3: Curtailment definition parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken, and must be repeated for each set of water allocation control and sub-system supply definitions to be applied (MNSTY, as described in **Section 11.1.1**):*				
1	NAL	Number of curtailment levels (starting at 0, e.g. 4 for "0", "1", "2" and "3")	1	*FM*.DAT
For each curtailment level defined (NAL), sets of parameter 2 must be defined:				
2	ALLRES	Supply proportion in each user priority class (i.e. portion of requirement supplied if given curtailment level is in force)	NCLS	*FM*.DAT

11.2 Sub-system supply definitions

11.2.1 Water requirement support definitions

Water requirement support definitions manage the way in which controlled water requirements are supplied from various supporting sub-systems. The number of support definitions provided is defined through parameter NSDMD and all controlled water requirements (i.e. all water supply master control channel, as described in **Section 8.2.1**) must be specified at least once – although a water requirement may be sub-divided and supported by more than one sub-system. The support definitions must be provided in the sequence in which the associated sub-systems are to be solved, which, in turn, depends on the order in which the sub-system short-term yield-reliability characteristics are defined (as described in **Section 11.2.2**). This, however, only applies if the sub-system support strategy option (SUPSTR) is set equal to 1. Other options are shown in the table below.

In some cases, the excess firm yield in a sub-system (i.e. which is unutilised in that sub-system) may be routed to adjoining sub-systems, to prevent spillage from the system as a whole. For this purpose, the maximum capacity of the associated inter-sub-system support channel (defined via parameter IPMPCN) can then be entered as a “requirement” on the sub-system with excess. It must be emphasised, however, that additional firm yield will only be routed in this way once the actual water requirements in the first sub-system have been met in full.

A special option for balancing among sub-systems with deficits has been developed for application in the Mgeni River system and can be enabled by setting parameter MGINT equal to 1. If this option is selected an additional balancing iteration is undertaken for the Mgeni River system among sub-systems with deficits. However, for all other systems the option must be disabled.

Finally it should be noted that the above information must be repeated for each set of water allocation control and sub-system supply definitions (*FM*.DAT-file) to be applied in the analysis (as described in **Section 11.1.1**).

Table 11-4: Water requirement support definition parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken, and must be repeated for each set of water allocation control and sub-system supply definitions to be applied (MNSTY, as described in **Section 11.1.1**):*				
1	NSDMD	Number of water requirement support definitions (may be greater than number of master control channels in the system, MNDCEN as described in **Section 8.2.1**, if a water requirement is supported by more than one sub-system	1	*FM*.DAT
For each water requirement support definition (NSDMD), parameters 2 to 11 must be defined. Note that the definitions must be provided in the sequence in which the associated sub-systems are to be solved.				
2	LDCEN	Water requirement number (assigned based on the sequential order in which it is defined, as described in **Section 8.2.1**)	1	*FM*.DAT
3	DNAM	Water requirement name (in single brackets, e.g. 'Durban')	1	*FM*.DAT
5	RAG	User group to which water requirement belongs, e.g. "Industrial" (number assigned based on the sequential order in which it is defined, as described in **Section 8.2.1**)	1	*FM*.DAT
6	NSUPG	Number of support sub-systems that may be progressively called on to supply shortfalls to the water requirement (≥ 1)	1	*FM*.DAT
7	NSSDMD	Primary support sub-system (number, assigned based on the sequential order in which sub-system short-term yield-reliability characteristics are defined, as described in **Section 11.2.2**)	1	*FM*.DAT
8	ISG1	Primary support sub-system (same as NSSDMD above)	1	*FM*.DAT
9	IAS1	Primary support channel number, for routing flows from the primary support sub-system to the water requirement	1	*FM*.DAT
10	ISG	Other support sub-systems (number, listed in the order that they may be progressively called on to supply shortfalls to the water requirement)	NSUPG – 1	*FM*.DAT
For each of the other support sub-systems (ISG(I)), parameter 11 must be defined:				
11	IAS	Support channel numbers for sequential routing of flows between sub-systems (5 values must be defined, with 0-values if less than 5 channels)	5	*FM*.DAT
12	NSS	Number of sub-systems for which short-term yield-reliability characteristics are defined	1	*FM*.DAT
For each sub-systems which short-term yield-reliability characteristics (NSS), parameters 13 to 15 must be defined:				
13	IS	Sub-system number (assigned based on the sequential order in which they are defined)	1	*FM*.DAT
14	SSDCH	Non-firm yield support routing channel numbers (4 values must be defined, with 0-values if less than 4 channels)	4	*FM*.DAT
15	SSDCH5	Non-firm yield support routing option: 0 or 1 (flow in each channel up to the upper transfer limit, QSUPM as described in **Section 11.2.3**, or according to supply proportion in each user priority class, ALLRES as described in **Section 11.1.3**	1	*FM*.DAT
16	SUPSTR	Sub-system support strategy option: 1, 2, 3, 4 or 5	1	*FM*.DAT
If the selected sub-system support strategy option ≥ 2, parameters 17 to 22 must be defined:				
17	NFIXP	Number of support sub-systems to be solved in a fixed position (note: these sub-system will always be solved first)	1	*FM*.DAT

No.	Name	Description	Number of inputs	Associated data file/s
For each of the support sub-systems to be solved in a fixed position (NFIXP), parameters 18 and 19 must be defined:				
18	IFPS(1)	Support sub-system number (assigned based on the sequential order in which they are defined)	1	*FM*.DAT
19	IFPS(2)	Fixed position in which support sub-system should be solved (number, ≤ NSS, as described above)	1	*FM*.DAT
20	NSOR	Number of support sub-systems to be solved in a specific sequential order	1	*FM*.DAT
For each of the support sub-systems to be solved specific sequential order (NSOR), parameters 21 and 22 must be defined:				
21	ISPOR(1)	Support sub-system number (assigned based on the sequential order in which they are defined)	1	*FM*.DAT
22	ISPOR(2)	Support sub-system that must be solved after ISPOR(1) above	1	*FM*.DAT
23	NPMPSS	Number of inter-sub-system support channels with control based on excess or deficit in particular sub-systems	1	*FM*.DAT
For each controlled inter-sub-system support channel (NPMPSS), parameters 24 and 27 must be defined:				
24	IPMPCN	Inter-sub-system support channel number for routing excess firm yield	1	*FM*.DAT
25	NPMPSU	Number of sub-systems controlling support channel	1	*FM*.DAT
For each sub-systems controlling support channel (NPMPSU), parameters 26 and 27 must be defined in pairs:				
26	IPMPSN	Support sub-system number (assigned based on the sequential order in which they are defined)	1	*FM*.DAT
27	FPMP	Factor defining the level of influence of the support sub-system	1	*FM*.DAT
28	MGINT	Special option for balancing among sub-systems with deficits in the Mgeni River system: 0 or 1 (disabled or enabled)	1	*FM*.DAT

11.2.2 Short-term yield-reliability characteristics

Sets of short-term yield-reliability characteristics must be provided for each sub-system which supports controlled water requirements (i.e. water supply master control channels, as described in **Section 8.2.1**, defined through parameter NSS) and must be provided for each water allocation decision date per year (NSM as shown below and NMTHDC as described in **Section 11.1.1**), as well as for each of the sub-system starting storage volumes (NSH).

Generally, six sub-system starting storage volumes are used, calculated as 100 %, 80 %, 60 %, 40 %, 20 % and 10 % of the total live storage of reservoirs located inside the sub-system in question. The system network numbers of the reservoirs are defined through parameter NRBS. At each decision date, the storage volume of each sub-system is evaluated and the appropriate set of characteristics selected for calculating the sub-system's short-term yield. If none of the sets provided corresponding exactly to the storage volume in question, the model derives intermediate curves, at runtime, by interpolation.

For each starting storage volume a set of NSD short-term yield-reliability curves are with a target draft (YDD) and four coefficients, a, b, c and d, that describe the shape of the corresponding base yield line using a third-order polynomial equation (CDD). Values for a, b, c and d are obtained from separate short-term yield analysis (as described in **Section 14.4.2**) and summarised in *.COF output file. Finally, it should be noted that target drafts (together with their associated curve coefficients) must always be defined in ascending order.

Finally, the above information must be repeated for each set of water allocation control and sub-system supply definitions (*FM*.DAT-file) to be applied in the analysis (as described in **Section 11.1.1**).

Table 11-5: Short-term yield-reliability characteristic parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken, and must be repeated for each set of water allocation control and sub-system supply definitions to be applied (MNSTY, as described in **Section 11.1.1**):*				
1	NYR	Number of years analysed to derive short-term yield reliability characteristics	1	*FM*.DAT
2	NSS	Number of sub-systems for which short-term yield-reliability characteristics are defined (same as NSS as described in **Section 11.2.1**)	1	*FM*.DAT
3	NSM	Number of decision dates per year (for implementing or reviewing water allocations) for which separate sets of short-term yield-reliability characteristics are defined (must correspond to NMTHDC, as described in **Section 11.1.1**)	1	*FM*.DAT
4	NDD	Selection of decision date number (i.e. 1, 2,… or NSM) to be applied in each month of the hydrological year (determines which set of short-term yield-reliability characteristics will be applied, only defined if NSM ≥ 1)	12	*FM*.DAT
5	NSH	Number of sub-system starting storage volumes for which separate sets of short-term yield-reliability characteristics are defined (generally = 6, for 100 %, 80 %, 60 %, 40 %, 20 % and 10 %)	1	*FM*.DAT
6	NSD	Number of target drafts for which short-term yield-reliability characteristics are defined under each set	1	*FM*.DAT
For each sub-system (NSS) as well as for each decision dates per year (NSM) for which a separate set of short-term yield-reliability characteristics is defined, parameters 7 to 23 must be defined. Note that the definitions must be provided in the sequence in which the sub-systems are to be solved.				
7	SSNAME	Sub-system name (generally also contains reference to associated month, e.g. *MAY, *JAN, etc.)	1	*FM*.DAT
8	NSSG	Number of the sub-system the yield characteristics of which are subtracted from those of above sub-system, SSNAME (assigned based on the sequential order in which they are defined)	1	*FM*.DAT

No.	Name	Description	Number of inputs	Associated data file/s
9	NSSP	Number of the sub-system that supports above sub-system, SSNAME (assigned based on the sequential order in which they are defined)	1	*FM*.DAT
10	NCHSSP	Support channel number for routing of flows from sub-system NSSP to SSNAME	1	*FM*.DAT
11	FIRM	Short-term yield for sub-system at a recurrence interval (RI) of 1:200 years and for a sub-system starting storage volume = 100 % (million m^3/a)	1	*FM*.DAT
12	FYLT	Long-term yield for sub-system at an RI of 1:200 years (million m^3/a)	1	*FM*.DAT
13	ANN83	Lowest annual volume of natural incremental hydrology inflows to sub-system (million m^3)	1	*FM*.DAT
14	SSCYR	Hydrological year in which this set of short term yield-reliability characteristics becomes active	1	*FM*.DAT
15	SSCMTH	Month number, in hydrological year, at the beginning of which this set of short term yield-reliability characteristics becomes active	1	*FM*.DAT
16	SSRYR	Hydrological year in which this set of short term yield-reliability characteristics becomes inactive (note: this may be preceded by the date on which another complete set of water allocation control and sub-system supply definitions becomes active, NYRSTP as described in **Section 11.1.1**)	1	*FM*.DAT
17	SSRMTH	Month number, in hydrological year, at the end of which this set of short term yield-reliability characteristics becomes inactive	1	*FM*.DAT
18	NFLG	Option for selecting type of yield that may be allocated from this sub-system: firm of non-firm ("FIRM" or "NON-FIRM")	1	*FM*.DAT
For each sub-system starting storage volume for which a separate set of short-term yield-reliability characteristics is defined (NSH), parameters 19 to 23 must be defined:				
19	FAMFT	Sub-system starting storage volume (fraction of live full supply volume, e.g. = 1.00 for 100 %, 0.80 for 80 %, etc.)	1	*FM*.DAT
20	IP	Decision date number (i.e. 1, 2,… or NSM) associated with this set of short-term yield-reliability characteristics data set (corresponding to NDD described earlier, data sets must be defined in chronological order)	1	*FM*.DAT
For each target draft for which short-term yield-reliability characteristics are defined (NSD), parameters 21 to 23 must be defined:				
21	YDD	Target draft (million m^3/a, must be defined in ascending order)	1	*FM*.DAT
22	CDD	Coefficients describing the base yield line using a third-order polynomial equation (a, b, c and d, as obtained from separate short-term yield analysis as described in **Section 14.4.2**)	4	*FM*.DAT
23	PDD	Assurance of supply associated with the break point on the base yield line (as a proportion, e.g. 0.95 for 95 %)	1	*FM*.DAT
For each sub-system for which a separate set of short-term yield-reliability characteristics is defined, parameters 24 and 25 must also be defined:				
24	NB	Sub-system number (assigned based on the sequential order in which they are defined)	1	*FM*.DAT

No.	Name	Description	Number of inputs	Associated data file/s
25	NRBS	Node numbers of reservoirs used for calculating sub-system starting storage volumes, FAMFT described earlier (20 values must be defined, with 0-values if less than 20 reservoirs)	20	*FM*.DAT

11.2.3 Inter-sub-system support

The allocation procedure can also be used directly for determining inter-basin support through channels defined with parameters MNIBC and IBCN. The upper transfer limit for each support channel is defined with QMIBC. Furthermore, since inter-sub-system support is determined based on the allocation procedure, appropriate support volumes must be provided through parameter D for each month at the beginning of the analysis prior to the first major allocation decision date (as described in **Section 11.1.1**). If the first month of the analysis coincides with a major decision date, however, such information is not required.

Table 11-6: Inter-sub-system support channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	MNIBC	Number of inter-sub-system support channels in the system	1	*F01.DAT
For each inter-sub-system support channels in the system (MNIBC), parameters 2 to 6 must be defined:				
2	IBCN	Inter-sub-system support channel number	1	*F01.DAT
3	QMIBC (QSUPM)	Upper transfer limit of inter-sub-system support channel (million m^3/a)	1	*F01.DAT
4	ASSDN	Selection of controlled water requirement with applicable monthly distribution factors (number, assigned based on the sequential order in which water requirements are defined, as described in **Section 8.2.1**, set = 0 if constant distribution	1	*F01.DAT
5	NCH	Inter-sub-system support channel number (same as IBCN above)	1	*HST.DAT
6	D	Monthly inter-sub-system support prior to first water allocation decision month, as described in **Section 11.1.1** (m^3/s; M = number of values required = number of months from analysis start month, MONST as described in **Section 2.3**, to first major allocation decision date, defined via parameters NMTHDC, MTHDEC and MTHCLS as described in **Section 11.1.1**)	M	*HST.DAT

12. HYDROPOWER MODELLING

This section describes the processes involved with modelling hydropower in the WRSM, firstly to determine the hydropower generation potential of a water resource system by undertaking a yield analysis, and then the modelling of hydropower in planning analyses.

12.1 Determining system hydropower generation potential

As explained in **Section 1.3**, the WRSM can be used for undertaking yield analyses to assessing the yield of a water resource system at a fixed selected development level and set of system operating rules. System yield can be expressed either as its long and short-term water resource capability at a particular point (as discussed in **Section 9**), or in terms of its hydropower generation potential.

The procedure for determining the hydropower generation potential of a system involves the creation of hydropower plants, defining a power supply master control channel and imposing target hydropower requirements. These are discussed in the following sections.

12.1.1 Creating hydropower plants

The characteristics of a hydropower plant are modelled in the WRSM using the special three-arc hydropower channel. The purpose is to estimate the amount of hydropower generated, based on the flow through the plant by releases from a source reservoir.

Hydropower plants consist of two components, the turbine and the generator. The turbine is designed to operate most efficiently at a design net head, in metres, with an associated maximum generation capacity, in megawatts, which occurs at the maximum flow rate. Also, a minimum net head and a maximum net head must be defined, in metres, which represent the range of permissible operating heads for the turbine. Generally these values will be in the order of 0.65 and 1.25 times the design net head, respectively.

The turbine efficiency of the power plant varies according to the net head and flow of water passing through the plant. Typically, the maximum plant efficiency is in the region of 90 % and this drops as the net head and flow diverge from the optimum values. This relationship is described by a table of plant efficiency factors and net head factors, which are provided in dimensionless form. Efficiency factors represent the efficiency of the plant, as a proportion of the combined efficiency at design head and maximum flow (discussed below), while the corresponding net head values are expressed as a proportion of the design net head.

There is, however, a physical limitation for the flow allowed to pass through the turbine at any given head, which is controlled by the maximum capacity of the hydropower generator, in units of megawatts. Also, the maximum capacity of the turbine, at the design head and maximum flow, must be defined in megawatts. The resulting combined plant efficiency, which represents the combination of the turbine and generator at design head and maximum flow, must be specified as a proportion.

The net head available for power generation at a plant depends on the difference between the water surface elevation of the reservoir and the water surface elevation of the tail-water. However, in many cases the tail-water elevation is not stationary and may depend on either the discharge through the plant, or on the water level in a downstream reservoir. In both cases, the tail-water level will obviously influence the power generating ability of the plant and must be taken into account. For this purpose, a relationship may be defined in a table between the tail-water elevation and either the plant discharge or the downstream reservoir elevation, depending on the option which is selected.

The head loss through the hydropower plant is defined as a constant value, based on the assumption that a plant will be operated at or near its design net head and maximum flow. The reason is that, in most cases, a power plant would be operated at full capacity some of the time rather than at a portion of its capacity all of the time.

The magnitude of hydropower releases through a plant can be controlled in the model by means of three separate mechanisms. These are: water requirements that are located downstream of the hydropower channel, target power requirements as defined for a power master control channel (as discussed in **Section 12.1.2** and **12.1.3**), or a range of specified minimum energy generation requirements and associated hydropower channel releases. In case of the latter, the relationship between minimum monthly power generation requirements (in units of megawatt-continuous) and minimum monthly hydropower channel releases (in units of m^3/s) must be defined, as shown in the table below.

For every hydropower channel information is also required on which other hydropower channels, if any, are located downstream of the channel and the associated source reservoir in question. This enables the model to make decisions concerning the power generation potential of a unit of water in the reservoir. Also, for every hydropower channel a corresponding spill channel must be defined. For this purpose, the general flow channel type (as discussed in **Section 8.1**) may be used.

Finally, it should be noted that hydropower plants can also be modelled in planning analyses using hydropower channels as shown in the table below. More information in this regard is provided in **Section 12.2**.

Table 12-1: Hydropower channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
1	MNPOW	Number of hydropower channels in the system	1	*F03.DAT
For each hydropower channel in the system (MNPOW), parameters 2 to 35 must be defined:				
2	NPOWCH	Hydropower channel number	1	*F03.DAT
3	RNAM	Hydropower channel name	1	*F08.DAT
4	RESUP	Upstream reservoir or node number	1	*F03.DAT
5	RESDOW	Downstream reservoir or node number	1	*F03.DAT
6	NTYPP	Penalty structure type associated with hydropower channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
7	NSPCH	Associated spill channel number	1	*F03.DAT
8	NRUP	Upstream node number for spill channel	1	*F03.DAT
9	NRDW	Downstream node number for spill channel	1	*F03.DAT
10	NTYPS	Penalty structure type associated with spill channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
11	NUM	Number of downstream hydropower channels along path of normal routing	1	*F03.DAT
12	POWDOW	Channel numbers of downstream hydropower channels along path of normal routing	NUM	*F03.DAT
13	NCH	Hydropower channel number (same as NPOWCH above	1	*F08.DAT
14	PFIRME	Minimum monthly power generation requirements (megawatt-continuous)	12	*F08.DAT
15	PMINQ	Minimum monthly hydropower channel releases (m^3/s, corresponding to PFIRME)	12	*F08.DAT
16	NCH	Hydropower channel number (same as NPOWCH above)	1	*F07.DAT
17	RNAM	Name of associated hydropower plant	1	*F07.DAT
18	EFST	Hydropower plant status option, does not or does exist (0 or 1)	1	*F07.DAT
19	CAP	Maximum capacity of hydropower generator (megawatt)	1	*F07.DAT
20	RCAP	Maximum capacity of turbine at design head and maximum flow (megawatt).	1	*F07.DAT
21	EFF	Combined efficiency at design head and maximum flow (proportion).	1	*F07.DAT
22	KHL	Head loss through hydropower plant (m)	1	*F07.DAT
23	HD	Design net head (m)	1	*F07.DAT
24	HMX	Maximum net head m)	1	*F07.DAT

No.	Name	Description	Number of inputs	Associated data file/s
25	HMN	Minimum net head (m)	1	*F07.DAT
26	HMNR	Level in reservoir (m) below which hydropower generation is discontinued	1	*F07.DAT
27	NEPTS	Number of points in the efficiency vs. net head factor relationship	1	*F07.DAT
28	EF	Range of efficiency factors (proportion)	NEPTS	*F07.DAT
29	HF	Net head factors (corresponding to EF)	NEPTS	*F07.DAT
30	NTWT	Tail-water function type option: 1 or 2	1	*F07.DAT
31	NPTS	Number of points in tail-water function,	1	*F07.DAT
If tail-water function type option (NTWT) = 1, parameters 29 and 30 must be defined:				
32	F	Range of discharges (m^3/s)	NPTS	*F07.DAT
33	TWL	Tail-water elevations (m, corresponding to F above)	NPTS	*F07.DAT
If tail-water function type option (NTWT) = 2, parameters 31 and 32 must be defined:				
34	F	Range of downstream levels (m)	NPTS	*F07.DAT
35	TWL	Tail-water elevations (m, corresponding to F above)	NPTS	*F07.DAT
*The following parameters are also defined for each reservoir and node with incremental hydrology inflows in the system (RESNUM), as described in **Sections 5.1** and **6**:*				
-	NUM	Number of hydropower channels downstream of reservoir or node, along path of normal routing	1	*F02.DAT
-	PDR	Channel numbers of downstream hydropower channels, along path of normal routing	NUM	*F02.DAT

Conditions associated with defining hydropower channels are summarised in the table below.

Table 12-2: Conditions for defining hydropower channels

Condition	Associated parameter/s	Reference
Hydropower channels must be three-arc channels	NTYPP, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with hydropower channel must exist	NTYPP, NTYP	This section, **7.2**
Associated spill channel must be one-arc channel	NTYPS, NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with spill channel must exist	NTYPS, NTYP	This section, **7.2**
Minimum net head ≤ design net head ≤ maximum net head	HMN, HD, HMX	This section

12.1.2 Defining a power supply master control channel

When undertaking a yield analysis, target hydropower requirements are imposed on the water resource system using the *power supply master control channel type*. Only one such channel may be defined in a particular system and is used as a mechanism controlling the magnitude of releases through a hydropower plant (as discussed in **Section 12.1.1**). It should be noted that, apart from the power supply master control channel, the user may also define a water supply master control channel for the purpose of determining a system's water resource capability (or *yield*) and details in this regard are provided in **Section 9**.

Extensive statistics are produced for the power supply master control channel in the yield analysis output results and can be used for detailed for evaluation and analysis purposes.

Table 12-3: Power supply master control channel parameters for yield analyses

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken:*				
1	MNMCHN	Number of master control channels in the system (one power supply and one water supply type, as discussed in **Section 9.1**, or one of each)	1	*F03.DAT
If a power supply master control channel is required, parameters 2 to 7 must be defined:				
2	NCHPC	Power supply master control channel number	1	*F03.DAT
3	RNAM	Power supply master control channel name	1	*F13.DAT
4	CODE	Master control channel supply type option: water or power (W or P, must set = P)	1	*F03.DAT
5	RESUP	Upstream reservoir or node number	1	*F03.DAT
6	RESDOW	Downstream reservoir or node number	1	*F03.DAT
7	NTYP	Penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT

Conditions associated with defining power supply master control channels are summarised in the table below.

Table 12-4: Conditions for defining power supply master control channels

Condition	Associated parameter/s	Reference
At least one master control channel must be defined for system, but only one of power supply type	MNMCHN, CODE	This section
Upstream node number cannot be zero	RESUP	This section
Power supply master control channels must be two-arc channels	NTYP, NCHARC	This section, **7.2**
Penalty structure type associated with power supply master control channel must exist	NTYP	This section, **7.2**

12.1.3 Imposing target hydropower requirements

The WRSM allows for up to 10 target hydropower requirement values to be specified for the analysis in a single run. If multiple target drafts are imposed, the model undertakes a separate analysis for each of the target requirements, in turn, and results are produced for each, enabling comparison of the associated results.

The monthly distribution associated with the target hydropower requirements must be defined and are used by the model to disaggregate annual requirements into monthly values. These are defined in terms of 12 monthly distribution factors which are calculated in a similar way to those for water supply master control channels (as discussed in **Section 9.2**). The resulting monthly hydropower requirements are calculated in units of megawatt -continuous.

Table 12-5: Parameters for imposing target hydropower requirements with power supply master control channels

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **yield analysis** is being undertaken and a power supply master control channel is modelled (i.e. CODE = P, as described in **Section 12.1.2**):*				
1	MNYLD	Number of target hydropower requirements to be analysed	1	*F01.DAT
2	POWER	Target hydropower requirement (megawatt-continuous)	MNYLD	*F01.DAT
3	NCH	Power supply master control channel number (same as NCHPC, as described in **Section 12.1.2**)	1	*F13.DAT.
4	ENERDF	Monthly hydropower requirement distribution factors	12	*F13.DAT

Conditions associated with defining target hydropower requirements are summarised in the table below.

Table 12-6: Conditions for defining target hydropower requirements

Condition	Associated parameter/s	Reference
Sum of monthly power requirement distribution factors must = 12	ENERDF	This section

12.2 Modelling hydropower in a planning analysis

Two alternative analysis approaches are available in the WRSM for modelling hydropower generation in a planning analysis. These are the *hydropower requirement-driven* and *allocation-driven* approaches, as discussed below.

a) Hydropower requirement-driven hydropower modelling

The first approach involves the creation of a hydropower plant and using the mechanism for controlling the magnitude of hydropower releases through the plant which involves defining a range of specified minimum energy generation requirements and associated hydropower channel releases (as described in **Section 12.1.1** for yield analyses).

Since hydropower generation depends on both flow and head, an iterative analysis process is followed as briefly discussed below. The requirement is disaggregated from an annual average energy demand (expressed as megawatt-continuous) into monthly average energy requirements. The analysis of each month starts without imposing a requirement on the hydropower plant. The network is solved and the energy generated by means of the operating rule as well as other water requirements are added together and compared with the monthly energy requirement. During this first iteration, minimum energy requirements may have been imposed on specific hydropower plants. If the energy generated is larger than or equal to the imposed requirement, the analysis of the month is complete. For energy generation lower than the requirement, the hydropower channel is used to increase the flow through the plant by imposing a water requirement on the system. The water requirement is then adjusted iteratively until the energy generated equals the requirement.

Finally, it is important to note that modelling hydropower in this way means that the energy requirement is not controlled based on the allocation procedure and can therefore not be curtailed in the same way as normal controlled water requirements (as discussed in **Section 8.2.1**).

b) Allocation-driven hydropower modelling

This analysis method was incorporated into the WRSM for the purpose of simulate the dual user allocation procedure implemented in the Orange River System and applies the basic approach that the water users in a water resource system have priority over hydropower generation. The basic analysis mechanism is that water is allocated annually for power generation based on an allocation principle (discussed later) and each set of twelve months (from one decision date to the next) is analysed iteratively until all the allocated water has been used. This is achieved by imposing an annual hydropower requirement on the system, which is adjusted during the iteration process in order to only release the allocated annual volume. Opposing seasonal distributions of releases for hydropower and, say, irrigation water requirements are also taken into consideration. The additional allocated water is used to fill shortfalls in the opposing distributions.

Two methods are available to calculate the annual allocation for power generation. The first method uses the allocation algorithm (as discussed in **Section 11**) to calculate the excess water available based on the short-term availability of water from supporting sub-systems. The user specifies at what reliability level (expressed as the recurrence interval, RI of non-supply, in years) the excess should be calculated. This flexibility allows for an operating RI to be evaluated and selected to satisfy water supply and hydropower reliability requirements. It is important to note that with this method, both the reservoir level and water requirements are included in the calculation of the allocated volumes. The second method applies a user-defined relationship between sub-system starting storage volumes and the volumes of excess available for allocation to hydropower generation. This method is more flexible than the first in that any relationship may be defined, but has the disadvantage that the requirement does not influence the allocation calculation. This limitation can, however, be overcome by performing scenario analyses to evaluate the relationship for different requirement levels.

It should be noted that both the abovementioned two methods for undertaking allocation-driven hydropower modelling do not directly integrate the reliability requirements of hydropower and water into the allocation procedure. Any dual user system, therefore has to be analysed using scenario analyses to ensure that the selected rules balance all requirements of water and hydropower generation.

Finally, allocation-driven hydropower modelling is undertaken in the WRSM by defining a *hydropower allocation master control channel* as a means of imposing an annual hydropower requirement on the system (as discussed earlier), as well as range of additional parameters, as shown in the tables below. It should be noted that only one such master control may be defined in the system and that master control channel type option (CODE) must be set to “H”.

Table 12-7: Hydropower allocation master control channel parameters for planning analyses

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken with allocation-driven hydropower modelling:*				
1	HYDSIM	Hydropower analysis option, yes or no (Y or N, must set = Y)	1	*F01.DAT
2	MTHHDC	Indicator of which water allocation decision date is the month when the hydropower allocation decision is also taken (define values for each of the NMTHDC decision months, as described in **Section 11.1.1**, with H for selected hydropower allocation decision and any other alphanumerical character for other months)	NMTHDC	*F01.DAT
3	MNMCHN	Number of master control channels in the system (including both water supply, as described in **Section 8.2.1** and one for hydropower allocation)	1	*F03.DAT
If a hydropower allocation master control channel is included in the system, parameters 4 to 14 must be defined:				
4	NCHMC	Hydropower allocation master control channel number	1	*F03.DAT
5	RNAM	Hydropower allocation master control channel name	1	*F13.DAT
6	CODE (MASCHC)	Master control channel type option: water or hydropower (W or H, must set = H)	1	*F03.DAT
7	RESUP	Upstream reservoir or node number	1	*F03.DAT
8	RESDOW	Downstream reservoir or node number	1	*F03.DAT
9	NTYP	Penalty structure type associated with channel (number, corresponding to NTYP, as described in **Section 7.2**)	1	*F03.DAT
10	NCH	Hydropower allocation master control channel number (same as NCHMC above)	1	*F13.DAT
11	NPAT	Number of alternative patterns of monthly target hydropower requirement distribution factors (assumed = 1.0 if undefined)	1	*F13.DAT
For each alternative pattern of monthly target hydropower requirement distribution factors (NPAT), parameter 12 must be defined:				
12	ENERDF	Monthly target hydropower requirement distribution factors	12	*F13.DAT
13	NCH	Hydropower allocation master control channel number (same as NCHMC above)	1	*HST.DAT
14	D	Monthly hydropower requirements prior to first hydropower allocation decision month (M = number of values required = number of months from analysis start month, MONST as described in **Section 2.3**, to MTHHDC = H, as described above)	M	*HST.DAT

Table 12-8: Parameters for controlling the allocation of excess for hydropower generation

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken with allocation-driven hydropower modelling:*				
1	NHYDF	Number of separate sets of hydropower allocation definitions to be applied	1	*DAM.DAT
For each set of hydropower allocation definitions (NHYDF), parameters 2 to 20 must be defined:				

No.	Name	Description	Number of inputs	Associated data file/s
2	HYDFNM	Name and directory of associated data file (*HYD*.DAT, name generally contains system identification code, RCODE as described in **Section 2.3.1**, and unique number, e.g. "VAALHYD1.DAT", "VAALHYD2.DAT", etc.)	1	*DAM.DAT
3	HFYR	Hydrological year in which this set of hydropower allocation definitions becomes active	1	*DAM.DAT
4	HNSUB	Number of sub-systems from which excess may be allocated for hydropower generation	1	*HYD.DAT
5	HSUBI	Sub-system numbers (assigned based on the sequential order in which sub-system short-term yield-reliability characteristics are defined, as described in **Section 11.2.2**)	HNSUB	*HYD.DAT
6	HPREX	Recurrence interval (RI) at which excess short-term yield for allocation is calculated (number, e.g. = 200 for 1:200 years, 100 for 1:100 years, etc.)	1	*HYD.DAT
7	HNCCH	Number of hydropower constraint channels	1	*HYD.DAT
For each hydropower constraint channel (HNCCH), parameters 8 to 14 must be defined:				
8	HCCI	Hydropower constraint channel number	1	*HYD.DAT
9	HCPSCN	Channel number of spill channel parallel to hydropower constraint channel (HCCI as described above)	1	*HYD.DAT
10	NCCH2	Channel number of a second channel that can be controlled in the same way as the hydropower constraint channel, HNCCH	1	*HYD.DAT
11	NREFR	Reference reservoir number (i.e. for calculating reference water levels, HRLEV as described below)	1	*HYD.DAT
12	NCNPN	Number of points in the reference reservoir water level vs. channel flow relationship (defined to cover range of possible water levels)	1	*HYD.DAT
13	HRLEV	Reference reservoir water levels (m above MSL)	NCNPN	*HYD.DAT
14	HQPER	Channel flows, as a % of defined flow constraints (corresponding to HRLEV)	NCNPN	*HYD.DAT
15	HNQPP	Number of points in the flow through hydropower plant turbines vs. hydropower energy requirement relationship (used to impose the initial energy requirement at the beginning of the iterative search routine)	1	*HYD.DAT
16	HPFLW	Flows through hydropower plant turbines (m^3/s)	HNQPP	*HYD.DAT
17	HPENR	Hydropower energy requirements (megawatt-continuous, corresponding to HPFLW)	HNQPP	*HYD.DAT
18	HNEXC	Number of points in the sub-system starting storage volume vs. volume of excess available for allocation to hydropower generation relationship	1	*HYD.DAT
19	HPSTR	Sub-system starting storage volumes (million m^3)	HNEXC	*HYD.DAT
20	HPEXC	Annual volumes of excess available for allocation to hydropower generation (million m^3/a, corresponding to HPSTR)	HNEXC	*HYD.DAT

Table 12-9: Hydropower allocation control channel parameters

No.	Name	Description	Number of inputs	Associated data file/s
The parameters in this table must be defined if a ***planning analysis*** *is being undertaken with allocation-driven hydropower modelling:*				
1	ACSIM	Hydropower allocation control channel option, yes or no (Y or N)	1	*F01.DAT
If the hydropower allocation control channel option (ACSIM) = Y, parameters 2 to 7 must be defined:				
2	ACFNM	Name and directory of hydropower allocation control channel data file (*ALO.DAT, name generally contains system identification code, RCODE as described in **Section 2.3.1**, e.g. “VAALALO.DAT”)	1	*DAM.DAT
3	ACREX	Recurrence interval (RI) at which excess short-term yield for allocation is calculated (number, e.g. = 200 for 1:200 years, 100 for 1:100 years, etc.)	1	*ALO.DAT
4	NACS	Number of hydropower allocation control channel definitions to be applied	1	*ALO.DAT
For each hydropower allocation control channel definition (NACS), parameters 5 to 7 must be defined:				
5	ACNSUB	Number of sub-systems from which excess may be allocated for hydropower generation	1	*ALO.DAT
6	ACSUBI	Sub-system numbers (assigned based on the sequential order in which sub-system short-term yield-reliability characteristics are defined, as described in **Section 11.2.2**)	ACNSUB	*ALO.DAT
7	ACCONC	Reference to channel defined for conveying flows from the support sub-system to the requirement (must be a one-arc min-max channel, as described in **Section 8.3.1**)		*ALO.DAT

Conditions associated with defining hydropower allocation control channel are summarised in the table below.

Table 12-10: Conditions for defining hydropower allocation control channel

Condition	Associated parameter/s	Reference
Channel for conveying flows from the support sub-system to the requirement must be defined externally to the Hydropower sub-model, by means of one-arc multi-purpose min-max channel	ACCONC, others	This section, **8.3.1**

13. UNDERTAKING ECONOMIC ANALYSES

When undertaking a planning analysis, the WRSM provides additional features for undertaking economic analyses based on simulated information such as pumping energy, capital costs of new infrastructure and the dis-benefit of not supplying water requirements. Economic parameters for economic and tariff calculations must be provided for the following system elements when undertaking a planning analysis:

- Reservoirs (as described in **Section 5**);
- Water supply master control channels (as described in **Section 8.2.1**);
- Pumping channels (as described in **Section 8.3.6**);
- Other time-controlled channels in the system (as described in **Section 7.4 (d)**);
- Reclamation plants (as described in **Section 8.3.9**).

Economic analysis parameters for the various system elements are shown below. In this regard it should be noted that, even if an economic analysis is not being undertaken, these parameters must still be populated with dummy values.

Table 13-1: Economic analysis parameters

No.	Name	Description	Number of inputs	Associated data file/s
*The parameters in this table must be defined if a **planning analysis** is being undertaken:*				
1	NPPY	Number of time periods per year, used in the economic analysis	1	*F01.DAT
2	YRSTRT	Start year for the economic analysis	1	*F01.DAT
3	NRATES	Number of discount rates to be applied in cost calculation scenarios	1	*F01.DAT
4	DRATE	Discount rates for cost calculation scenarios	NRATES	*F01.DAT
*For each reservoir in the system (MNDAMS, as described in **Section 5.1**), parameters 5 to 9 must be defined:*				
5	DLIFE	Economic life of reservoir (i.e. number of years over which cost is amortised)	1	*DAM.DAT
6	DAMCC	Capital cost of reservoir (R million)	1	*DAM.DAT
7	DFOAM	Fixed operating and maintenance costs of reservoir (R million)	1	*DAM.DAT
8	NYCD	Number of years in construction schedule for reservoir	1	*DAM.DAT
9	CSDAM	Capital cost schedule (as a portion of capital cost in each year of construction)	NYCD	*DAM.DAT
*For each water supply master control channel in the system (MNDCEN, as described in **Section 8.2.1**, parameters 10 to 15 must be defined:*				
10	DCHN	Water supply master control channel number (as defined in **Section 7.4 (a)**)	1	*DBF.DAT
11	DFC1 (R1)	Coefficients A of a third-order equation defining the dis-benefit of the cost of non-supply	1	*DBF.DAT

No.	Name	Description	Number of inputs	Associated data file/s
12	DFC2 (R2)	Coefficients B of a third-order equation defining the dis-benefit of the cost of non-supply	1	*DBF.DAT
13	DFC3 (R3)	Coefficients C of a third-order equation defining the dis-benefit of the cost of non-supply	1	*DBF.DAT
14	DFC4 (R4)	Coefficients D of a third-order equation defining the dis-benefit of the cost of non-supply	1	*DBF.DAT
15	DERATE	Annual dis-benefit function escalation rates, to be applied in each of the years for which time-related control data are provided for water supply master control channels (MNYP as described in **Section 7.4 (a)**)	MNYP	*DBF.DAT
16	MNYP	Number of years with tariff information for water supply master control channels	1	*TAR.DAT
*For each water supply master control channel in the system (MNDCEN, as described in **Section 8.2.1**), parameters 17 to 19 must also be defined:*				
17	DCHN	Water supply master control channel number (same as DCHN above)	1	*TAR.DAT
18	TAR	Unit tariff for water supply to master control channel (R/m^3)	1	*TAR.DAT
19	TARESC	Annual tariff escalation rates, to be applied in each year (MNYP as described above)	MNYP	*TAR.DAT
*For each pumping channel in the system (MNPMP, as described in **Section 8.3.6**), parameters 20 to 27 must be defined:*				
20	NOPCH	Pumping channel number (as defined in **Section 7.4 (b)**)	1	*PMP.DAT
21	PLIFE	Economic life of pumping channel (i.e. number of years over which cost is amortised)	1	*PMP.DAT
22	PMPCC	Capital cost of pumping channel (R million)	1	*PMP.DAT
23	PFOAM	Fixed operating and maintenance costs of pumping channel (R million)	1	*PMP.DAT
24	PVOAM	Variable operating and maintenance costs of pumping channel (R million)	1	*PMP.DAT
25	NYCP	Number of years in construction schedule for pumping channel	1	*PMP.DAT
26	CSPMP	Capital cost schedule (as a portion of capital cost in each year of construction)	NYCP	*PMP.DAT
27	PERATE	Annual escalation rates in operating costs, to be applied in each of the years for which time-related control data are provided for pumping channels (MNYP as described in **Section 7.4 (b)**)	MNYP	*PMP.DAT
*For each time-controlled channel in the system (MNPUR, as described in **Section 7.4 (d)**), parameters 28 to 35 must be defined:*				
28	PFCHN	Time-controlled channel number, associated with purification plant (as defined in **Section 7.4 (d)**)	1	*PUR.DAT
29	PFLIFE	Economic life of purification plant (i.e. number of years over which cost is amortised)	1	*PUR.DAT
30	PURCC	Capital cost of purification plant (R million)	1	*PUR.DAT
31	PFFOAM	Fixed operating and maintenance costs of purification plant (R million)	1	*PUR.DAT
32	PFVOAM	Variable operating and maintenance costs of purification plant (R million)	1	*PUR.DAT

No.	Name	Description	Number of inputs	Associated data file/s
33	NYCPF	Number of years in construction schedule for purification plant	1	*PUR.DAT
34	CSPUR	Capital cost schedule (as a portion of capital cost in each year of construction)	NYCPF	*PUR.DAT
35	FERATE	Annual escalation rates in operating costs, to be applied in each of the years for which time-related control data are provided (MNYP as described in **Section 7.4 (d)**)	MNYP	*PUR.DAT
For each reclamation plant in the system (MNREC, as described in ***Section 8.3.9****), parameters 36 to 43 must be defined:*				
36	RECHN	Channel number associated with reclamation plant (as defined in **Section 7.4 (c)**)	1	*REC.DAT
37	RLIFE	Economic life of reclamation plant (i.e. number of years over which cost is amortised)	1	*REC.DAT
38	RECCC	Capital cost of reclamation plant (R million)	1	*REC.DAT
39	RFOAM	Fixed operating and maintenance costs of reclamation plant (R million)	1	*REC.DAT
40	RVOAM	Variable operating and maintenance costs of reclamation plant (R million)	1	*REC.DAT
41	NYCR	Number of years in construction schedule for reclamation plant	1	*REC.DAT
42	CSREC	Capital cost schedule (as a portion of capital cost in each year of construction)	NYCR	*REC.DAT
43	RERATE	Annual escalation rates in operating costs, to be applied in each of the years for which time-related control data are provided for reclamation plants (MNYP as described in **Section 7.4 (c)**)	MNYP	*REC.DAT

14. MODEL RUN RESULT OUTPUT OPTIONS

Various sets of result output information may be obtained from a WRSM model run, including:

- Detailed monthly simulation results provided for selected system components in time-series format. This includes average channel flows, reservoir and system storage volumes, reservoir elevation levels, rainfall on and evaporation losses from reservoir water surfaces, incremental sub-catchment inflows and water requirement supplies and system curtailment levels.
- Analysis summary information for the system, including details of the yield, pumping energy (in cases where hydropower generation analyses are undertaken), failures, average length and deficit of critical periods, as well as the average drawdown period.

The model allows for result output to be tailored according the specific requirements and interests of the model user, or whether historical or stochastic yield analyses or planning analyses are being undertaken. Various options can be selected to control the output files generated, as well as the level of detail of the output data. More information in this regard is provided in the remainder of this section. Also details are provided on the graphical display of run results through post-processing.

14.1 Output file options

Various run result output files may be generated for a WRSM analysis depending on the type of analysis being undertaken. Output files are written to a directory specified by the user (DIRO, as described in **Section 2.2**) and the files are given standard names coupled with the file name prefix selected by the user (RCODE, as described in **Section 2.1**). For example, if an analysis of the Vaal River system is being undertaken, a prefix "VAAL" might be selected, which means that the *SUM.OUT data output file will be called *VAAL*SUM.OUT, the *PLT.OUT-file *VAAL*PLT.OUT and so on. Also, the three lines containing the general run title and description (RUNTITLE, as described in **Section 2.1**) are written as a header to the appropriate places in the data output files, serving as a means of identification and reference between the input and output data sets.

A summary of the WRSM data output files for yield analyses is provided below:

- The *SUM.OUT-file is generated for all model runs and is the main data output file for the model. It contains month-end reservoir information, average monthly channel flows and analysis summary information for the system, including details of the yield, pumping energy, failures, critical periods and storage drawdown. The level of detail for the *SUM.OUT-file is specified by the user with values ranging from “0” for a brief summary to “2” for detailed output.
- The *PLT.OUT-file contains selected month-end reservoir and system storage volumes, as well as average monthly channel flows. The file is useful when stochastic analyses are undertaken in which case it is impractical to write such large amounts of information to the detailed summary output file.
- The *HYD.OUT-file contains hydropower simulation results.
- The *DAT.OUT-file mirrors the basic information specified by the user in the model data input files. This enables checking of whether data have been input correctly.
- The *DBG.OUT-file includes details on the step-wise calculations undertaken by the model. It is mostly used to solve complex data input problems or for model development purposes. The level of detail for the debug output file is specified by the user with values ranging from “-3” for no debug output to “7” for highly detailed debug output
- The *YLD.OUT-file stores detailed system outflow channel results for incorporation into another modelled system using the *.INF-file (as discussed in **Section 8.3.7**).

A summary of the WRSM data output files for planning analyses is provided below:

- The *SUM.OUT-file is the main data output file for the model and contains, firstly, month-end reservoir information, average monthly channel flows and analysis summary information for the system (as for a yield analysis). Furthermore, the user may select specific information to be printed to the file, including pumping energy, channel flows, annual supplies, lowest storages in each reservoir, sub-system curtailment levels, allocation results (when the manual water allocation control option is selected) and economic analysis results.
- The *SYS.OUT-file contains annual water allocation results.
- The *RES.OUT-file contains annual water requirement vs. supply results.
- The *PLN.OUT-file provides detailed water allocation results.
- The *PLT.OUT-file contains selected month-end reservoir and system storage volumes, as well as average monthly channel flows (as for a yield analysis).
- The *DAT.OUT-file mirrors the basic information specified by the user in the model data input files (as for a yield analysis). This enables checking of whether data have been input correctly.

- The *DBG.OUT-file includes details on the step-wise calculations undertaken by the model and the level of detail for the debug output file is specified by the user (as for a yield analysis).

The definition of data output file control parameters for yield and planning analyses is shown below.

Table 14-1: Data output file control parameters

No.	Name	Description	Number of inputs	Associated data file/s
*Parameters 1 to 4 must only be defined if a **yield analysis** is being undertaken:*				
1	OPTSUM	Level of detail for detailed summary output file (*SUM.OUT): 0, 1 or 2	1	*F01.DAT
2	OPTPLT	Create plot output file of reservoir and water requirement results (*PLT.OUT) option: yes or no (Y or N); and Create hydropower output file (*HYD.OUT) option: yes or no (Y or N)	1	*F01.DAT
3	OPTDAT	Create output file of input data (*DAT.OUT) option: no or yes (0 or 1)	1	*F01.DAT
4	OPTSAV	Create output file of detailed system outflow channel results (*YLD.OUT) option: no or yes (0 or 1, used for implementing outflows from this system as inflows into another system, as described in **Section 8.3.7**)	1	*F01.DAT
*Parameters 5 to 11 must only be defined if a **planning analysis** is being undertaken:*				
5	OPTDS	Create detailed summary output file (*SUM.OUT) option: yes or no (Y or N); and Create annual water allocation results output file (*SYS.OUT) option: yes or no (Y or N); and Create annual water requirement vs. supply results output file (*RES.OUT) option: yes or no (Y or N)	1	*F01.DAT
6	OPTAS	Option for selecting specific results to be printed to the SUM.OUT-file: Q, D, Y or N (Q = pumping energy and channel flows; D = annual supplies, lowest storages in each reservoir and sub-system curtailment levels; Y = both Q and D; N = none)	1	*F01.DAT
7	OPTSS	Option for printing allocation results to the SUM.OUT-file when manual water allocation control option is selected (i.e. for PLAN = M, as described in **Section 11.1.1**): yes or no (Y or N)	1	*F01.DAT
8	OPTCA	Option for printing economic analysis results to the SUM.OUT-file: yes or no (Y or N)	1	*F01.DAT
9	OPTPS	Create detailed water allocation results output file (*PLN.OUT) option: yes or no (Y or N)	1	*F01.DAT
10	PLOT	Create plot output file of reservoir and water requirement results (*PLT.OUT) option: yes or no (Y or N)	1	*F01.DAT
11	OPTIS	Create output file of input data (*DAT.OUT) option: yes or no (Y or N)	1	*F01.DAT
*Parameters 12 to 14 must be defined for both **yield analyses** and **planning analyses**:*				

No.	Name	Description	Number of inputs	Associated data file/s
12	LDEBUG	Level of detail for debug output file (*DBG.OUT) file: range of values from -3 (none) to 7 (full details)	1	*F01.DAT
13	IDEB1	Start month number for output to *DBG.OUT-file	1	*F01.DAT
14	IDEB2	Final month number for output to *DBG.OUT-file (usually set = INTMAX, as described in **Section 2.3**)	1	*F01.DAT
Related parameters and interdependencies:				
-	-	Name of data output files contains system identification code (RCODE as described in **Section 2.1**, e.g. “VAALSUM.OUT”, “VAALPLT.DAT”, etc.)	N/A	Selected files
-	-	General run title and description (RUNTITLE, 3 lines, as described in **Section 2.1**) printed as headers in appropriate data output files tables)	N/A	Selected files
-	-	Data output files are written to specified directory (DIRO, as described in **Section 2.2**)	N/A	Selected files

Conditions associated with defining data output file parameters are summarised in the table below.

Table 14-2: Conditions for defining data output file parameters

Condition	Associated parameter/s	Reference
Lowest level of detail for *SUM.OUT-file (= 0) and *DBG.OUT-file (= -3) should be selected for multi-sequence stochastic yield analyses	OPTSUM, LDEBUG, HISTO	This section, **2.4**

14.2 Reservoir output options

Detailed result output information may be obtained from a WRSM model run for any of the active reservoirs in the water resource system. The user is allowed to select the specific reservoirs for which output is required, in which case the relevant data sets are written to the appropriate data output files (as detailed in **Section 14.1**). This includes the *SUM.OUT-file, for which tables are created containing the following monthly reservoir data:

- Month-end storage volumes (million m^3);
- Month-end elevation levels (m);
- Net runoff from incremental sub-catchments contributing to reservoir inflows (million m^3);
- Rainfall on the reservoir water surface (average m^3/s);
- Evaporation losses from the reservoir water surface (average m^3/s).

Reservoir-related output to the *PLT.OUT-file includes month-end reservoir and system storage volumes in units of million m^3. These data are useful mainly when stochastic runs are being undertaken, in which case separate plotting utilities and post-processors are used to process the data and generate box plots and other graphical representations.

Details in this regard are provided below.

Table 14-3: Reservoir results output control parameters

No.	Name	Description	Number of inputs	Associated data file/s
*For each reservoir in the system (MNRES, excluding nodes with incremental sub-system hydrology inflows, as described in **Section 5.1**), parameter 1 must be defined:*				
1	NRPRT	Option for printing reservoir results to the *SUM.OUT and *PLT.OUT output files: N, Y, L or B (N = no; Y = yes with volumes to *PLT.OUT; L = yes with levels to *PLT.OUT; B = yes with both volumes and levels to *PLT.OUT)	1	*F02.DAT
*If a **planning analysis** is being undertaken, parameter 2 must also be defined for each reservoir in the system:*				
2	IVOL	Option for adding reservoir storage to total system storage volume results printed to *SYS.OUT output file	1	*F05.DAT
Related parameters and interdependencies:				
-	-	Name of data output files contains system identification code (RCODE as described in **Section 2.1**, e.g. "VAALSUM.OUT", "VAALPLT.DAT", etc.)	N/A	Selected files
-	-	Reservoir name (RESNAM) and number (RESNUM) written as headers to appropriate data output file tables	N/A	Selected files
-	-	Data output files are written to specified directory (DIRO, as described in **Section 2.2**)	N/A	Selected files

14.3 Channel output options

Detailed result output information may be obtained from a WRSM model run for any of the active channels in the modelled water resource system. The user is allowed to select the specific channels for which output is required, in which case the relevant data sets are written to the appropriate data output files (as detailed in **Section 14.1**). This includes the *SUM.OUT-file, for which tables are created containing a record of average modelled flows in the selected channel, corresponding to each month of the analysis (in units of m^3/s). Similar information is output to the *PLT.OUT-file, which is used mainly when stochastic runs are being undertaken in which case separate plotting utilities and post-processors are used to process the data and generate box plots and other graphical representations.

Details in this regard are provided below.

Table 14-4: Channel results output control parameters

No.	Name	Description	Number of inputs	Associated data file/s
*Parameters 1 to 5 must be defined for both **yield analyses** and **planning analyses**:*				
1	MNSCHN	Number of channels selected for results output	1	*F03.DAT
2	MNSYLD (MNPCHN)	Number of channels for flow output to PLT.OUT-file; and Number of channels for yield result output to SUM.OUT-file (applies to first MNSYLD of MNSCHN channels)	1	*F03.DAT
For each channels selected for results output (MNSCHN), parameters 3 to 5 must be defined:				
3	NSCH	Channel number	1	*F03.DAT
4	SCNAM	Channel name or description	1	*F03.DAT
5	NCPRT	Option for printing channel flow results to *SUM.OUT-file: yes or no (Y or N)	1	*F03.DAT
*Parameter 6 must only be defined if a **planning analysis** is being undertaken and for each water supply master control channel in the system (MNDCEN, as described in **Section 8.2.1**):*				
6	ADPLT	Option for printing results for water supply master control channel to the output files: yes or no (Y or N)	1	*F01.DAT
*Parameter 7 must only be defined if a **planning analysis** is being undertaken and for each inter-sub-system support channel in the system (MNIBC, as described in **Section 11.2.3**):*				
7	BCT	Option for printing annual inter-sub-system support requirement vs. supply results for channel to the *RES.OUT-file (as described above): yes or no (Y or N)	1	*F01.DAT
Related parameters and interdependencies:				
-	-	Name of data output files contains system identification code (RCODE as described in **Section 2.1**, e.g. "VAALSUM.OUT", "VAALPLT.DAT", etc.)	N/A	Selected files
-	-	Channel name (SCNAM) and number (NSCH) written as headers to appropriate data output file tables	N/A	Selected files
-	-	Data output files are written to specified directory (DIRO, as described in **Section 2.2**)	N/A	Selected files

Conditions associated with defining channel results output control parameters are summarised in the table below.

Table 14-5: Conditions for defining channel results output control parameters

Condition	Associated parameter/s	Reference
Channel selected for results output must exist	NSCH	This section

14.4 Graphical presentation of run results

All output of run results from the WRSM is in the form of data files. Separate plotting utilities and post-processors are therefore used to process the data and generate box plots and other graphical representations. These are discussed in the following sections.

14.4.1 General

The monthly simulated behaviour of any selected system component (or combination of components) may be plotted on a set of axes representing time (x-axis) and the units for the system component being plotted (y-axis). System components for plotting include average channel flows, reservoir and system storage volumes, reservoir elevation levels, rainfall on and evaporation losses from reservoir water surfaces, net incremental catchment runoff into the system at a particular point, as well as pumping energy results.

If a historical or single-sequence stochastic yield analysis was undertaken, the plot may be in the form of a line graph, where a single line is used to represent the component in question. Line graphs can also be combined by plotting more than one system component on a single set of axes so that they may be viewed simultaneously for comparison purposes. Such plots are extremely useful for checking the inter-dependence of system components and related operating rules.

For multi-sequence stochastic sequences, results are often shown in the form of “box-and-whisker”-plots. These plots provide a convenient way of depicting a probability distribution, especially if there are a number of probability distributions to be displayed on a particular graph. A box plot is essentially a plan view of a probability distribution “bell” curve indicating the locations of specified exceedance probabilities within that curve. An example is shown below.

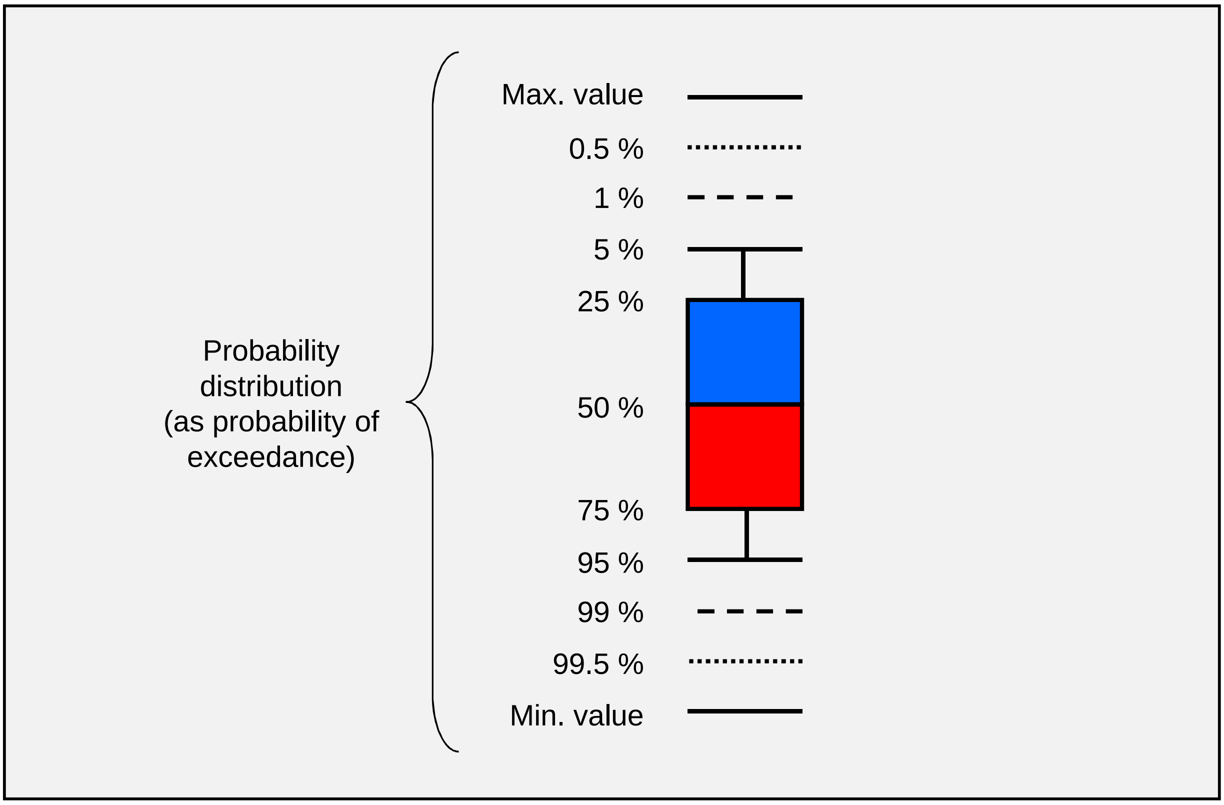


Figure 14-1: Example of a "box-and-whisker"-plot, showing a probability distribution as probability of exceedance

It should be noted that a detailed assessment was made for the DWAF, Directorate: Water Resource Planning Systems of the software utilities required for displaying basic run results from WRSM analyses. These features are now being implemented in the *Water Resources Information Management System* (WRIMS, discussed in **Section 1.4**) and include the presentation of:

- Water user supply-reliability characteristics and monthly supply patterns;
- Compliance with water user assurance criteria;
- Duration and frequency of deficits;
- Surplus allocable amounts;
- Aggregation of results;
- Modelled operating rules;
- Simulated system behaviour;
- Information of water requirement channels;
- Displaying networks on a GIS-background.

More information in this regard is provided in the document *Detailed Business Requirements for the WRYM and WRYM-IMS to Support Allocation Modelling* (DWAF, 2006).

14.4.2 Yield analysis results

As explained in **Section 1.3 (a)**, the main purpose of a yield analysis is to assess the total long- and short-term resource capability (or *yield*) at a particular point in a water resource system at a fixed selected development level and set of system operating rules. The yield of a system can be determined based either on a historical yield analysis, in which case the yield is typically expressed as a historical firm yield, or based on a stochastic yield analysis, in which case assurance of supply (or risk of non-supply) may be determined for a variety of yields.

The historical firm yield (HFY) of a system is determined by means of an iterative process, where a range of target drafts are imposed on the system and the yield (or supplied amount) determined for each target draft. The firm yield is then taken to be the maximum target draft that can be imposed without causing the system to fail (i.e. yield equals target draft). The results of this process, which is discussed in **Section 9**, can be presented graphically in a "target draft vs. yield"-diagram. An example is shown below.

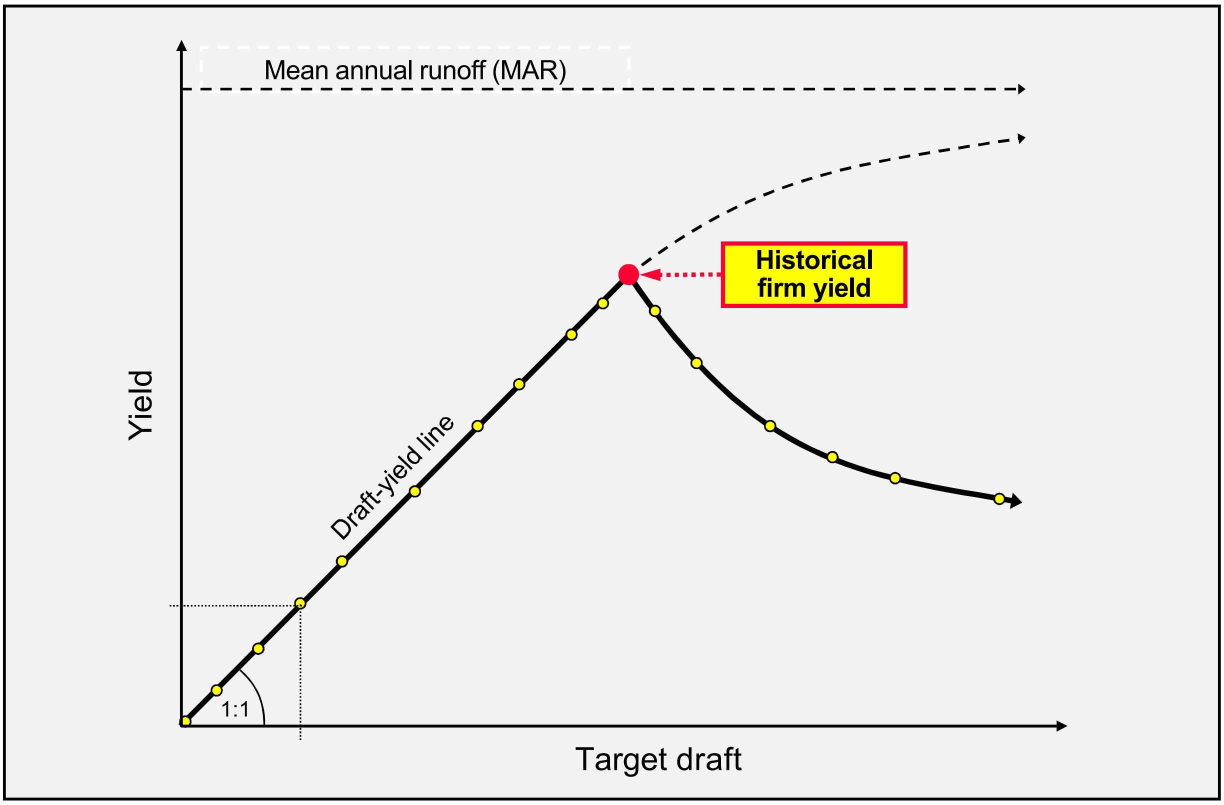


Figure 14-2: Example of a "target draft vs. yield"-diagram

For stochastic analyses, the reliability of supply associated with a particular target draft is determined by the model based on the number of analysed sequences for which failures were recorded. The assessment of the reliability characteristics of a system is also discussed in

Section 9 and generally involves the analysis of a range of target drafts and the results are displayed in a table showing target drafts (in units of million m^3/a), together with the associated reliability of supply (as a %) and risk of failure as a recurrence interval (RI, in years). Again, these results can be displayed graphically as a set of “yield-reliability characteristics” (YRC) curves and an example is shown below.

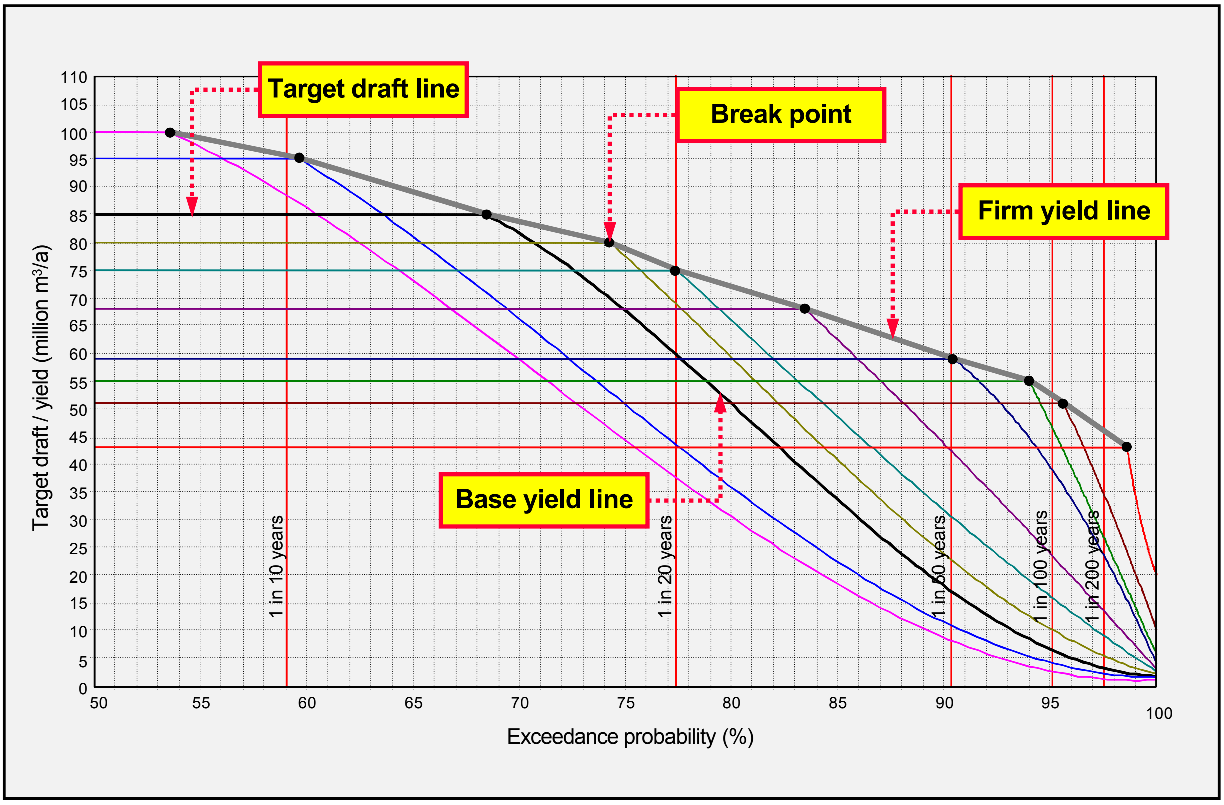


Figure 14-3: Example of a set of “yield-reliability characteristics”-curves

The figure shows a number of lines, each of which represents a separate analysed target draft and consists of a “target draft line”, a “break point” and a “base yield line”. The latter is (generally) a third-order polynomial equation which is fitted to data points that represent the yield of the system for each individual sequence analysed. The yield value is calculated based on the lowest total supply to the master control channel for a 12 months-window. The “firm yield line” connects the break points for all analysed target drafts.

For short-term multiple period length yield analyses (as described in **Section 2.4**) separate graphs may be generated for the 1-year, 2-year, etc. period lengths, all of which may be plotted on a common plotting plane (usually 5 years). Such analyses are usually undertaken to determine the short-term yield reliability characteristics for defined sub-systems in a water resource system and are applied when undertaking planning analyses as part of the process of managing water allocations (as described in **Section 11**). The characteristics are defined in terms of four coefficients, a, b, c and d, that describe the shape of the third-order polynomial equation mentioned above.

14.4.3 Planning analysis results

Planning analysis results are generally presented in the form of "box-and-whisker"-plots (as discussed in **Section 14.4.1**) and these are used to depict the projected probabilistic behaviour of a specific system element. The most important box-plots from a planning analysis are listed below, together with information on how the plots in question are generated:

- Projected annual system water curtailments are plotted using the LTPLT.EXE and WRPBOX.EXE post-processing utilities based on planning analysis results from the *SYS.OUT-file (as described in **Section 14.1**)
- Projected annual system water requirements vs. supplies are also plotted using LTPLT.EXE and WRPBOX.EXE from the *RES.OUT-file;
- Projected annual system storage volumes are also plotted using LTPLT.EXE and WRPBOX.EXE from the *SYS.OUT-file;
- Projected reservoir storage volumes are plotted using WPLT_10.EXE and WRPBOX.EXE from the *PLT.OUT-file, as well as a special "CONTROL"-file detailing the location of individual *PLT.OUT-files containing information from separate sequence run sets;
- Projected channel flows are plotted using PMP_10.EXE and WRPBOX.EXE from the *PMP.OUT-file, as well as a "CONTROL"-file detailing the location of individual *PMP.OUT-files containing information from separate sequence run sets.
- Projected inter-sub-system support volumes are plotted using LTPLT.EXE and WRPBOX.EXE from the RES.OUT-file.

Examples of the plots of projected annual system water curtailments, system water requirements vs. supplies and system storage volumes are shown in **Appendix B**.

15. REFERENCES

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Appendix A

Example of a simple system network diagram

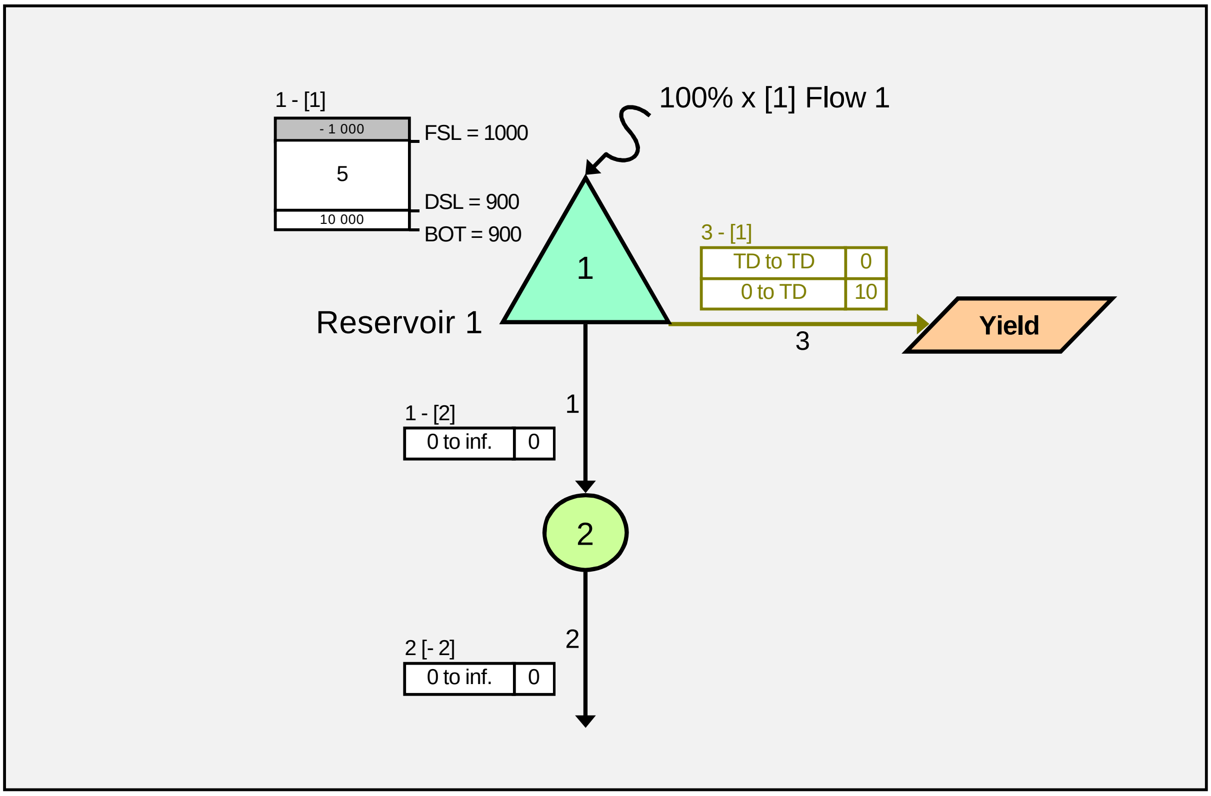

Figure A-1: Example of a simple system network diagram

Appendix B

Examples of plotted results from a planning analysis

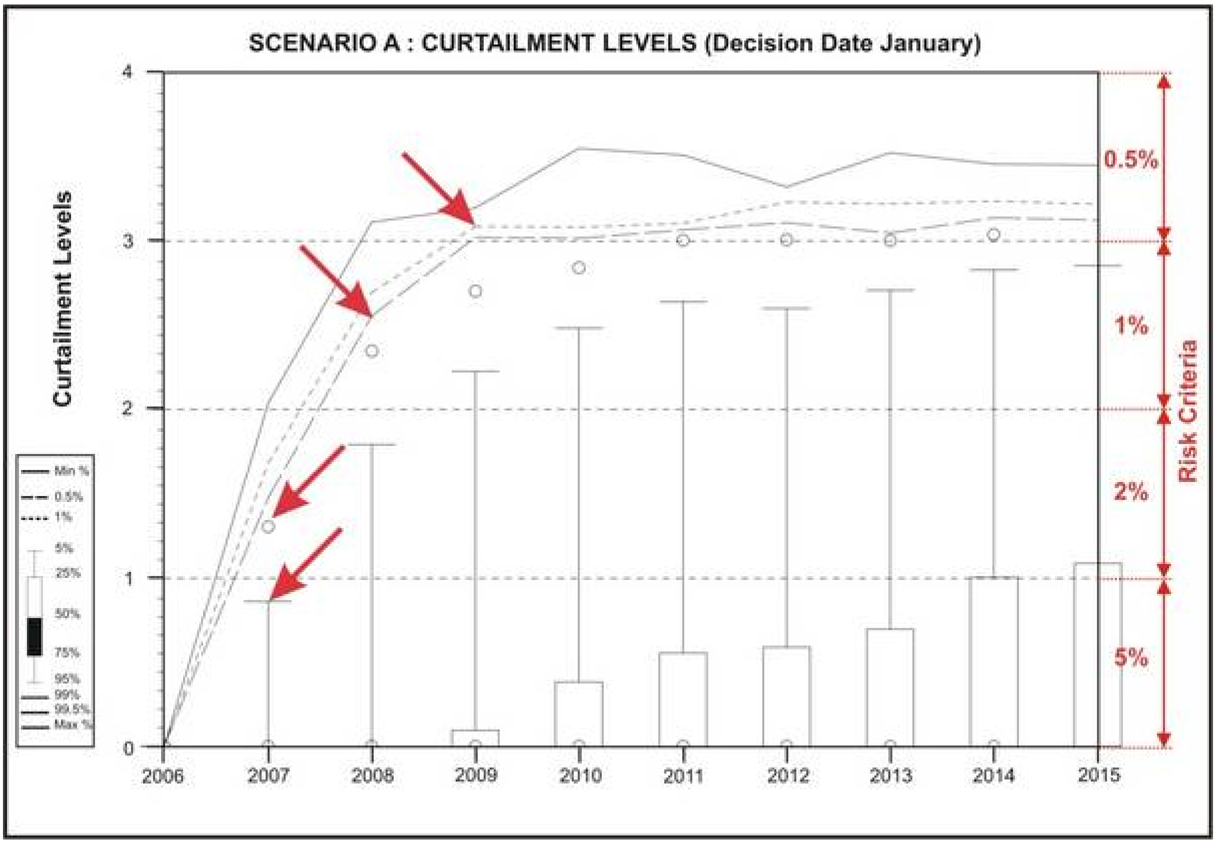

Figure B-1: **Example plot of projected annual system water curtailments**

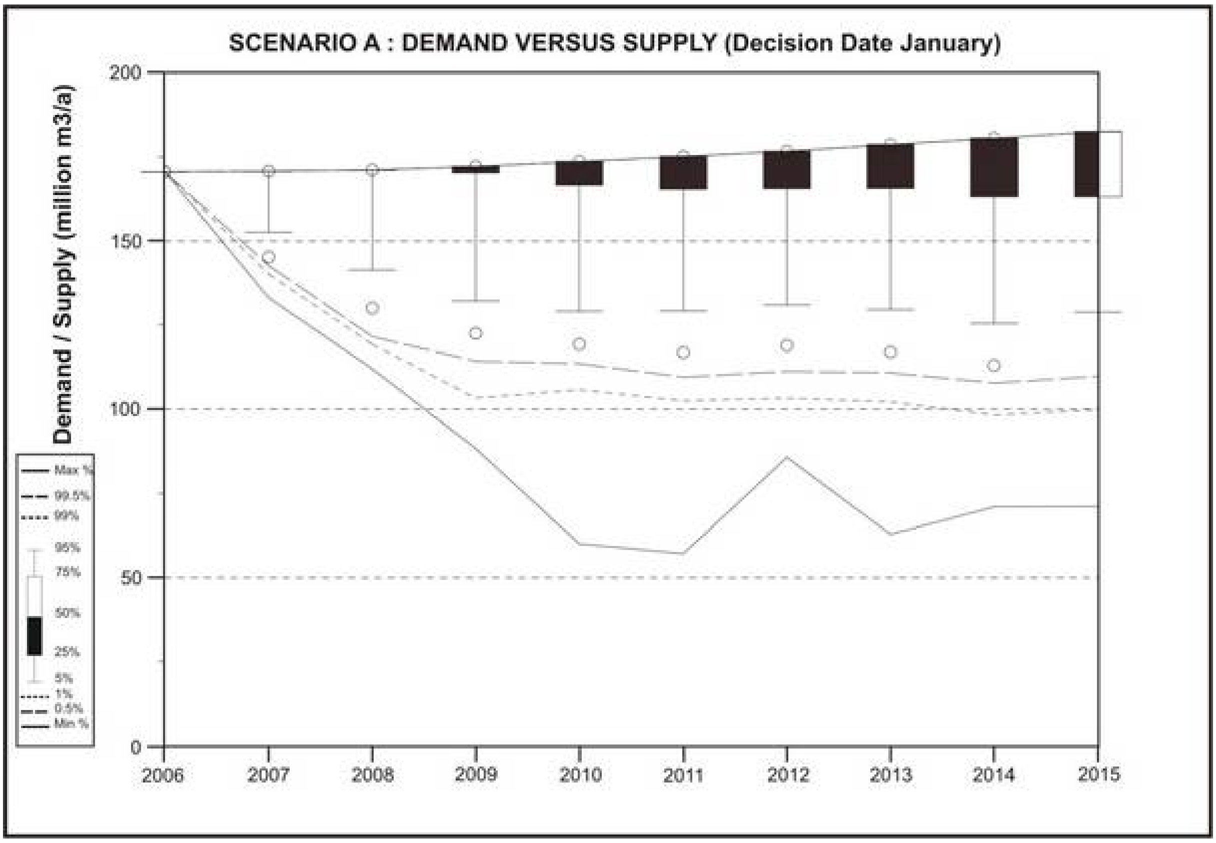

Figure B-2: **Example plot of projected system water requirements vs. supplies**

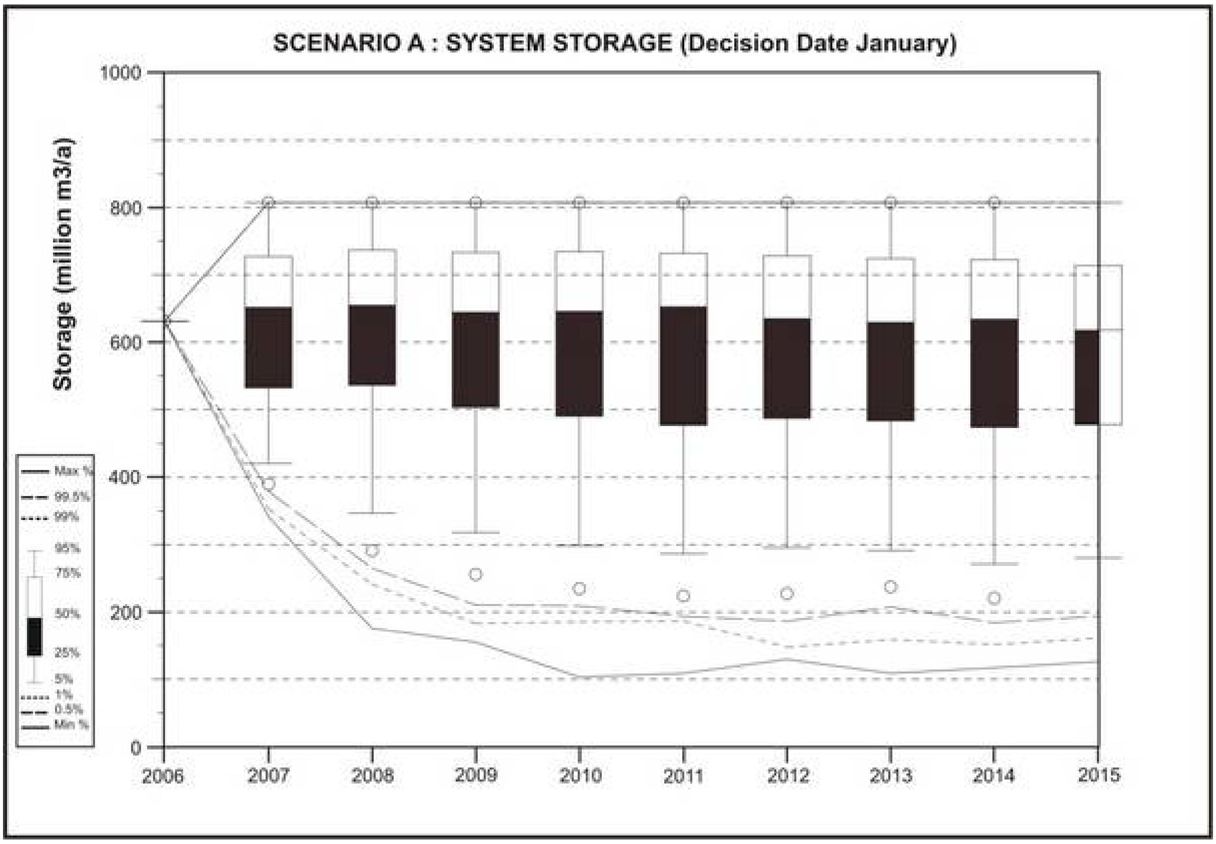

Figure B-3: Example plot of projected system storage volumes