Development of a Practical Methodology for Assessing the Potential Impacts of Climate Change on the Yield Characteristics of Reservoirs

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by

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EXECUTIVE SUMMARY

Scientists agree that Climate Change will result in more extreme rainfall events (both droughts and floods) and that for Sub-Saharan Africa, there will most probably be a shift in the seasons, in general resulting in a shorter wet season in arid areas. Such a change could have a severe impact on the available resource. Indeed, some recently completed hydrological studies (Schulze et al., 2005 & 2009) on the impact of Climate Change on water resources in South Africa, indicated that Climate Change will impact on runoff – albeit in varying degrees.

The IPCC, and locally the WRC, have expressed the need for scientific research results to be applied in practical tools that can be utilised by Water Resource Planners in order to facilitate the incorporation of research findings on Climate Change into the Planning Process.

In South Africa, Water Resource Planning is synonymous with reservoirs as almost all catchments in the country are controlled, directly or indirectly, by reservoirs. The supply capability of these reservoirs is mostly assessed by means of yield analysis. In a yield analysis the volumetric yield of reservoirs is assessed and by making use of stochastically simulated inflow sequences, which is often associated with a specific risk of failure. These yield estimates are then compared with water requirements and assurance criteria to determine the likelihood that users will experience shortages of supply.

The purpose of this assignment was to adapt the existing stochastic yield analysis methodology, which in essence is based on the characteristics of historical climatic behaviour in order to account for the possible relative changes in reservoir yield under various Climate Change outcomes. The new methodology was applied to three South African reservoirs, i.e. the Berg River Dam, Midmar Dam in the Mgeni River and Grootdraai Dam in the upper Vaal River in order to test the methodology in climatically diverse areas with expected varying climate change impacts.

The investigation of published research results on the topic yielded many insights into the different methods that can be followed in deriving Climatic Change data sets. As such, the project team also appreciates the fact that the results obtained from different Climate Change models (GCMs), downscaling models (RCMs) and methods can and do provide different results when working at a catchment scale. As a result it was found that Present-day time horizon results (in rainfall and as a result thereof, also in natural runoff) were not in line with naturalised observed data.

Another obstacle identified in applying GCM-based climate and surface water runoff results was that the sequences simulated using the various GCMs only spanned 19 hydrological years – which is considered to be too short to obtain reliable long-term yield results.

Therefore, in order to address these limitations, a simplistic statistically-based data pre-processing method was developed for generating long, stationary runoff data sets representative of each climate change scenario, which are also in line with observed runoff characteristics over the Present-day time-horizon. Although it is acknowledged that the method is crude and may be substantially refined through further research, it does provide a reasonable basis for applying available climate change scenario information in traditional long-term yield analysis methodologies and, as such, the means for identifying possible generalised future trends in yield characteristics.

Using the latest available set of catchment-based surface water runoff derived from Climate Change data and the above data pre-processing method, long-term stochastic yield analyses were performed for each of the selected reservoirs and for five selected GCMs. In all cases, the present live full supply capacity (FSC) was assumed.

Based on the underlying assumptions regarding the change in runoff characteristics under the various Climate Change outcomes, the results of the analyses were as expected and can be summarised as follows:

- The projected impacts of climate change on long-term reservoir yields vary significantly from certain climatic region to others and also depend largely on the climate model used.
- A total of four GCMs were included for the analysis of Berg River Dam. Results for the *Intermediate Future* (2046 to 2065) time-horizon are inconsistent but suggest a significant possible decrease in yield for the *Distant Future* (2081 to 2100).
- In the case of Midmar Dam, five GCMs were included in the analysis and results suggest a significant possible increase in yield for both the *Intermediate Future* and *Distant Future* time-horizons.
- As above, five GCMs were included in the analysis of Grootdraai Dam and results suggest a significant possible increase in yield for both the *Intermediate Future* and *Distant Future* time-horizons.

Overall, the project resulted in the first substantial step towards the development of a practical methodology for assessing the potential impacts of climate change on long-term reservoir yields based on runoff time-series data derived from the downscaled results of General Circulation Models (GCMs) for various time-horizons.
However, the methods applied are crude and further research in this regard is considered to be essential. Within this context, the following recommendations are made:

- Improved communication channels should be established between water resource planners and climate change researchers in order to ensure that research outputs are better aligned with the requirements of water resource planning tools. Of particular concern is the apparent discrepancy between runoff characteristics derived from downscaled GCM information for the present-day time-horizon and that of observed naturalised historical runoffs.
- While a statistically-based data pre-processing method was developed for generating long, stationary runoff data sets from available climate change scenario information for application in traditional long-term yield analysis methodologies, the validity of the method remains essentially untested. Other approaches should therefore be actively considered including the possibility of developing alternative yield analysis methodologies that accommodate the inherent non-stationarity of a changing climate.
- The methodologies developed should be applied in a national study aimed at providing broad-scale information to the water resources planning community on possible future climate change impacts. Results can be presented on a quaternary catchment scale and in the form of colour-coded maps showing indices representing the possible impacts on reservoir yields for a range of reservoir storage sizes and assurances of supply.
- Methodologies developed for assessing climate change impacts on yield should also be tested and applied in an integrated water resources system context using more sophisticated yield assessment tools such as the *Water Resources Yield Model* (WRYM).
- Runoff time-series data applied in this project were developed by simulation using the daily time-step ACRU agro-hydrological model. The possibility should, however, be investigated of using other hydrological models for this purpose (e.g. the monthly-time step WRSM2000 rainfall-runoff model) as this may provide opportunities for the improved alignment of results with other studies, such as those undertaken for planning purposes by the Department of Water Affairs (DWA).
- Climate modelling methodologies are continually improved upon and refined and in order to enhance the credibility of climate change impact assessment methodologies and results, assessments should be extended to include results obtained from a larger number of GCMs, greenhouse gas emission scenarios and alternative downscaling methods.
- For the purpose of simplicity, the modelling undertaken in this research project focused on the potential impacts of climate change on catchment runoff and ignored other factors that were considered to be of secondary importance.

These include climate change related changes in natural vegetation, land use, migration patterns, socio-economic activities, as well as rainfall directly onto and evaporation directly from the exposed surface area of the reservoir. These aspects could impact on yield in varying degrees depending on the system in question and requires further research.

- Possibly the most significant challenge regarding climate change impact assessments is the incorporation of results into the mainstream water resources planning process. Specifically, research is required for the development of a framework to guide the practical response to projected climate change impacts, including, for example:

  - The need for and timely implementation of additional augmentation in cases where projections indicate a possible decrease in runoff and reservoir yields.
  - The possible deferment of planned augmentation schemes in cases where projections indicate a possible increase in yield.
  - The possible adaptation of flood emergency plans, flood design parameters and sediment management plans in cases where the frequency and severity of flood flows are projected to change.
  - Managing impacts on water quality resulting from higher air and water temperatures, sediment loads, etc.
  - Assessing the credibility of climate change impact projections and also the associated risk of their consideration in the implementation of planning decisions.

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List of Abbreviations

C-CAM	Conformal-Cubic Atmospheric Model
CSAG	Climate Systems Analysis Group (UCT)
CSIRO Mk3 OAGCM	Commonwealth Scientific and Industrial Research Organisation Ocean Atmosphere General Circulation Model
CV	Coefficient of Variability
DWA	Department of Water Affairs
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
IWRP	Integrated Water Resource Planning
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual (Natural) Runoff
RCM	Regional Circulation Model
SBEEH	School of Bioresources Engineering and Environmental Hydrology (UKZN)
SDF	Storage-Draft-Frequency (curves)
SDFPrep	Storage-Draft-Frequency Pre-processor
STOMSA	Stochastic Model of South Africa
UCT	University of Cape Town
UKZN	University of KwaZulu-Natal
WRC	Water Research Commission
WRSM2000	Water Resources Simulation Model 2000
WRYM	Water Resources Yield Model

1. Introduction

It is predicted that on the African continent, between 75 million and 250 million people will be exposed to increased water stress as a direct result of Climate Change (CC) by the year 2020 and by 2050 the risk of decreased runoff and consequential drought is likely to increase in southern Africa (IPCC, 2007). In aligning research focus areas to address this issue, the WRC has initiated a research portfolio (Green, 2008) on CC and the impacts thereof on water resources, specifically aimed at

> '…gaining insight into the magnitude of the impacts and the consequential adaptation needs in the [water] sector.'

Such impacts will be key towards determining the intervention strategies that should be implemented by Water Resource Managers and Policy Makers.

Within this context, the IPCC, and locally the WRC, have expressed the need for scientific research results to be put into practical tools that can be utilised by Water Resource Planners in order to facilitate the incorporation of research findings on Climate Change into the Planning Process.

In South Africa, Water Resource Planning is synonymous with reservoirs as almost all catchments in the country are controlled, directly or indirectly, by reservoirs. The supply capability of these reservoirs is mostly assessed by means of yield analysis. In a yield analysis the volumetric yield of reservoirs is assessed and, making use of stochastically simulated sequences, is often associated with a specific risk of failure (e.g. 50 million m3/a at a recurrence interval of failure of 1:100 years or at an annual assurance of supply of 99%). These yield estimates are then compared with water requirements and assurance criteria to determine the likelihood that users will experience shortages of supply.

The purpose of this study was to adapt the existing stochastic yield analysis methodology, which in essence is based on the characteristics of historical climatic behaviour, in order to account for the possible relative changes in reservoir yield under various Climate Change outcomes. The new methodology was applied to three South African reservoirs, i.e. the Berg River Dam, Midmar Dam in the Mgeni River and Grootdraai Dam in the upper Vaal River in order to test the methodology in climatically diverse areas with expected varying climate change impacts, as well as the process of applying the method.

The investigation of published research results on the topic yielded many insights into the different methods that can be followed in deriving Climatic Change data sets. As such, the project team also appreciates the fact that the results obtained from different Climate Change models (GCMs), downscaling models (RCMs) and methods can and do provide different results when working at a catchment scale. As a result it was found that ‘Present’ time horizon results (in rainfall and as a result thereof, also in natural runoff) were not in line with naturalised observed data. Another obstacle identified in applying GCM-based climate and surface water runoff results was that the sequences simulated using the various GCMs only spanned 19 hydrological years – which is considered to be too short to obtain reliable long-term yield results.

Therefore, in order to perform long-term yield analyses, the project team developed a procedure to adjust these sequences to overcome these obstacles. This adaptation was not originally foreseen as part of the project and the need for such an intervention only became clear after the hydrological results were made available to the project team.

One of the high-priority Research and Development objectives identified in the WRC Research Portfolio is the improvement of stakeholder engagement, specifically improving communication between scientists and end-users (or Water Resource Planners). This project aimed to be a step in that direction – translating valuable scientific findings into results that can directly be used in the Integrated Water Resources Planning environment.

2. Background

Climate encompasses the statistics of temperature, humidity, atmospheric pressure, wind, rainfall, atmospheric particle count and numerous other meteorological elements in a given region and over long periods of time. *CC* therefore implies the variation in climate (with respect to variability and/or average state) over a long time period.

Among scientists there is growing consensus that CC will have a significant impact on our water resources. Changes in rainfall (such as the increased frequency and severity of extreme events such as droughts and floods) will impact on runoff or river flow, which in turn could impact on the reliability of supply from water supply infrastructure. This could have far-reaching implications for South Africa, an arid country hosting the majority of sub-Saharan industrial and economic activity, which is heavily dependent on reliable water resources.

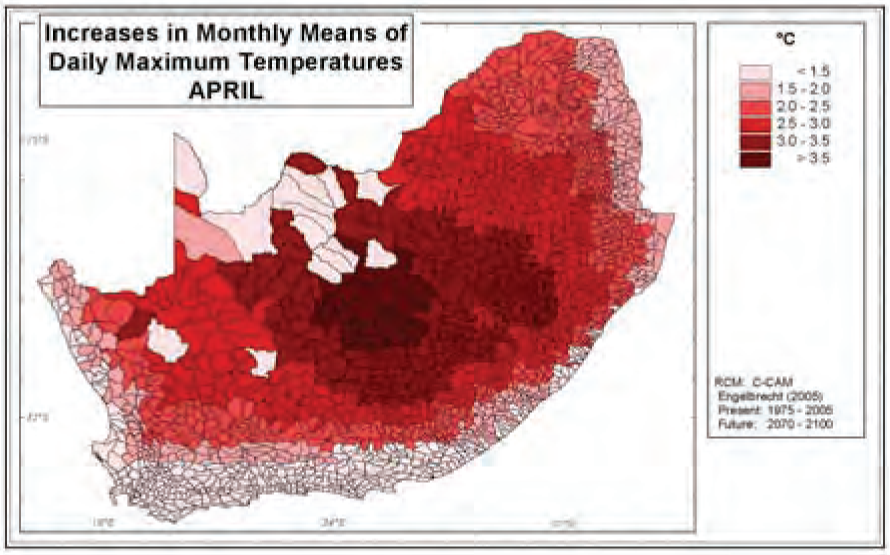
The supply capability of a reservoir is dependent on two main factors: the volume and variability of water that enters the reservoir as runoff from an associated catchment area and the size or capacity of the reservoir itself and, as a result, the amount of water lost from the reservoir in the form of evaporation and spillages.. These two aspects, runoff and reservoir capacity, were therefore the major focus of this study, together with the possible impacts of CC on runoff and, hence, reservoir yield.

In the following sections a brief overview of the projected state of a number of climatic variables as well as surface water runoff are discussed. These are the results of a number of recently (in the last 10 years) completed local and international studies.

2.1 Temperature

Historical temperature records of Southern Africa indicate two clusters of warming. One cluster is located in the Western Cape and the other cluster of stations is around the midlands of KwaZulu-Natal, along with a band of stations along the KwaZulu-Natal coast (Warburton et al., 2005). This finding of Warburton et al. is echoed in an analysis reported on by the IPCC (2007), who also report increased surface air temperature over South Africa from 1979 to 2004, estimating it to have been between 1°C and 2°C over the 25 year period.

However, future CC scenarios suggest that more severe and more rapid temperature changes could be expected in future (2070-2100), ranging roughly between increases of 1.5°C and over 3.5°C (Schulze et al., 2005), as shown in **Figure 2.1**.



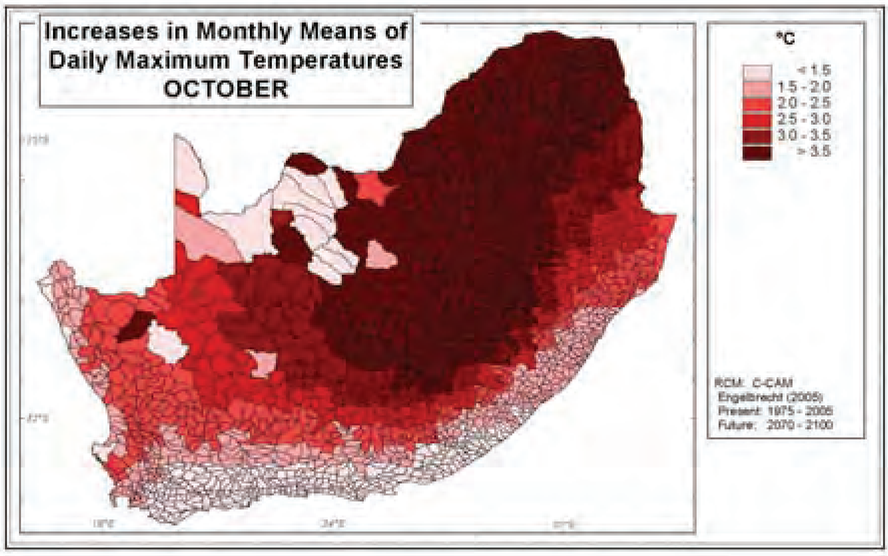


Figure 2.1: Increases in Monthly Mean Maximum Temperatures (April and October); Schulze et al., 2005

In a more recent study (Knoesen et al., 2009) this expected increase in temperature is even more pronounced, ranging between 1.5°C and 3.5°C by 2046 and as much as 7°C by 2081. (**Figure 2.2**)

Increased surface air temperature will impact on reservoir yields both directly (through increased evaporative losses from exposed water surface areas) and indirectly through, amongst others, changes in runoff as a result of increased evapotranspiration of catchment vegetation, decreased soil moisture, increased river or transfer canal losses and associated changes in global climatic systems.

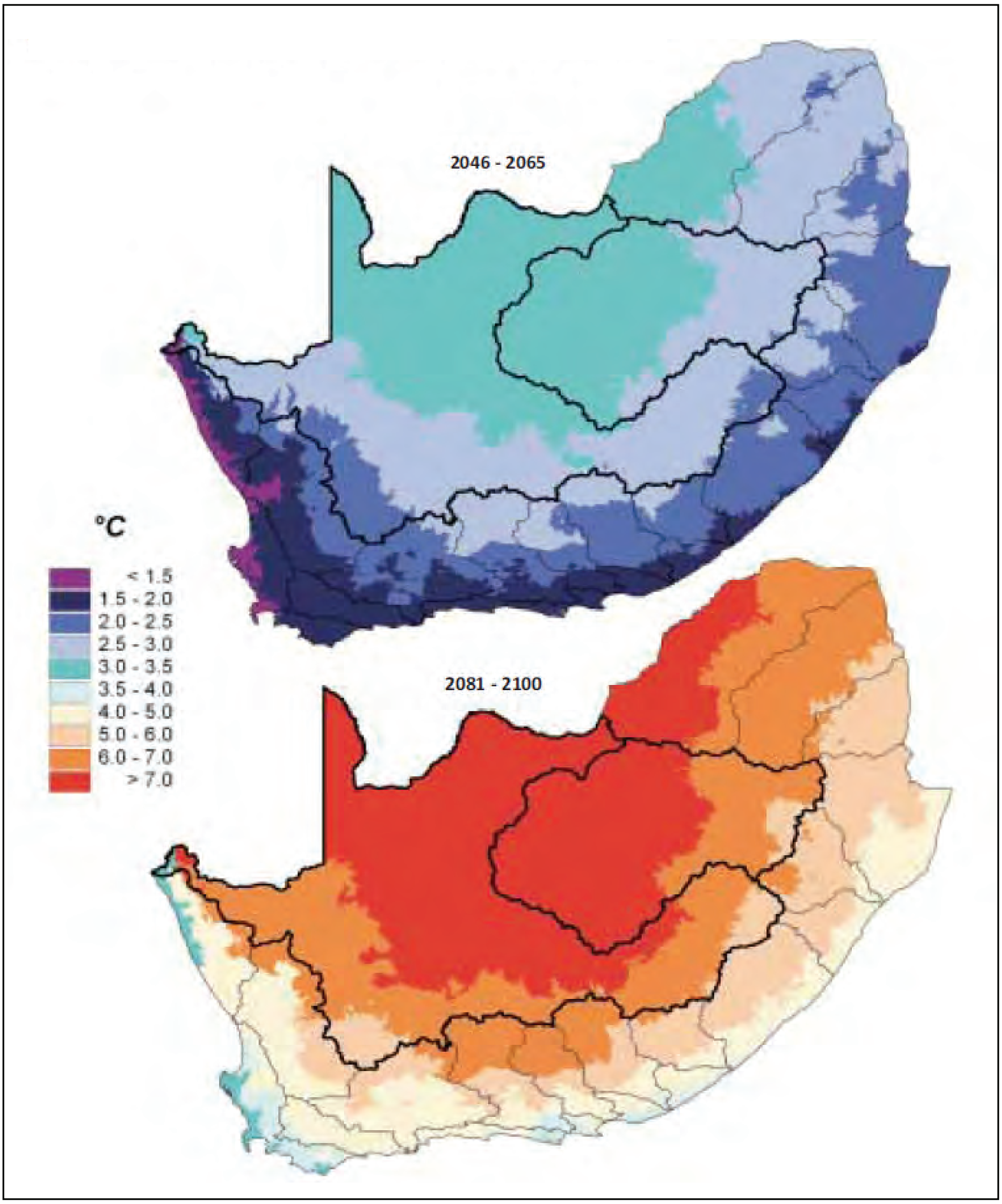


Figure 2.2: Differences in mean annual temperatures between the intermediate (2046-2065) and distant (2081-2100) future scenarios from the present, modelled using the ECHAM5 GCM; Knoesen et al., 2009

2.2 Evaporation

Potential evaporation (or atmospheric evaporative demand) encompasses evaporation losses from open water bodies, plant intercepted water and evaporation from the soil surface, as well as transpiration from plants. Atmospheric evaporative demand is estimated from climatic variables and is expressed as potential evaporation using a selected reference technique.

Increased air temperature (as discussed above) could result in increased evaporation from open surface water areas. Indeed, Schulze et al. (2005) indicates that mean annual potential evaporation is generally expected to increase by roughly 5 to 15%) by the year 2070, as shown in **Figure 2.3**. The direct implications of such an increase in evaporation could be severe for reservoir operators and irrigators.

A more recent study (Knoesen et al., 2009) suggests that this increase in potential evaporation could in fact be as high as 20% to 25% over most of South Africa by the year 2081, as shown in

Figure 2.4.

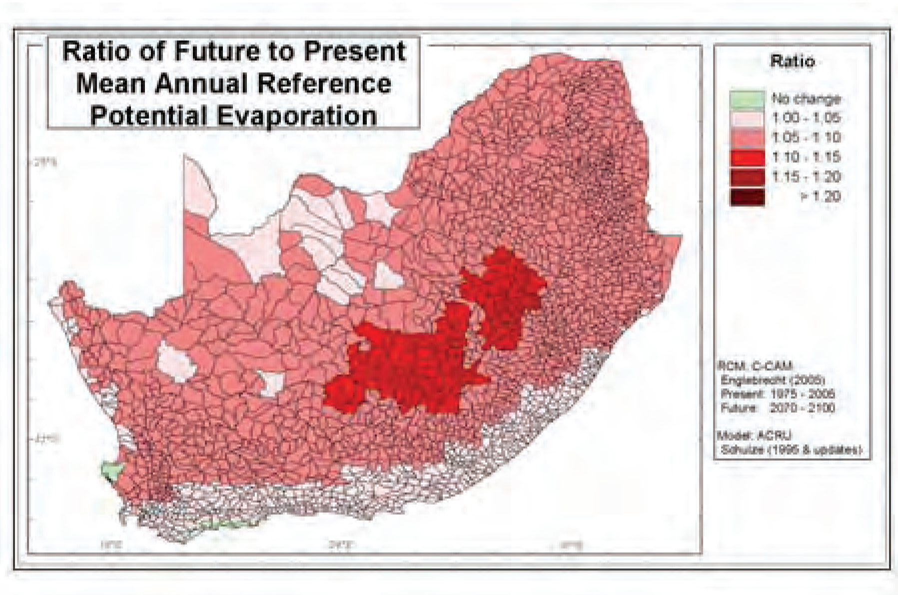


Figure 2.3: Ratios of future to present mean annual potential evaporation using the Hargreaves and Samani (1985) equation; Schulze et al., 2005

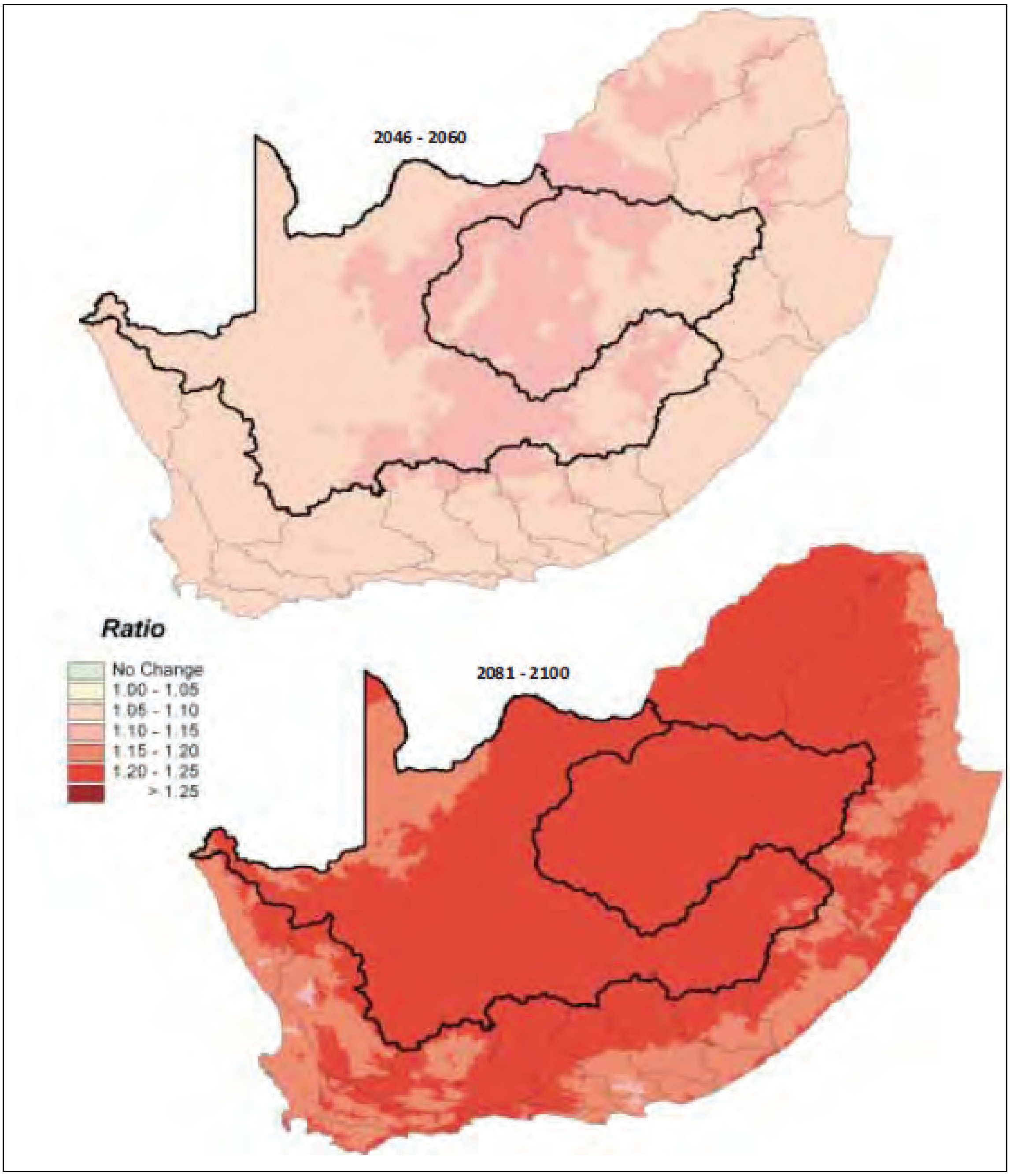


Figure 2.4: Ratios of intermediate future to present (top) and more distant future to present (bottom) mean annual reference crop evaporation, derived from evaporation equations and input from the ECHAM5 climate model; Knoesen et al., 2009

It should be noted that the impact of evaporative losses from open water bodies will not be considered in the analyses for this study, as this is beyond the scope of this research project. Suffice to say that evaporation from the surface area of reservoirs will need to be incorporated into the analyses as research into this area moves forward.

2.3 Rainfall

While the temperature signal of CC is clear, the precipitation signal is mostly still dominated by natural climate variability (Green, 2008). However, changes or trends in total annual rainfall over Southern Africa have been detected in analyses of historical rainfall records (IPCC, 2008). These changes range from an increase of up to 20% per decade in the arid Northern Cape, to a decrease of up to 20% in the Western Cape, as observed for the period 1979-2005 (see **Figure 2.6**).

In terms of projected CC scenarios, rainfall is expected to follow similar or even more drastic trends than those observed in historical records. However, there seems to be less agreement between research results on the expected direction and magnitude of change in rainfall.

2.3.1 Mean Rainfall

Schulze et al. (2005), using CSIRO Mk3 OAGCM results as downscaled with the dynamic C-CAM (Engelbrecht, 2005), indicates that mean annual precipitation (MAP) is expected to decrease for the period 2070 to 2100 to roughly 90 to 95% of the present MAP, over most of southern Africa, as shown in **Figure 2.5**.

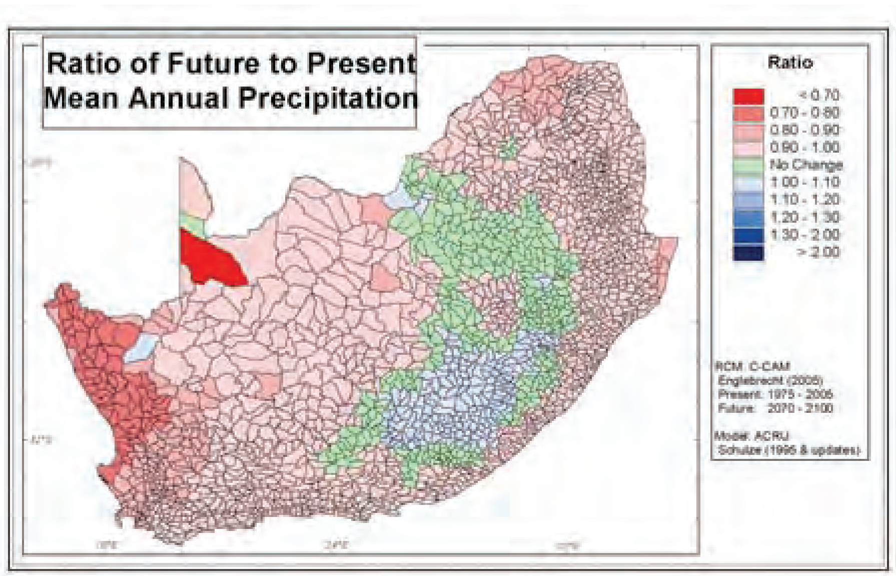


Figure 2.5: Ratios of future to present mean annual precipitation derived from C-CAM RCM scenarios; Schulze et al., 2005

The area in central South Africa, ranging from the North West province to Lesotho and the central KwaZulu-Natal Province, however, is expected to experience an increase in MAP of up to 10% for the same time horizon

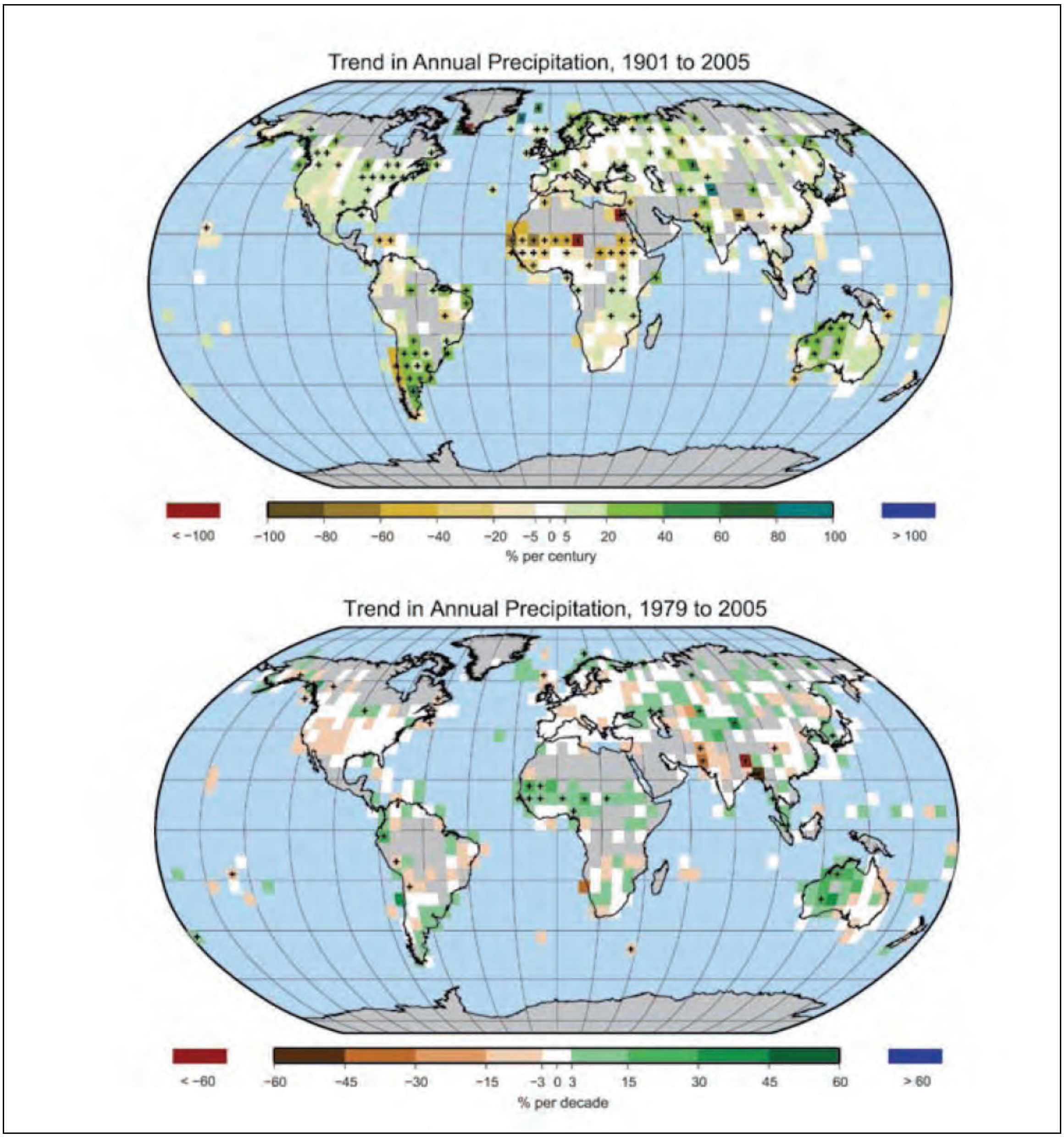


Figure 2.6: Trend of annual precipitation amounts, 1901-2005 (upper, % per century) and 1979-2005 (lower, % per decade), as a percentage of the 1961-1990 average, from GHCN station data. Grey areas have insufficient data to produce reliable trends. (IPCC, 2008)

In a report by Hewitson et al. (2005), a summary is provided of the expected changes in terms of regional CC of Southern Africa, which includes the following:

- Increased precipitation on the **escarpment and eastward**, although there is not agreement between different GCMs in terms of the seasonality.
- Increased intensity of precipitation over the **interior regions**, with a slight increase in total annual rainfall.
- Relatively stable or increased precipitation over **coastal regions**.

- Decreased annual precipitation over winter rainfall regions in the **Western Cape**, with more winter months indicating drying.

A more recent study (Knoesen et al., 2009) paints a less alarming picture, suggesting that MAP will mostly increase to up to as much as double the present MAP. It should be noted, however, that in these projections the Western Cape is still expected to be worse off than the rest of the country, potentially expecting a reduction of up to 20% of present MAP by the year 2081, as shown in **Figure 2.7**.

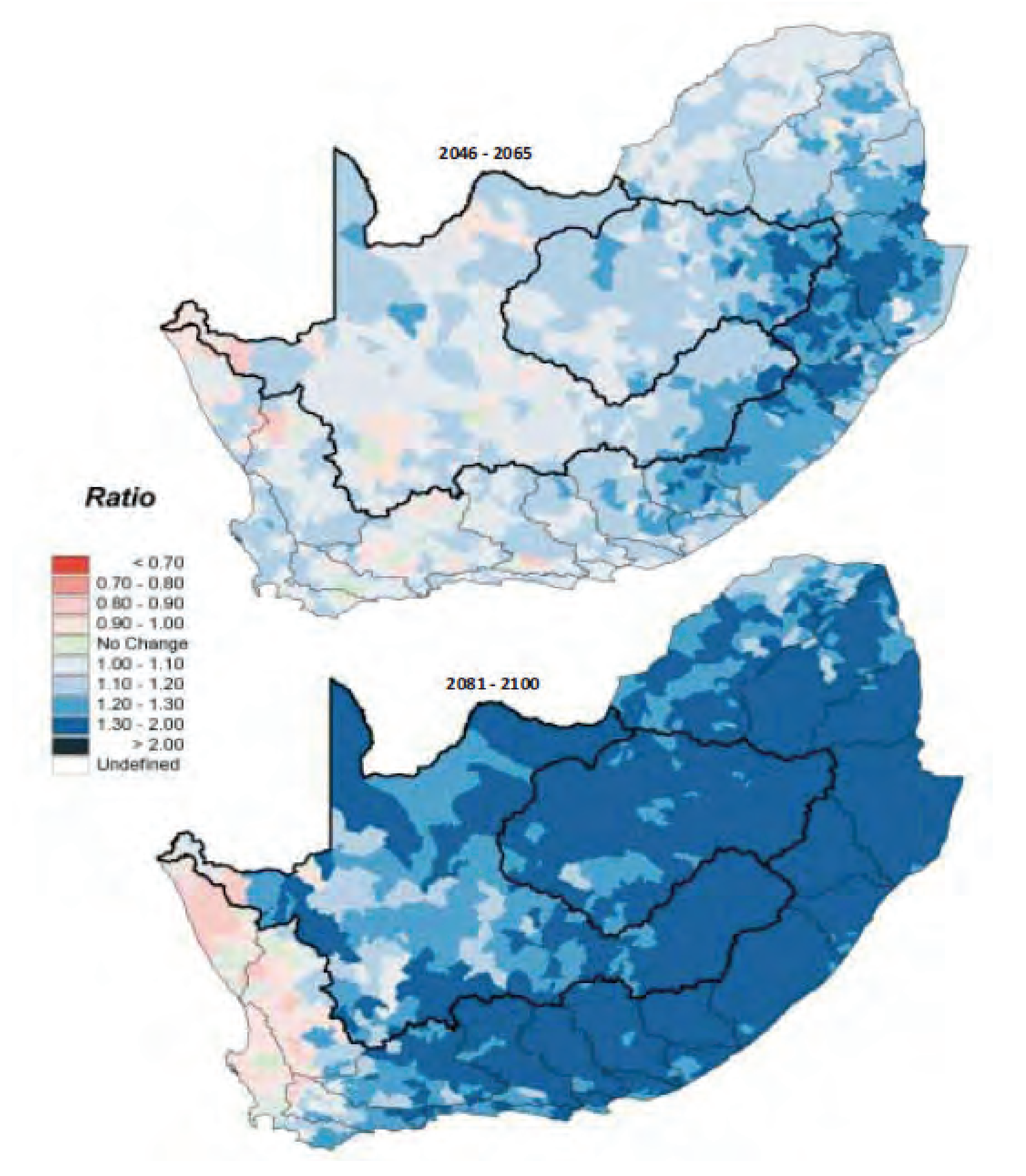


Figure 2.7: Ratios of the intermediate future to present (top) and more distant future to present (bottom) MAP as projected when using output from the ECHAM5 climate model. Knoesen et al., 2009

2.3.2 Variability in rainfall

Future year-to-year deviations of annual precipitation from the mean was also analysed in Schulze et al. (2005), making use of the *coefficient of variation* or CV. C-CAM simulated rainfall records predict decreasing variability along the coastal regions, as shown in **Figure 2.8**. This could well result in less variability in runoff, which in turn could result in higher water yields (assuming that the total runoff volume remains unchanged).

However, an increase in CV is indicated for most of southern Africa, including the Northern Cape, Limpopo, Eastern Mpumalanga and KZN. Following a similar argument than the one above, this could result in lower yields.

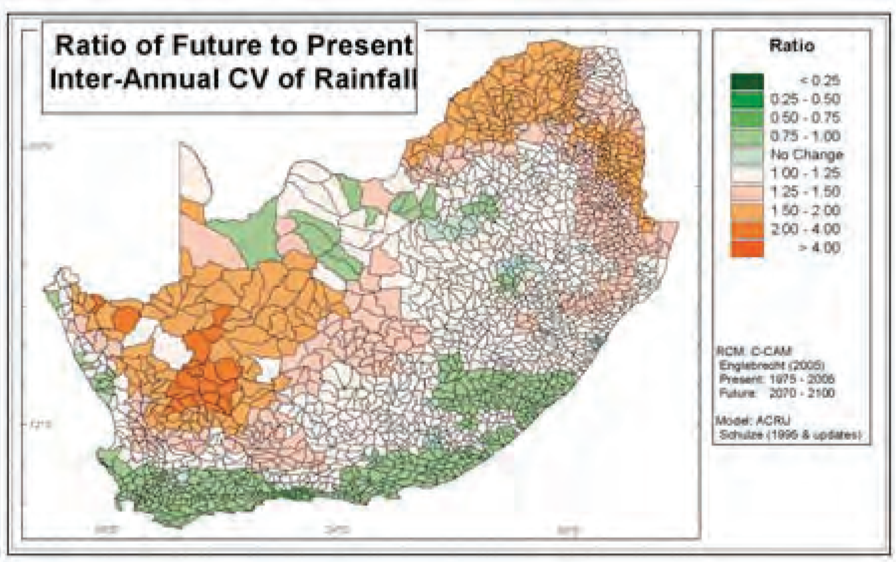


Figure 2.8: Ratios of future to present CV of annual precipitation derived from C-CAM RCM scenarios; Schulze et al., 2005

2.4 Runoff

Runoff, although not a climatic variable in itself, is strongly dependent on the climate. Runoff (associated with a specific CC scenario) is estimated by making use of a rainfall-runoff (or hydrological) model.

At present the only regional runoff records for Southern Africa are simulated by the SBEEH team at UKZN, using the ACRU model. For more detail on the data chain, see **section 4**. As was the case with rainfall, results on runoff projections from various studies agree to a lesser extent than those of temperature.

2.4.1 Mean runoff

An analysis undertaken by Schulze et al. (2005) indicates that significant changes in *mean annual runoff* (MAR) may be expected by the year 2070, as shown in **Figure 2.9**. In particular, the results indicate that increased runoff is expected over the eastern regions of the country, generally increasing to between 125% and 200% of present MAR. This is in line with the expected increase in precipitation over the escarpment and eastward, as described by Hewitson et al. (2005).

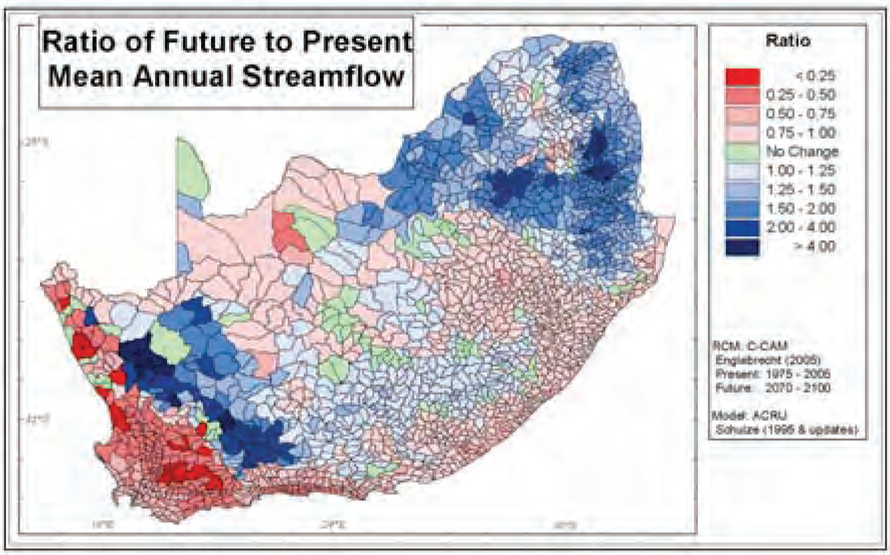


Figure 2.9: Ratios of future to present MAR; Schulze et al., 2005

Furthermore, Schulze et al. reports that a drastic reduction in future runoff volumes may be expected over the Western Cape, with future MARs as low as 25% of the present in some areas. Changes with regard to MAR over other coastal regions are expected to be minimal, ranging between 75% and 125% of the present.

A more recent study (Knoesen et al., 2009) indicates that, although runoff is expected to decrease in the Western Cape by the year 2081 to roughly 70% of the present, the rest of South Africa can expect an increase to more than 130% of the present, with the eastern regions possibly expecting more than double the present MAR. See **Figure 2.10**.

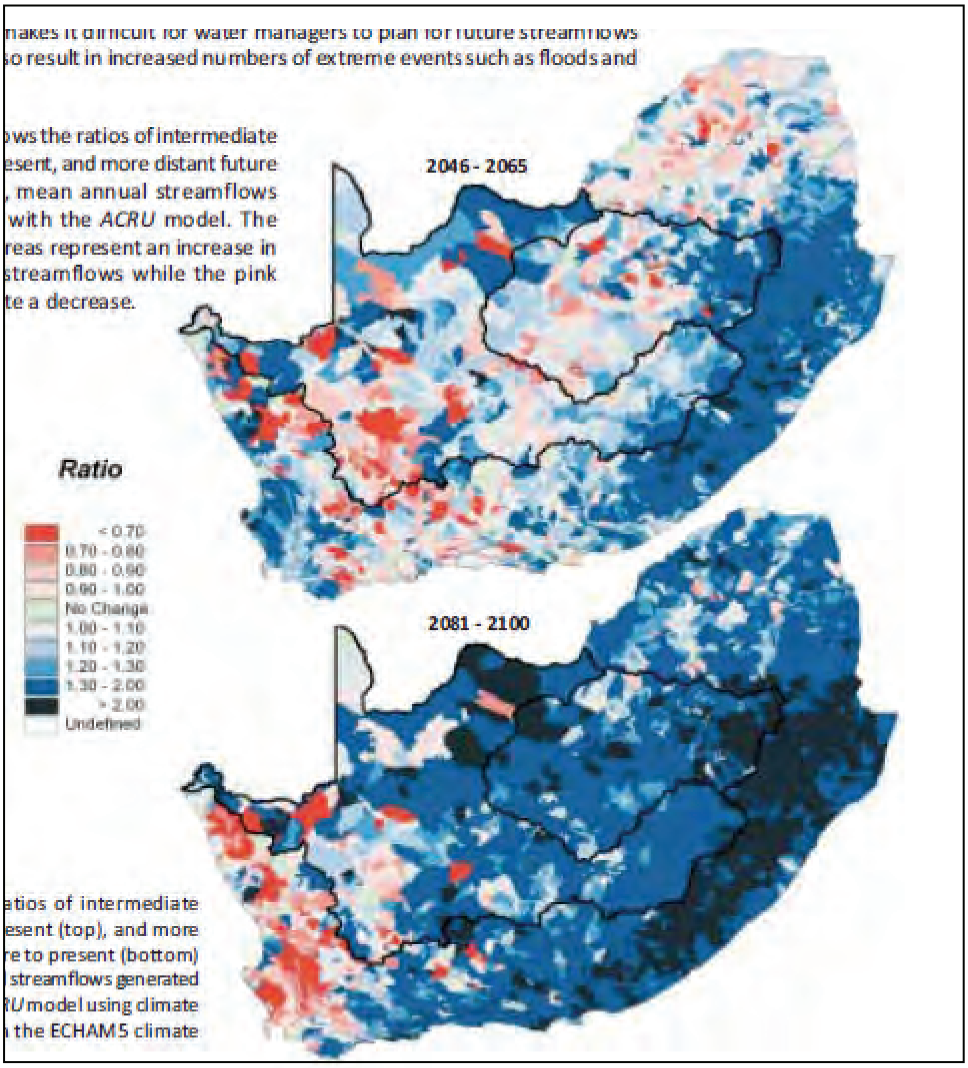


Figure 2.10: Ratios of intermediate future to present (top) and more distant future to present (bottom) MAR generated with the ACRU model using climate output from the ECHAM5 climate model; Knoesen et al., 2009

These reports of a potential reduction in future water availability in the Western Cape are echoed in low resolution findings published by the Wit et al., 2006 (**Figure 2.12**) as well as the IPCC (2007) – the latter indicating significant reductions in runoff volumes (mostly between 0% and 20%, but up to as much as 50% in the Western Cape) by the year 2081, as shown in **Figure 2.11**. These studies, however, predict less drastic change in the Eastern Highveld.

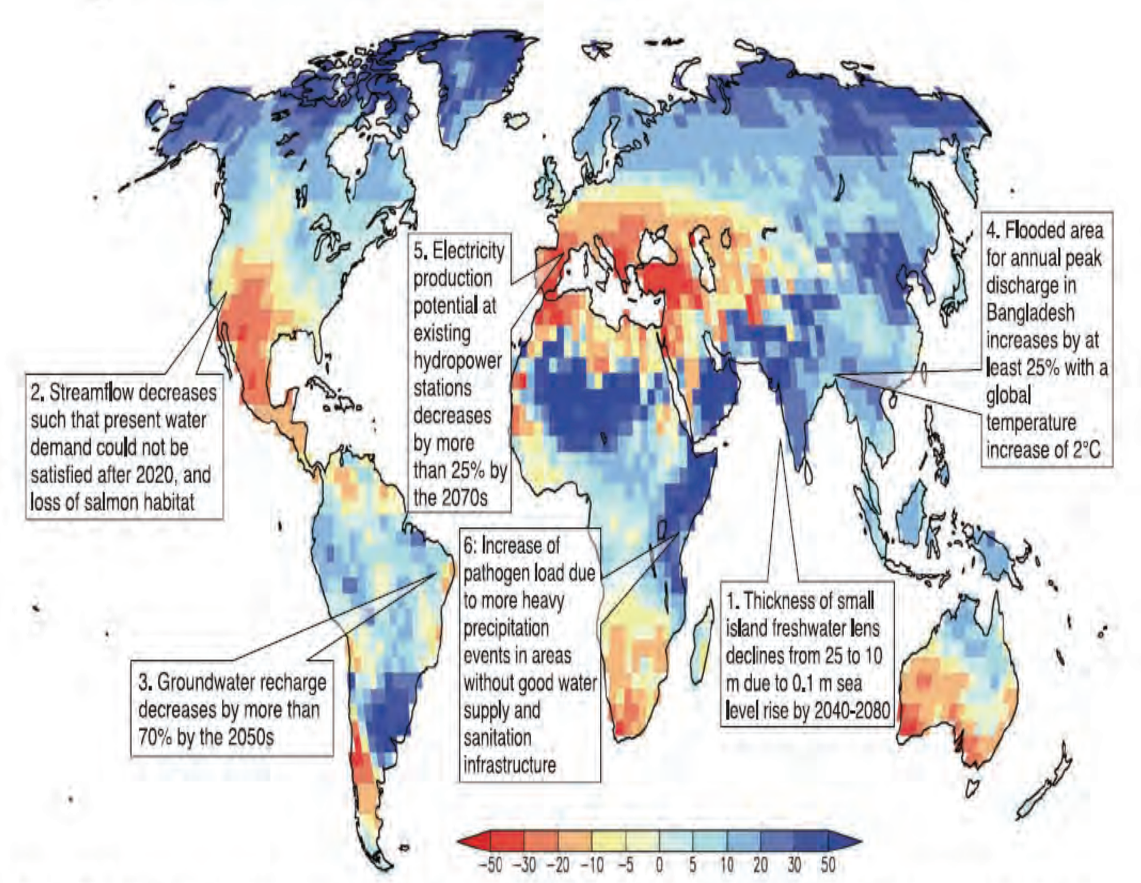


Figure TS.5. *Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions. Background shows ensemble mean change of annual runoff, in percent, between the present (1981-2000) and 2081-2100 for the SRES A1B emissions scenario; blue denotes increased runoff, red denotes decreased runoff. Underlying map from Nohara et al. (2006) [F3.8].*

Figure 2.11: Mean change in annual runoff (%)

2.4.2 Variability in runoff

It is generally accepted that rainfall in sub-Saharan Africa will become more variable as result of CC. This variability in rainfall is expected to translate into an even higher variability in runoff (De Wit et al, 2006), as shown in **Figure 2.12**. The 'amplified' variability in runoff could be the most serious consequence of CC, requiring the most urgent attention from both researchers and decision makers.

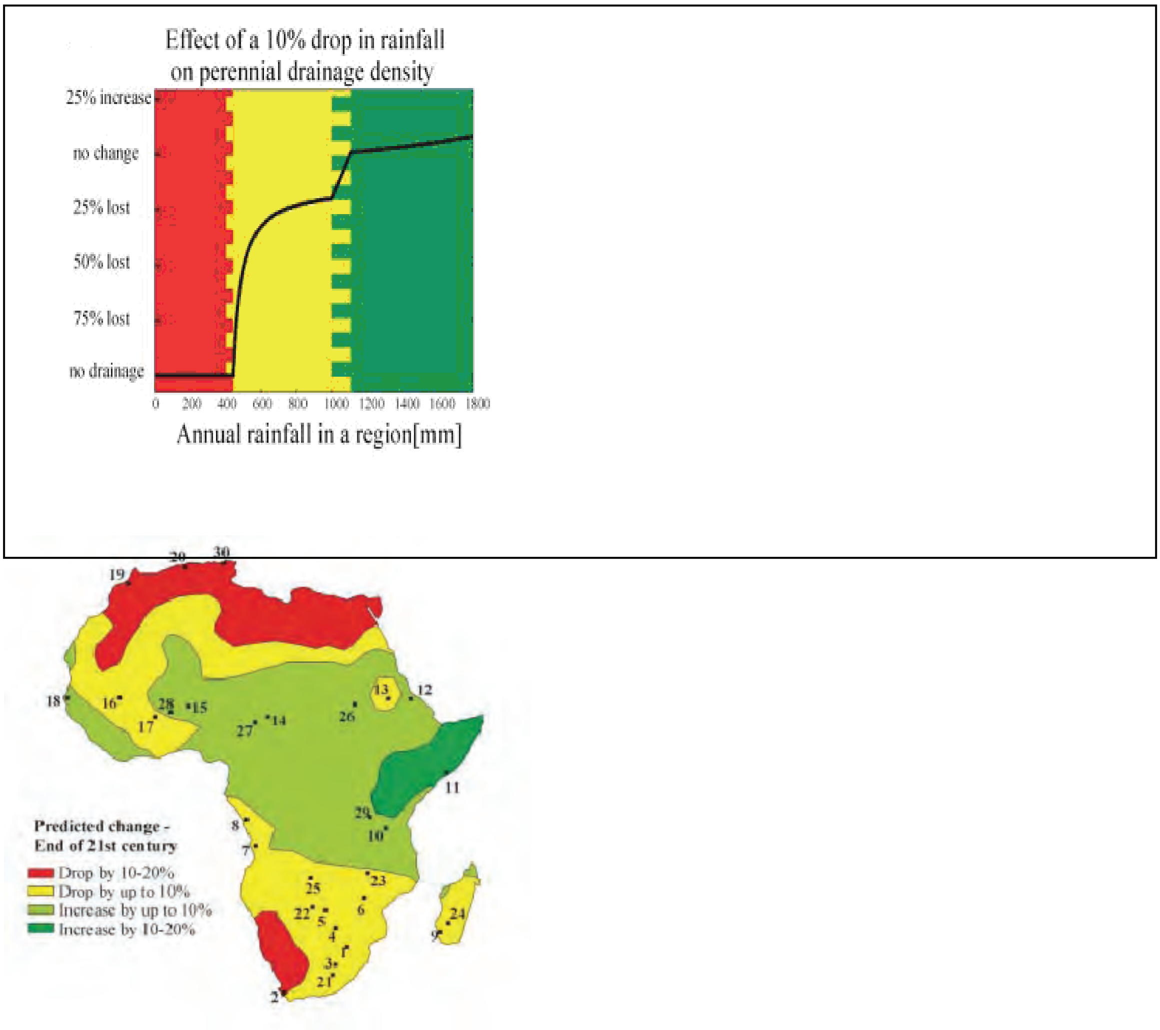


Figure 2.12: (a) Expected change in runoff relative to a 10% reduction in MAP for a range of current MAP values (b) Expected change in runoff. De Wit et al., 2006

In their analysis of future variability of runoff, Schulze et al. (2005) (**Figure 2.13**) report an expected change in CV to between 75% and 1.25% of the present CV for the Western Cape. This change is small compared to the expected change in mean annual runoff (0.25-0.75% of present MAR). Increased variability (up to four times the present CV of runoff) is expected in the Northern Cape.

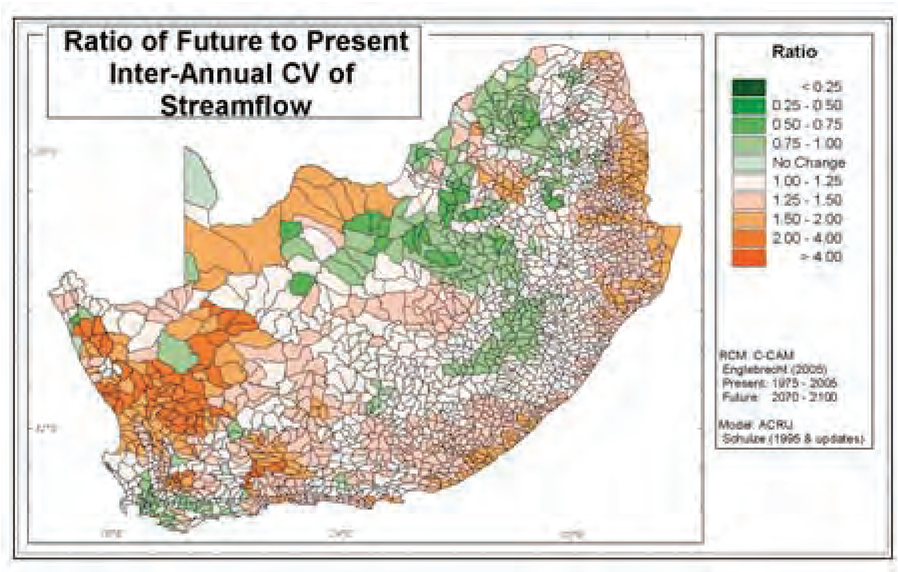


Figure 2.13: Ratios of future to present inter-annual CV of stream-flow; Schulze et al., 2005

From the discussion above it follows that change in climate may impact – in varying degrees – on the surface water runoff in South Africa. This should be taken into account by Water Resource Planners in their assessment of resource infrastructure capability, as the assumptions made in earlier analyses of yield characteristics may not be valid in future.

3. Methodology

The aim of this study is do develop and test a methodology that allows for the incorporation of scientific research results on Climate Change into the Water Resource Planning context. This movement from scientific knowledge to practical implementation is crucial in the quest to prepare for and manage the impacts that CC could have on our water resources and, in particular, the long-term yield of reservoirs. Although the direct application of this process will be in the water resources field, the impacts on society, economics, health and the environment are immeasurable. In fact, the ability to quantify the possible impacts of CC on available water resources could provide the first step towards quantifying and managing the far-reaching consequences of CC on other sectors of society.

3.1 Introduction

As the typical statistical characteristics (location, magnitude and variability) of runoff changes, it can have a significant impact on the yield of reservoirs.

To elaborate on this point we will assume a dam of fixed size with a particular historical natural inflow. The inflow is represented by a monthly time series (of N years), from which the total annual inflow can be calculated for each of the N years. These N values can be described statistically by the mean and the CV. Also, assuming a specific CC scenario, a new inflow sequence of N^1 years can be simulated. As for the original time series, the mean and CV can again be calculated.

Now, for the first example we shall assume the total annual runoff (or mean) of the CC scenario time series to be higher than the historical mean, but the variability to be unchanged. This will result in *higher water yields* from the reservoir, as the total amount of inflow into the dam increases, but the variability remains unchanged.

If however, the mean of the CC scenario time series is assumed to be the same as that of the historical sequence, but the variability is higher than that of the historical sequence, the yield of the reservoir will *decrease*.

In **Section 2.4** above, reference is made to the Schulze et al. report which indicated an expected decrease in MAR, but at the same time, also a decrease in CV for the Western Cape.
For the Eastern Highveld, increased MARs are expected, but changes in CV vary across the area. The important question that therefore arises is: *How will these changes in runoff*

characteristics impact on the yield characteristics of reservoirs? To answer this question in terms of yield and associated risk of failure, long-term stochastic yield analyses need to be performed.

3.2 Stochastic Yield Analysis

3.2.1 Stochastic generator

In order to determine the yield characteristics of a reservoir, stochastic yield analyses need to be performed on the specific inflow sequence, assessing the yield of the reservoir (in million m^3/a) at different assurances of supply (or conversely, at different risks of failure to supply). The South African Department of Water Affairs (DWA) have for a long time managed many national reservoir networks based on stochastic yield analyses. These analyses generally describe the volumetric yield of a particular reservoir (in million m^3/a) at an associated risk of non-supply. Using this methodology, different yields, associated with different risks, can be determined for a particular reservoir.

This method was developed in the 1980s as part of the Vaal River System Analysis (VRSA) study undertaken for the, then, Department of Water Affairs and Forestry, and has subsequently been published (Basson et al., 1994). As a detailed explanation of the stochastic yield analysis process is given in the reference, only a brief description of the process is provided here, assuming that only a single inflow sequence is input for the analysis.

A particular naturalised (historical) inflow sequence is input into the stochastic generator. Two very important assumptions are made with regard to this inflow sequence.

1. The sequence is stationary (i.e. statistical characteristics such as mean, variance, autocorrelation, etc. are all constant over time).
2. The period covered by the sequence is long enough to accurately reflect the statistical characteristics of the inflow (especially regarding prolonged drought periods).

The inflow sequence is characterised using a number of statistical parameters. A number of (e.g. 500) statistically similar sequences of prescribed length (say 100 years) are then simulated, using a random number generator and then literally ‘back tracking’ through all the statistical parameters determined at the start of the analysis. This ‘back tracking’ process also includes the dis-aggregation of annual total flows into monthly volumes.

The result is 500 synthetically generated monthly inflow sequences, having statistical characteristics that are similar to that of the original historical inflow sequence.

3.2.2 Yield analysis

Each of the 500 synthetically simulated sequences, the generation of which is described above, is then analysed individually as inflow into a reservoir of particular size. Assuming a fixed abstraction or target draft from the reservoir and a starting storage of the reservoir itself, (monthly) time-step modelling is then undertaken to determine how often the target draft cannot be supplied from the reservoir. This time step analysis is repeated 500 times, each time assuming a different, but statistically similar, inflow sequence.

Now, repeating the process described above for a range of target drafts, the risks of failure to supply, as associated with various target drafts, from a particularly sized reservoir can be determined based on the number of sequences that result in supply failures. So, for example, the result may be as indicated in **Table 3-1** below:

Table 3-1: Yield characteristics: Blyderivierpoort Dam (FSC = 56.05Mm^3; Analysis done in 2006)

Risk of failure:	**1:10**	**1:20**	**1:50**	**1:100**	**1:200**
Yield (Mm3/a):	157.3	157.0	150.0	146.5	143.5

This procedure (i.e. the *Stochastic generator* and *Yield analysis* described above) has been used widely in detailed water resource studies in South Africa over the last few decades.

3.2.3 Adaptation proposed for this study

The procedure described above is based on a specific reservoir, i.e. of a specific size or live full supply capacity (FSC). However, this study proposes an additional step to the procedure described above, the incorporation of differing possible reservoir sizes. Although similar analyses have been undertaken in the past as part of the validation of the stochastically simulated sequences, the process was done in the reverse order, i.e. fixing the yield and then determining the required reservoir size.

The idea here is therefore to fix different reservoir sizes and to determine the yields associated with different risks of failure for each of the reservoir sizes. In this way a more generic result can be obtained, allowing water resource planners to extrapolate results for a specific reservoir to reservoirs of differing sizes in areas with similar runoff characteristics and topography. Furthermore, it will also indicate what the impact of raising the specific existing dam wall would be on yield.

The results of the above analysis are presented in the form of graphs that show the relationship between live reservoir storage and gross yield (i.e. not accounting for the impact of evaporation losses from the exposed surface area of the reservoir in question) for a particular catchment and at varying assurances of supply. These graphs are generally referred to as *storage-draft-frequency* (SDF) curves or yield-capacity-relationship curves.

3.3 Limitations of the methodology

As already highlighted, the results of a yield analysis undertaken for any reservoir are largely reliant on the accuracy of the associated hydrological data set, in particular modelled inflows from the reservoir's catchment area. In turn, the characteristics of the modelled runoff data for particular climate change scenario are very much reliant on the outcome of the particular CC model and downscaling method used. It therefore follows that any inaccuracies or problems that may be present in the CC modelling or downscaling processes would follow the information chain and ultimately impact on the reliability of the yield results obtained.

A further challenge presented by this extended information chain is that a vast array of GCMs, RCMs, other downscaling methods and hydrological models are available, which gives rise to a very high number of combinations required to cover all possible outcomes. This, in turn, results in the need to analyse a very high number of alternative inflow sequences, each of which would require a separate stochastic yield analysis. This poses a challenge with regard to the sheer volume of data processing required.

As explained in **Section 3.2.1** above, there are 2 basic assumptions regarding the reservoir inflow sequence on which the yield analyses are based. The first is *stationarity* and the second is a long (typically more than 50 years) *record period*. However, the methodology currently employed in a typical CC analyses does not allow for the models to produce stationary time-series of climatic variables, since the very purpose of the CC analyses is to model the climatic changes caused by changes in, say, atmospheric CO_2 concentrations. Furthermore, the time-series simulated by these CC models are generally 30 years in length, at most.
Although the limited record period may then be considered to be stationary (simply by virtue of its short record length), this poses a new challenge for the yield analysis process as the short record does not provide adequate information on the inherent temporal variability of flow and the length of severe periods of below average flow that determine reservoir yield.

It is therefore of critical importance that improved communication channels between water resource planners and CC researchers need to be established in order to ensure that research outputs are aligned with the requirements of water resource planning tools to ensure that the scientific findings can be incorporated into the planning process and implemented in practice.

Finally, although evaporation and rainfall are two key climatic variables that will be impacted upon as a result of CC, the impact of these two variables with regard to net evaporation from the open water surface of the reservoir is not accounted for in the present methodology. The impact of CC on evaporation and rainfall is, however, incorporated in the hydrological rainfall-runoff model and, therefore, the resulting impact of CC on modelled catchment runoff – the main driver of reservoir yield.

4. Data pre-processing

4.1 Background

Climate change scenarios are simulated making use of General Circulation Models or GCMs, assuming a particular future greenhouse gasses emission scenario or 'story line'. A number of CC story lines exist, four of which have been defined by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios (2000) (or SRES), a summary of which is shown below. It is important to note that, for the purpose of this study, scenario "A2" was assumed in all analyses. Scenario A2 is essentially based on the assumption that CO_2-emissions continue relatively unabated into the next century and is considered by many CC experts to represent the most likely future situation.

The output from the GCMs is at a large geographical scale and in order to obtain corresponding results that are representative of specific areas (i.e. at a smaller scale), the GCM results can either be passed through a Regional Circulation Model (or RCM e.g. C-CAM) or be empirically downscaled using statistical methods.

Table 4-1: SRES (IPCC, 2000)

Economic emphasis →

Global integration ↑ | Regional emphasis ↓

A1 storyline World: market-oriented Economy: fastest per capita growth Population: 2050 peak, then decline Governance: strong regional interactions; income convergence Technology: three scenario groups: • **A1FI**: fossil intensive • **A1T**: non-fossil energy sources • **A1B**: balanced across all sources	**A2 storyline** World: differentiated Economy: regionally oriented; lowest per capita growth Population: continuously increasing Governance: self-reliance with preservation of local identities Technology: slowest and most fragmented development
B1 storyline World: convergent Economy: service and information based; lower growth than A1 Population: same as A1 Governance: global solutions to economic, social and environmental sustainability Technology: clean and resource-efficient	**B2 storyline** World: local solutions Economy: intermediate growth Population: continuously increasing at lower rate than A2 Governance: local and regional solutions to environmental protection and social equity Technology: more rapid than A2; less rapid, more diverse than A1/B1

← Environmental emphasis

Two of the main (down scaled) results of the GCMs are time-series of the temperature and rainfall associated with three distinct time-horizons, each 20 years in length, namely, *present* climate (from 1971 to 1990), *intermediate future* climate (from 2046 to 2065), and *distant future* climate (from 2081 to 2100). This information can then be input into a hydrological rainfall/runoff model in order to simulate time-series of surface water runoff that can be associated with the CC scenario and time-horizon in question.

This information chain is simplified in a diagrammatic representation provided in **Figure 4.1**.

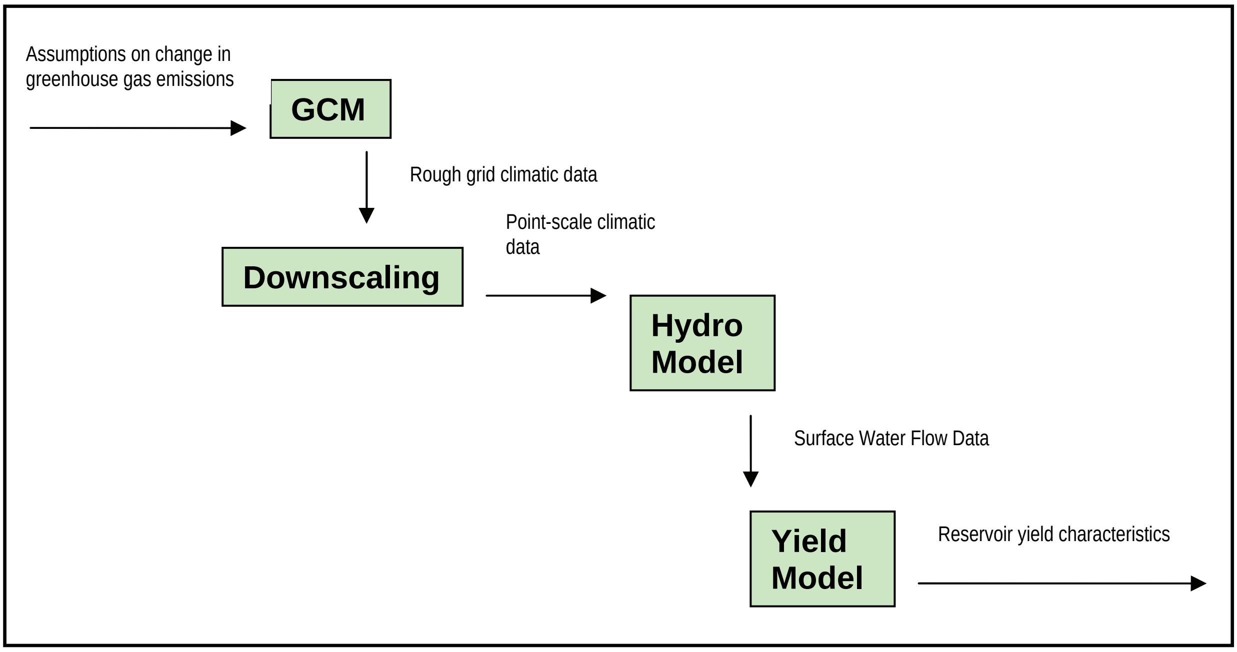


Figure 4.1: Ratios of future to present inter-annual CV of stream-flow; Schulze et al., 2005

4.2 Focus areas

In **Section 2**, reference was made to two regions within southern Africa that consistently show the most extreme change for climatic and hydrological variables, for a range of CC scenarios. These are the Western Cape and the Eastern Highveld, with the Western Cape probably being the region that could expect the most severe decrease in water resource availability. Conversely, the Eastern Region of South Africa could possibly experience an increase in water resource availability.

Indeed, Schulze et al. (2005) emphasize this vulnerability of the Western Cape, referring to the region as a "hotspot" of hydrological change that is a cause for major concern. They go on to say that this hydrological change is:

> '…critical to the management of local to regional water resources, and these "hotspots" may require acting upon sooner rather than later by decision makers.'

De Wit (2006) also stresses the vulnerability of this region saying that:

> 'Areas near Cape Town will likely suffer most, losing more than half their perennial supply. This means there will be no relief for this drought-stricken region.'

Within this context, it was decided at a reference group meeting held in September 2009 that three reservoir sites should be analysed in order to apply and test the suggested methodology as part of the current study. These are shown below and include existing reservoirs in the Western Cape, the Eastern Region, as well as on the Highveld where no extreme changes in future rainfall or runoff are expected due to CC.

1. Berg River Dam (Western Cape)
2. Midmar Dam (KwaZulu-Natal Midlands)
3. Grootdraai Dam (Eastern Highveld)

4.3 Data used in this study

As a point of departure, long-term sequences of naturalised historical inflows were obtained for each of the three selected reservoirs from earlier detailed hydrological studies. These are summarised below and, since the studies were based on naturalised historically observed hydro-meteorological data, were considered to be stationary and representative of the *present* climatic situation (i.e. prior to any significant climate change impacts).

1. Berg River Dam (DWAF, 2008) for the period. 1928-2004 (hydrological years)
2. Midmar Dam (DWAF, 1997) for the period 1925-1995 (hydrological years
3. Grootdraai Dam (DWAF, 1999) for the period 1920-2004 (hydrological years).

The CC runoff information used in this study, provided by the University of KwaZulu-Natal (UKZN), emanated from scenarios developed by the Climate Systems Analysis Group (CSAG) at the University of Cape Town (UCT). The results were derived from global scenarios produced by five GCMs (Lumsden *et al*., 2009), as summarised below:

1. CGCM3.1 (Canadian Center for Climate Modelling and Analysis),
2. CNRM-CM3 (Meteo-France / Centre National de Recherches Meteorologiques, France),
3. ECHAM5/MPI-OM (Max Plank Institute for Meteorology, Germany),
4. GISS-ER (NASA / Goddard Institute for Space Studies, USA) and the
5. IPSL-CM4 (Institut Pierre Simon LaPlace, France).

It is important to note that there are other GCMs also currently being run by the CSAG, but that associated runoff data are not yet available.

The GCM results were statistically downscaled by CSAG to more than 2 500 rainfall stations and 400 temperature stations in southern Africa (Lumsden *et al*., 2009).

Hydrological modelling, using the GCM-simulated climatic data, was undertaken by Schulze et al., first in 2005 using dynamically downscaled GCM results and again in 2009, using empirically downscaled GCM results. Hydrological modelling was undertaken using the physically based, daily time-step ACRU model. In both studies, Schulze et al. incorporated daily temperature and rainfall data related to specific CC scenarios. These data, together with baseline land cover information as delineated by Acocks (1988), were used to simulate daily time-series results of hydrological variables, including surface water runoff. Flow sequences spanning a period of 19 hydrological years were simulated and the latest set of hydrological data, for which modelling was undertaken at a quinary (sub-quaternary) catchment scale, was made available to the study team.

Three time-horizon runs were undertaken for each GCM, as summarised below:

1) a present-day run, representing historical rainfall and Acocks land cover for the time period 1971-1989, hydrological years (i.e. October to September)
2) a CC scenario run, representing 'intermediate future' climate, for the time period 2046-2064, hydrological years.
3) a CC scenario run, representing 'distant future' climate (for the time period 2081 to 2099, hydrological years)

A comparison of the downscaled present-day runoff characteristics obtained from the five selected GCMs is provided in **Table 4-2**, together with the characteristics of the naturalised historical inflow sequences obtained from the earlier detailed hydrological studies. This comparison clearly highlights a cause for concern regarding the GCM-based time-series, since their present-day MAR estimates differ significantly from one another, as well as from that of the naturalised historical inflow sequences (which, as explained earlier, is considered to be stationary and representative of the *present* climatic situation).

Table 4-2: Present time horizon MAR (Mm^3/a) of GCM-based short-term sequences and observation-based long term sequences

	GCM					
Reservoir site	**ECHAM5**	**GISS-ER**	**IPSL-CM4**	**CGCM3.1**	**CNRM-CM3**	**Detailed study**
Berg River Dam	32.43	16.6	24.38	25.78	23.68	142.0
Midmar Dam	119.43	362.74	199.56	131.38	226.88	201.0
Grootdraai Dam	325.28	1 075.83	628.83	316.8	682.27	457.68

The implication of this difference in present time horizon results is that the starting point of the GCM results differs from the actual reality, so it is not possible to get a fair indication of the planning horizons that should be assumed in terms of the interpretation of yield estimates based on projected future climate.

Although many researchers prefer to report the projected change in climate or runoff-related statistics in terms of relative proportions, this still does not account for the fact that the models do not always start off with consistent estimates of climate (or runoff) for the present time horizon. As the projected change in statistics on climatic (or runoff) variables is not linear, one cannot assume the relative change in modelled climate (or runoff) to be applicable to actual observed climate (or runoff). Thus, in order to bring yield analysis results for the various time horizons into line with measurement-based results, a methodology for the adjustment of CC time series had to be developed. This limitation was, however, accepted for the purposes of the present study but further research in this regard is required.

4.4 Time series adjustment

In **Section 3.2** the need for long-term inflow sequences (typically 50 years or more) was highlighted – the reasoning being that in order to obtain reliable yield estimates, one should get a fair indication of the length of the most severe period of below average flow (or "critical period") of the catchment in question. Having too short an inflow sequence could result in under-estimation of the critical period and therefore over-estimation of the reservoir yield. Therefore, a methodology was required in order to obtain inflow sequences that reflect future flow regimes for specific CC scenarios, but with longer record periods and stationary data.

Another limitation in the GCM-based runoff sequences is the fact that, as shown in **Section 4.3**, the characteristics of the present time-horizon results differs significantly from one GCM to another, as well as from that of the historical sequence. This difference is both with regard to the MAR and the seasonality or monthly distribution pattern.

In view of the above limitations, a methodology was developed as part of this project to adjust the GCM-based short-term time-series in order to account for these discrepancies.

The method requires four time-series data sets as input, i.e. the three 19-year GCM-based runoff sequences obtained from the SBEEH, as well as the as well as naturalised historical inflow sequences obtained from the earlier detailed hydrological studies (typically with record periods of more than 50 years).

A brief outline of the methodology is provided below, with a detailed discussion in **APPENDIX A**.

1. The annual totals are calculated for each of the three 19-year GCM-based runoff sequences as well as the long-term historical inflow sequence. This results in four annual inflow sequences.
2. The following percentiles are calculated for each of the annual inflow sequences: 0, 25, 50, 75 and 100.
3. For each of the two future time-horizon 19-year GCM-based runoff sequences, the percentiles are expressed as sets of factors, representing the ratio of *future* vs. *present* (e.g. *IntFut%50 / Present%50*, for the 50 percentiles of the *intermediate future* and *present* sequences).
4. The percentiles calculated earlier for the long-term historical inflow sequences are then multiplied, first, with the set of factors for the *intermediate future* and then, with the set of factors for the *distant future*. The result is three sets of percentiles for the long-term sequence, i.e. the *Original*, *Original*IntFut* and *Original*DistFut*. The last two sets represent the percentiles of the two future time-horizon GCM-based runoff sequences, but over a long period.
5. Linear interpolation is applied to determine factors that are required to adjust total annual flow values in the original long-term historical inflow sequence that do not correspond with one of the five mentioned earlier. The result is two new long-term annual inflow sequences that capture some of the changes in the characteristics of the two future time-horizon GCM-based runoff sequences relative to that of the present day GCM-based sequence.
6. Finally, to disaggregate the annual totals into monthly values, the mean monthly distribution of the two future time-horizon GCM-based runoff sequences is calculated, per quartile.
7. The above monthly distributions are then used to disaggregate the total annual flow volumes in the new long-term sequence, for each particular quartile

(Steps 8 and 9 to follow).

The above procedure achieves two main objectives:

i. Obtaining long-term, stationary runoff sequences representing the *intermediate future* and *distant future* situations.
ii. Bringing the changes represented by GCM future time-horizon results in line with actual present naturalised flow conditions.

Upon further investigation, the research team found that in some instances the seasonality (i.e. the monthly distribution of annual total flows) of the 19-year GCM-based present time-horizon sequence differed significantly from that of the long-term historical sequence. In order to facilitate the comparison of yield results between the different time-horizon results of the GCM-based runoff sequences, the long-term historical sequence was adjusted to reflect a seasonal distribution similar to that of the 19-year GCM-based present time-horizon sequence. Thus, the methodology was adapted to also include the following steps:

8. Calculate the mean monthly distribution (per quartile – as for the future time-horizons in step 6 above) of the 19-year GCM-based present time-horizon sequence.
9. Having characterised both the long-term historical and 19-year GCM-based present time-horizon sequences, disaggregate the total annual flow volumes of the long-term historical sequence using the mean monthly distribution of the 19-year GCM-based sequence for each particular quartile.

The two additional steps (i.e. 8 and 9 above) resulted in a new long-term historical sequence that has the same MAR as the original historical sequence, but with a seasonal distribution similar to that of the 19-year GCM-based present time-horizon sequence.

The resulting three stationary long-term flow sequences (for each of the five GCMs) represent the cumulative inflow into a reservoir under three different time horizons, i.e. *present*, *intermediate future* and *distant future* as described in **Section 3.2**, and were subsequently used to perform the yield analyses.

Finally, in the light of the discussion above, the information flow chain shown earlier in **Figure 4.1** can now be expanded upon in order to incorporate the methodology described above. This 'updated' information flow chain is summarised in **Figure 4.2**.

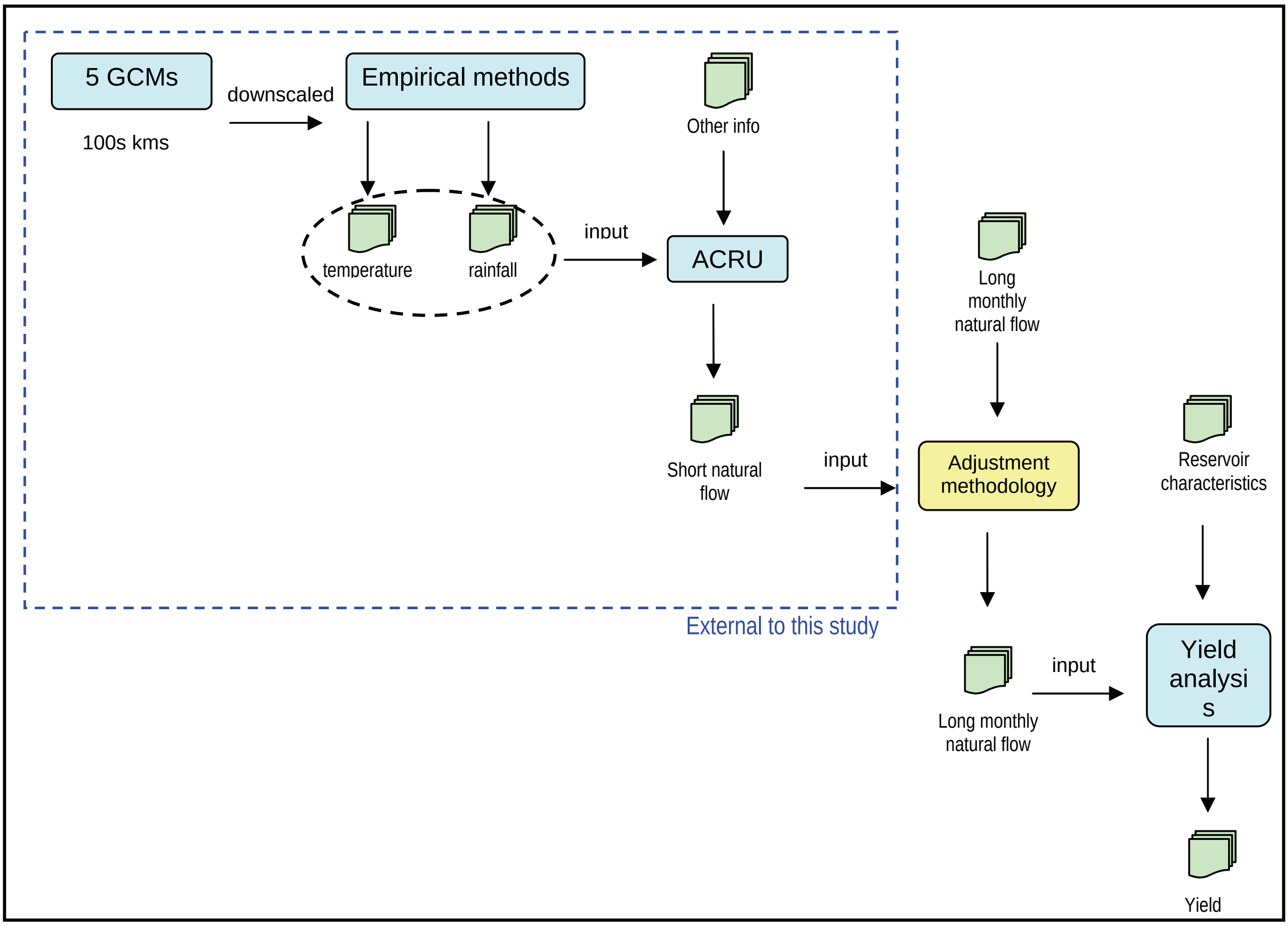


Figure 4.2: Climate change information chain for this study

In this study, different CC time horizons and different GCMs will be represented by the results obtained from the various adjusted naturalised inflow sequences, as described above.

5. Analysis software

The project team initiated the development of a Stochastic and Yield-Capacity (or Storage-Draft-Frequency) curve pre-processor (or SDFPrep.exe) to facilitate analyses performed for this and similar studies.

The purpose of the SDFPrep.exe is two-fold. Firstly, it serves as an interface that allows access to stochastic generators, also performing standard validation and verification tests on the various stochastically simulated monthly sequences. At present SDFPrep incorporates the existing Stochastic Model of South Africa (STOMSA) software for stochastic streamflow generation, but the development team is in the process of investigating the possibility of adding alternative stochastic generators. The incorporation of other stochastic models (especially the Variable Length Bootstrapping method) is expected to enhance the stochastic analyses associated with CC modelling – particularly if methodologies are developed at a later stage that would enable the performing of yield analyses on non-stationary time-series. The software does however currently allow for the importation of sequences simulated externally to the system, to perform verification, validation and yield-capacity curve derivation.

The secondary purpose of the software is to automate the previously manual process of generating yield-capacity curves (storage-draft-frequency curves) to assess reservoir yield characteristics. This process determines a median storage, and proceeds to calculate the yields (at different assurances) of reservoirs of varying sizes for each runoff sequence that has associated stochastically generated sequences. The analyses can be undertaken based on either the incremental or cumulative catchment upstream of the dam in question.

In order to achieve the above results, various analyses are performed by the software and these are briefly discussed in the following sections.

5.1 Stochastic analysis

The stochastic functionality incorporates the stochastic analyses, simulation and graphical tests provided by the STOMSA software. In order to perform the yield-capacity analysis, the current version of Sdfprep.exe requires that 500 sequences are generated, each 100 years in length.

A detailed description of STOMSA is provided in the STOMSA *User Guide* (Van Rooyen & McKenzie, 2004).

5.2 *Yield-capacity analysis*

This functionality allows for the derivation of the yield-capacity curve and mimics the G6b_sdfmedian.exe software, developed in 2003 specifically for the purpose of deriving the yield-capacity curve as reflected in the Water Situation Assessment Model (WSAM).

The main steps of the yield-capacity analysis are as follows:

1. Median starting storages are determined for a range of reservoir sizes (see DWAF report no. 14/12/4/2)
2. Yields are determined for the various reservoir sizes by means of detailed long-term stochastic yield analyses (see DWAF report no. 14/12/4/2)
3. Finally, results of the yield analysis are represented on a graph indicating *Yield* vs. *Storage Capacity*.

Yields are determined at recurrence intervals of failure of 1:10, 1:20, 1:50, 1:100 and 1:200 years and for dams of sizes of 10%, 20%, 30%, 50%, 75%, 100%, 125%, 150%, 200%, 300%, 500% and 1 000% of MAR.

These yields then represent points on a yield-capacity curve, an example of which is shown below in **Figure 5.1.**

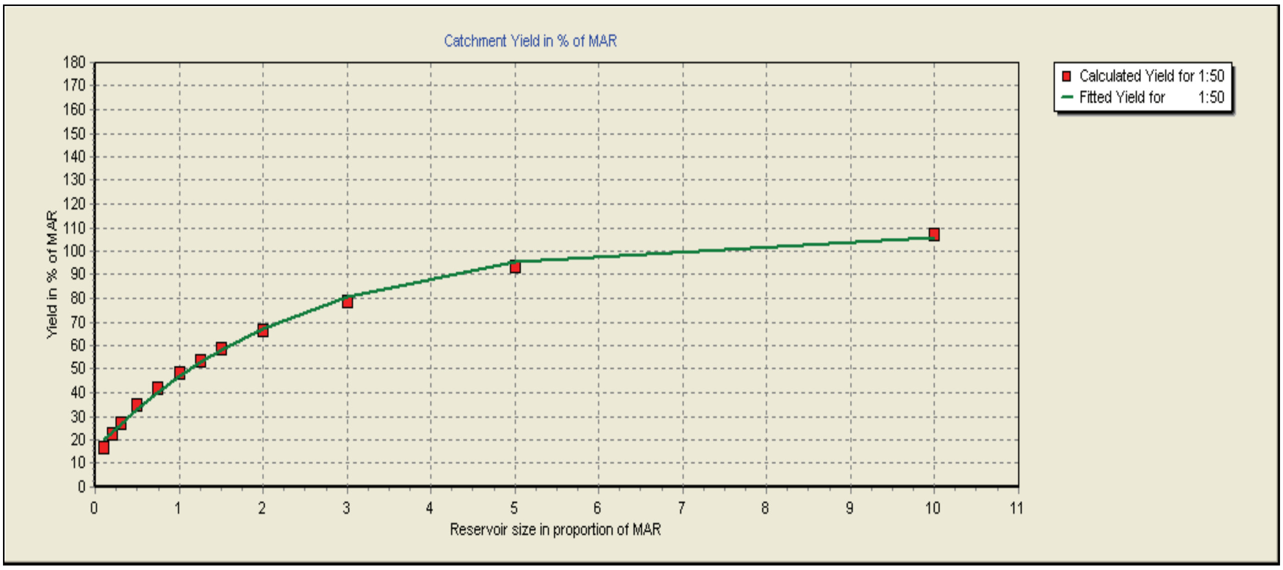


Figure 5.1: Example of a Yield-Capacity Curve

6. Discussion of results

6.1 Data pre-processing

In **section 4** of this report a detailed discussion on the data pre-processing procedure was provided. This procedure involves the adjustment of the future time-horizon of the GCM-based runoff sequences (spanning 19 hydrological years and reflecting various CC scenarios) in order to achieve the following two main objectives:

1. To ensure that the changes represented by the GCM-based sequences relative to GCM-based sequences for the *present* time-horizon are brought in line with naturalised historical inflow sequences obtained from earlier detailed hydrological studies.
2. To create a long, stationary runoff sequences representative of a particular CC scenario and time-horizon, in order to achieve more reliable yield results.

Making use of the time-series adjustment methodology, three *long-term* runoff sequences (representing the *present*, *intermediate future* and *distant future* time-horizons) were derived for each of the three selected reservoirs and for each of the five GCMs (with the exception of CGCM3.1, for which only present and intermediate future time-horizon sequences were available).

This time-series adjustment methodology, although quite crude, still relies on relatively similar frequency distributions of the detailed study-based long-term sequence and the short-term GCM-based sequences. For example, if the detailed study-based sequence exhibits a relatively high frequency of low-flow occurrences, the GCM-based sequence should also reflect a similar distribution. If this is not the case it could, for example, result in a situation where the median flow of the adapted sequence is lower than the 25^{th} percentile flow of the same sequence. Clearly this situation would be incorrect, but some minor modifications to the adjustment methodology could remedy this problem. In the case of the Berg River Dam, some of the GCM-based sequences exhibited such inconsistent underlying statistical distributions.

A total of 14 long-term sequences were therefore derived for each reservoir which served as basis for the stochastic and subsequent yield analysis.

The MAR and CV estimates based on the 19-year GCM-based runoff sequences are summarised in **Table 6-1a** and **b**. Similar results for the corresponding long-term runoff sequences derived using the time-series adjustment methodology are shown in **Table 6-3a** and **b**.

The MAR and CV estimates based on the 19-year GCM-based runoff sequences are summarised in **Table 6-1a** and **b** Similar results for the corresponding long-term runoff sequences derived using the time-series adjustment methodology (as described earlier) are shown in **Table 6-3a** and **b**.

Table 6-1a: MAR estimates (Mm^3/a) of 19-year GCM-based runoff sequences (for the *present*, *intermediate future* and *distant future* time-horizons)

	Berg River Dam			Midmar Dam			Grootdraai Dam		
	Present	**Int. Fut**	**Dist. Fut**	**Present**	**Int. Fut**	**Dist. Fut**	**Present**	**Int. Fut**	**Dist. Fut**
ECHAM5	32.43	37.06	30.20	119.43	238.55	300.38	325.28	459.12	722.42
GISS-ER	16.60	18.09	15.37	362.74	360.67	373.10	1075.83	1151.99	1099.83
IPSL-CM4	24.38	17.02	18.22	199.56	308.47	340.62	628.83	811.58	731.40
CGCM3.1	25.78	26.03	-	131.38	231.94	-	316.80	539.91	-
CNRM-CM3	23.68	22.39	17.44	226.88	253.11	299.09	682.27	874.58	1002.43
Observation-based long-term sequence	142.07	-	-	201.71	-	-	457.68	-	-

Table 6-2b: CV estimates of <u>19-year GCM-based runoff</u> sequences (for the *present*, *intermediate future* and *distant future* time-horizons)

	Berg River Dam			Midmar Dam			Grootdraai Dam		
	Present	Int. Fut	Dist. Fut	Present	Int. Fut	Dist. Fut	Present	Int. Fut	Dist. Fut
ECHAM5	0.438	0.211	0.252	0.475	0.444	0.449	0.305	0.372	0.391
GISS-ER	0.312	0.383	0.364	0.303	0.344	0.367	0.312	0.330	0.391
IPSL-CM4	0.284	0.318	0.379	0.572	0.514	0.361	0.657	0.612	0.465
CGCM3.1	0.265	0.248	-	0.537	0.408	-	0.429	0.560	-
CNRM-CM3	0.329	0.373	0.375	0.421	0.466	0.538	0.367	0.389	0.535
Observation-based long-term sequence	0.324	-	-	0.495	-	-	0.782	-	-

Table 6-3a: MAR estimates (Mm^3/a) of <u>long-term</u> sequences (for the *present*, *intermediate future* and *distant future* time-horizons)

	Berg River Dam			Midmar Dam			Grootdraai Dam		
	Present	Int. Fut	Dist. Fut	Present	Int. Fut	Dist. Fut	Present	Int. Fut	Dist. Fut
ECHAM5	142.07[1]	175.46[1]	144.68[1]	201.71	414.73	556.51	457.68	723.58	1218.44
GISS-ER	142.07	167.28	139.67	201.71	221.70	222.19	457.68	568.88	543.73
IPSL-CM4	142.07	104.09	112.63	201.71	334.58	356.26	457.68	655.24	547.80
CGCM3.1	142.07[2]	155.85[2]	-	201.71	359.62	-	457.68	883.31	-
CNRM-CM3	142.07	139.00	109.22	201.71	231.34	297.70	457.68	654.52	858.46

Table 6-4b: CV estimates of <u>long-term</u> sequences (for the *present*, *intermediate future* and *distant future* time-horizons)

	Berg River Dam			Midmar Dam			Grootdraai Dam		
	Present	Int. Fut	Dist. Fut	Present	Int. Fut	Dist. Fut	Present	Int. Fut	Dist. Fut
ECHAM5	0.324[1]	0.203[1]	0.191[1]	0.495	0.525	0.590	0.782	0.849	0.912
GISS-ER	0.324	0.515	0.471	0.495	0.650	0.628	0.782	0.790	0.907
IPSL-CM4	0.324	0.424	0.471	0.495	0.564	0.410	0.782	0.763	0.631
CGCM3.1	0.324[2]	0.395[2]	-	0.495	0.483	-	0.782	0.879	-
CNRM-CM3	0.324	0.480	0.456	0.495	0.628	0.846	0.782	0.842	1.071

[1] Time-series adjustment was done using manual estimates of minima conversion factors. This was required due to gross differences in statistical distribution of the GCM-based time-series and the long-term sequence obtained from the detailed study.

[2] Time-series adjustment was done using the 55th percentile as opposed to the 50th percentile. This minor alteration was required as there were inconsistencies in statistical distribution of the GCM-based time-series and the long-term sequence obtained form the detailed study.

6.2 Stochastic analysis

Having derived the long-term, stationary runoff sequences for each reservoir for the five GCMs (i.e. 42 sequences in total), each sequence was assessed individually to establish the statistical properties thereof. This statistical characterisation was used to derive 500 statistically similar runoff sequences, each spanning 100 years, for every long-term sequence. Having simulated the additional sequences, it was possible to perform risk-based yield analyses.

Basic tests were undertaken to ensure that the generated sequences were realistic and plausible. This involves comparing the characteristics of the source data with those of the generated sequences and the results are shown in APPENDIX B. These include box-and-whisker plots of the monthly and annual means and standard deviations, as well as the yield-capacity validation curves. Based on these tests, the generated stochastic sequences were concluded to be acceptable.

6.3 Yield-capacity analysis

The stochastically generated sequences allowed for risk-based yield analyses (i.e. expressing reservoir yield in terms of risk of failure or assurance of supply) to be performed.

As a final step in the analysis procedure, each of the 500 simulated sequences was assumed to represent individual inflow sequences into a reservoir. The assessment of reservoir yield as associated with each individual inflow sequence was undertaken by defining a fixed demand (or target draft) on the reservoir for the period covered by the sequence, and then repeating the process for a range of demands. Not only were the inflows into the reservoir and demand on the reservoir varied for the individual assessments, but also the reservoir sizes. The latter variation allowed for the assessment of yield capability of reservoirs of differing capacities, assuming the same set of 500 inflow sequences. (See **section 3.2** for a detailed discussion.)

The yield-capacity analysis therefore allowed for the assessment of the yield characteristics of a reservoir at a specific location, for a range of capacities and at varying levels of assurance.

The results of these runs were expressed as points on the yield-capacity curve, characterising the reservoir yield. These are discussed below for the various time-horizons analysed.

Although the results presented in this section only reflect yield results for the 1:50-year recurrence interval of failure, results for 1:10, 1:20, 1:100 and 1:200 are provided in **APPENDIX C**.

6.3.1 Berg River Dam

Berg River Dam, situated in the upper reaches of the Berg River catchment (quaternary catchment G10A), has a gross full supply capacity (FSC) of 130.01 Mm^3 and a present time-horizon naturalised MAR of an estimated 142.07 Mm^3/a. Therefore the capacity of Berg River Dam translates to roughly **92% of MAR**.

6.3.1.1 Present time horizon

Analysis of present time horizon yield characteristics were based on the GCM-based long-term present time horizon sequence with seasonality-adaptation as discussed in Section 6.1. The original observation-based sequence was included as a sixth sequence in this analysis. This procedure was followed in order to serve as a control to ensure that the present time horizon yield-characteristics of the five GCM-based sequences are in line with the actual present time horizon yield-characteristics. From the results it is clear that the GCM-based yield characteristics were very close to that of the actual present yield (**Figure 6.1**).

Note: The yield (Y-axis) on this graph is expressed as % MAR. For the present time horizon all analysed sequences indicate the same MAR of 142.07 Mm^3/a, so that the absolute yield values (and not just the yield expressed as % MAR) are near-equal for reservoirs of size 1 MAR and bigger. For smaller reservoirs, the original detailed study-based sequence provided more conservative yield estimates. This is due to differences in seasonality between the detailed study-based sequence and the GCM-based sequences. The GCM-based sequences indicate a slightly less peaked and longer wet season than the detailed study-based sequence does, so that the revised seasonality exhibits slightly less intra-annual variation and thus results in higher yield-estimates. For reservoirs bigger than 1 MAR, this difference in seasonality does not impact on yield.

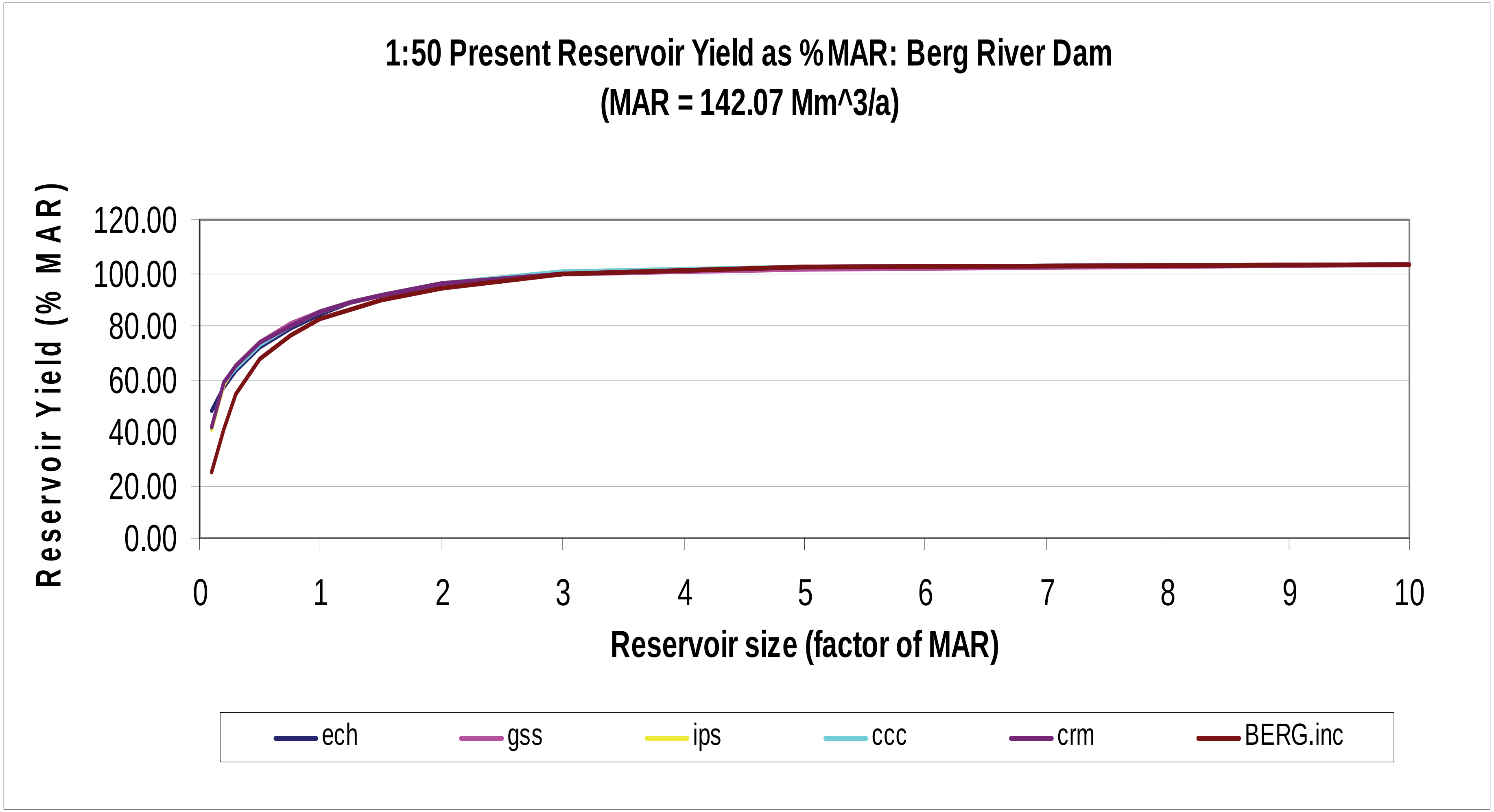


Figure 6.1: Yield-capacity (1:50) curves for the Present time horizon: Berg River Dam

6.3.1.2 Intermediate future time horizon

Yield-capacity analyses for the intermediate future time horizon were based on the adjusted long-term time-series as derived from the short-term GCM-based sequences. A total of four GCMs were included in analyses for the intermediate future time horizon. The MAR estimates associated with each of the adapted five long-term sequences are shown earlier in **Table 6-3**. Yield-capacity curves are provided in **Figure 6.2**.

Figure 6.2 suggests that there is a degree of difference in reservoir yield characteristics between the GCMs considered for the in the intermediate future time horizon (that is, when yield is expressed as % MAR, the yield characteristics at the specific dam site, as based on the various GCMs, do not all correspond). With the exception of CNRM-CM3 and IPSL-CM4 that indicates correspondence, there is a broad variation width for a reservoir of size 1 MAR, varying from a yield of 66.81% of MAR (associated with GISS-ER) to 80.10% of MAR (associated with CGCM3.1). ECHAM5 indicates a yield of 93.60% of MAR for a 1 MAR reservoir.

In **Figure 6.3** the intermediate future reservoir yield is expressed relative to the present time-horizon yield. Most notably, this graph indicates that the expected intermediate future yield associated with reservoirs smaller than 1 MAR is less than the yield associated with the present time-horizon. This result agrees with local and international literature cited in **section 2** of this report. For two of the GCMs (CNRM-CM3 and IPSL-CM4) yield is estimated to be below present yield, irrespective of reservoir size, while two other GCMs (GISS-ER and CGCM3.1) suggest increased reservoir yield for dams larger than 2 MAR.

This disagreement in yield results is as a result of disagreement in GCM-based runoff estimates and needs to be investigated further.

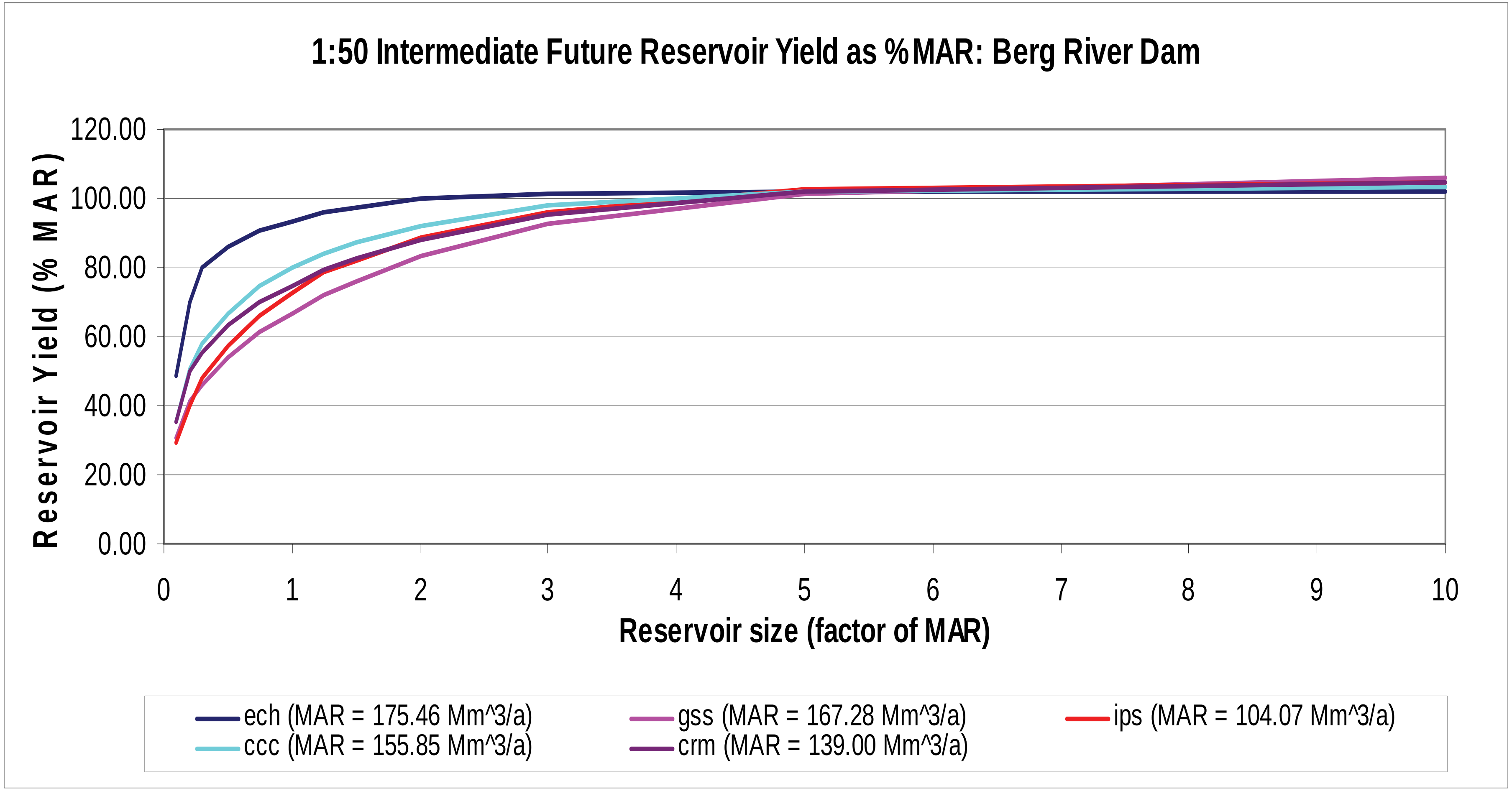


Figure 6.2: Yield-capacity (1:50) curves for the Intermediate Future time horizon: Berg River Dam

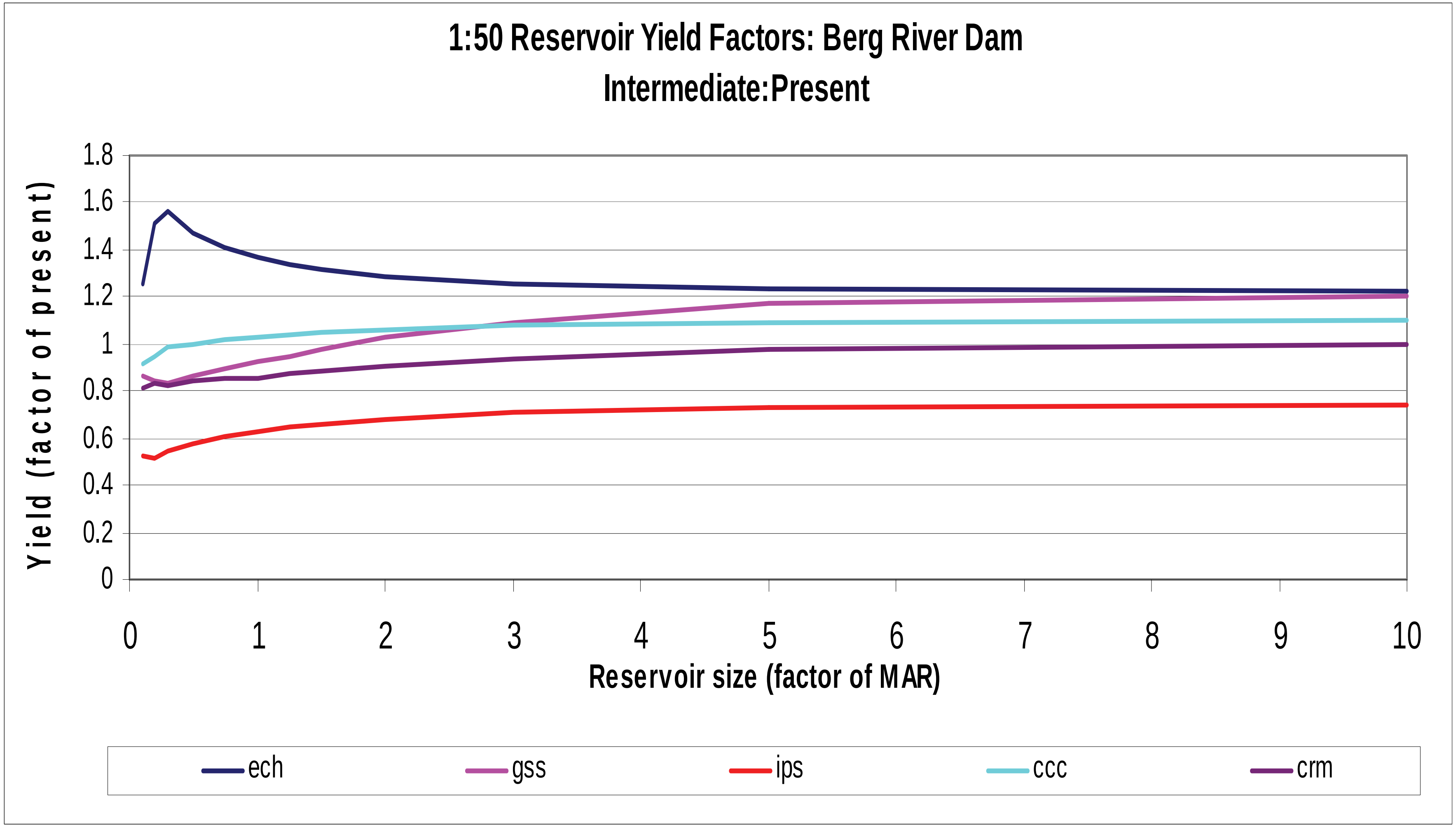


Figure 6.3: Intermediate Future Yield: Present Yield (1:50) (Berg River Dam)

6.3.1.3 Distant future time horizon

Yield-capacity analyses for the distant future time horizon were based on the adjusted long-term time series as derived from the short-term GCM-based sequences. A total of four GCMs were included in analyses. The MAR estimates associated with each of the four long-term sequences are shown earlier in **Table 6-3**. Yield-capacity curves are provided in **Figure 6.4**.

Figure 6.4 suggests that there a higher degree of agreement in reservoir yield characteristics between GCMs in the distant future than in the intermediate. The yield-estimates associated with a 1 MAR dam vary from 73.22% of MAR (associated with IPSL-CM4) to 78.40% of MAR (associated with CNRM-CM3). ECHAM5 indicates a yield of 95.280% of MAR for a 1 MAR reservoir.

In **Figure 6.5** the distant future reservoir yield is expressed relative to the present time-horizon yield. As was the case for intermediate future time-horizon results, reservoir is expected to decrease. This result holds for estimates based on all three sets of GCM results considered, irrespective of reservoir size. Of the three GCMs considered for the distant future analysis, GISS-ER provides the most optimistic results – projecting near-present time horizon yields for reservoirs exceeding 4 MAR in capacity.

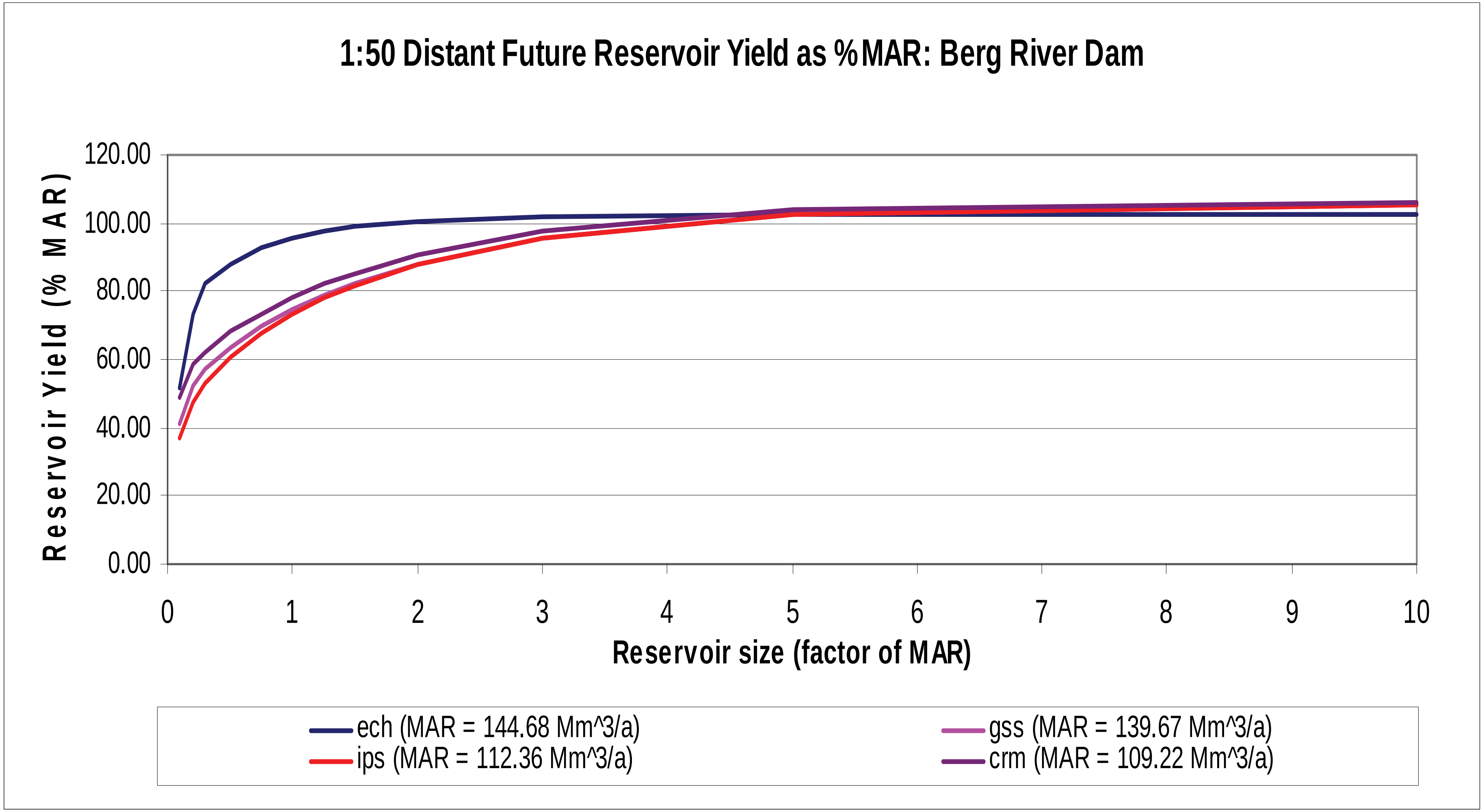


Figure 6.4: Yield-capacity (1:50) curves for the Distant Future time horizon: Berg River Dam

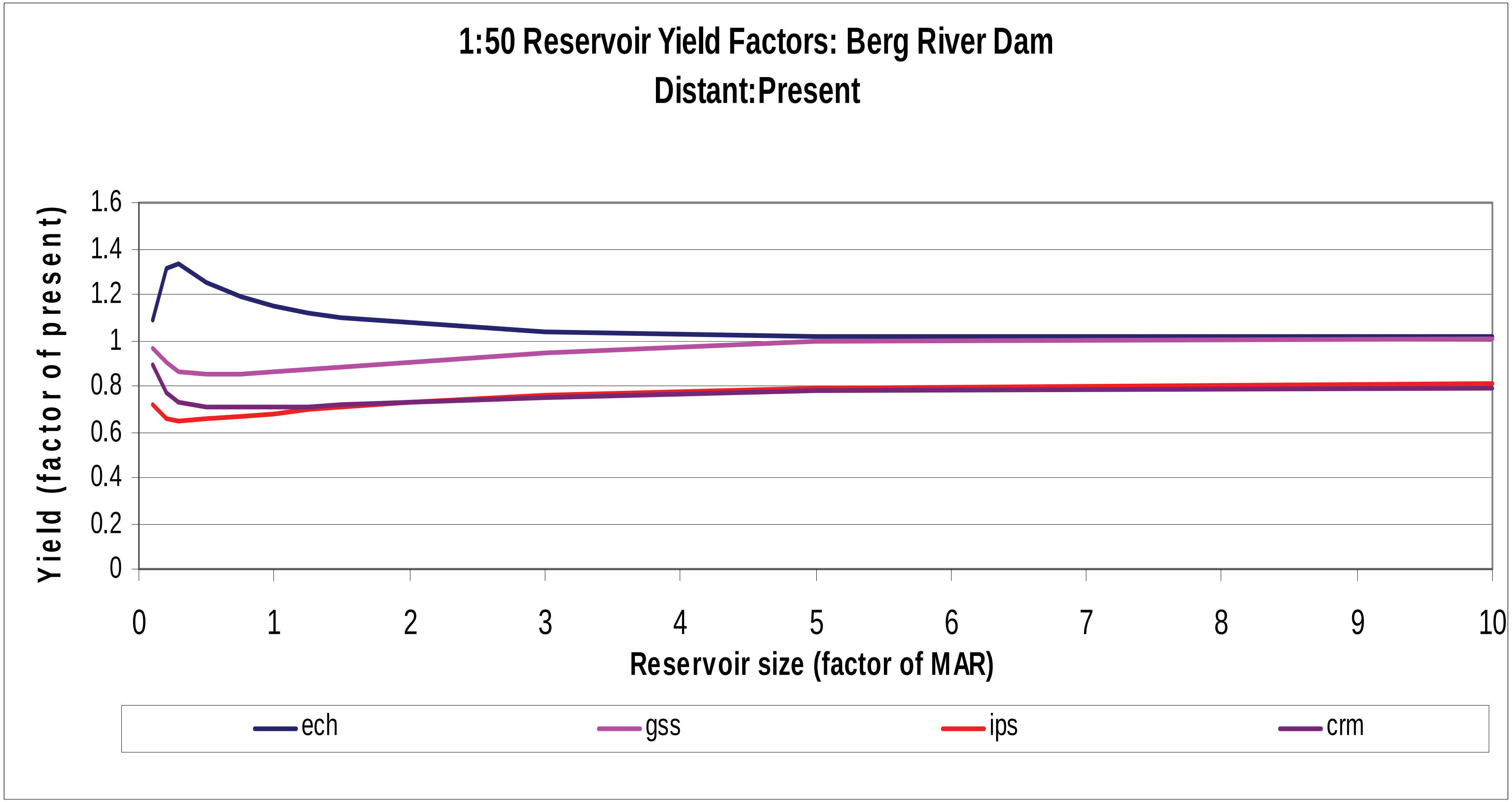


Figure 6.5: Yield-capacity (1:50) curves for the Distant Future time horizon: Berg River Dam

6.3.2 Midmar Dam

Midmar Dam, situated in the Mgeni River catchment (quaternary catchment U20C), has a Gross FSC of 235.42 Mm^3 and a present time-horizon MAR of around 201.71 Mm^3/a. Therefore the capacity of Midmar Dam translates to roughly **117% of MAR**.

6.3.2.1 Present time horizon

Analysis of present time horizon yield characteristics were based on the observation-based long-term present time horizon sequence with seasonality-adaptation as discussed above (**section 4.4**). . The original observation-based sequence was included as a sixth sequence in this analysis. This procedure was followed in order to serve as a control to ensure that the present time horizon yield-characteristics of the five GCM-adapted sequences are in line with the actual present time horizon yield-characteristics. From the results it is clear that the GCM-based yield characteristics were very close to that of the actual present yield (**Figure 6.11**).

Note: The yield (Y-axis) on this graph is expressed as % MAR. For the present time horizon all analysed sequences indicate the same MAR of 201.71 Mm^3/a, so that the absolute yield values (and not just the yield expressed as % MAR) are near-equal.

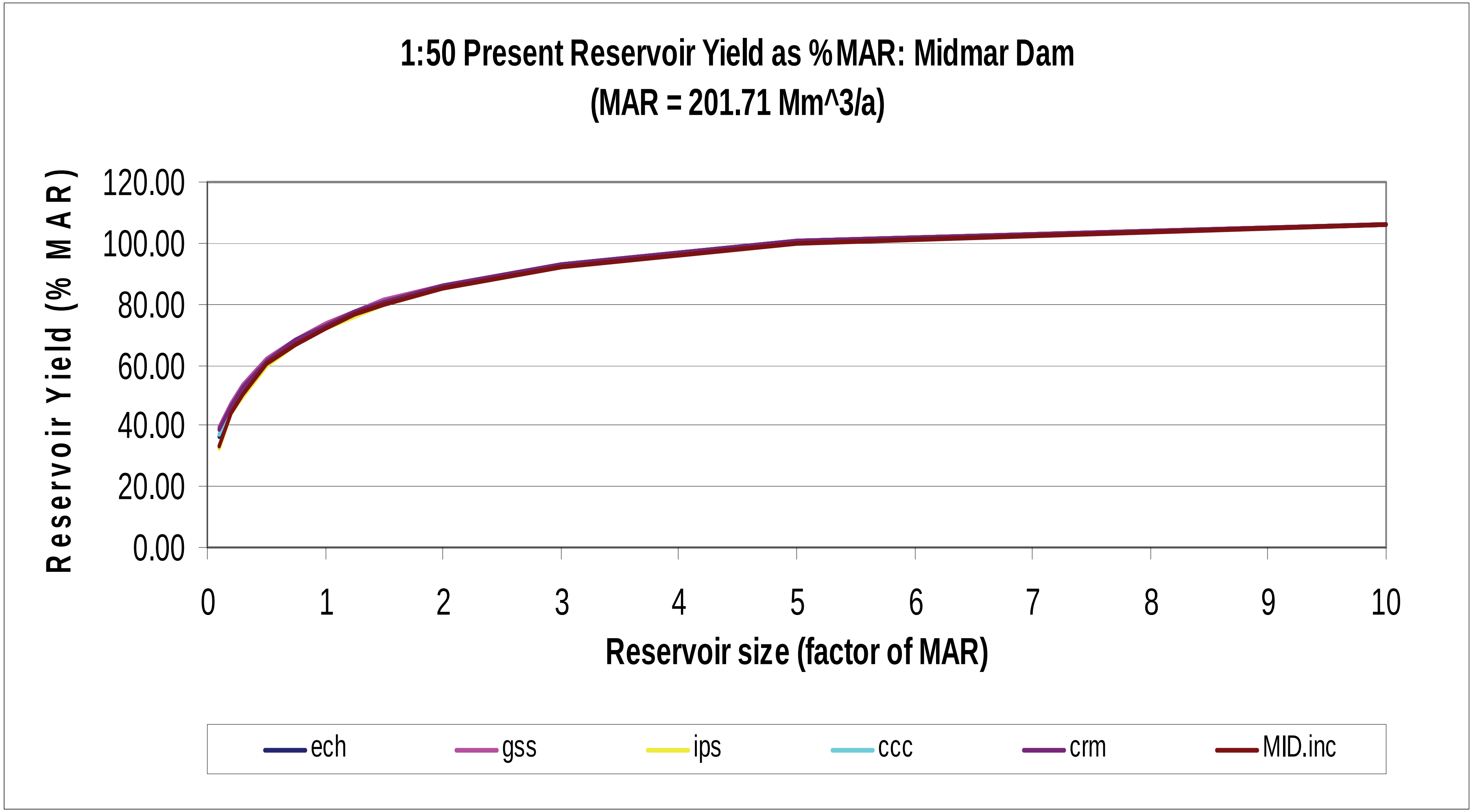


Figure 6.6: Yield-capacity (1:50) curves for the Present time horizon: Midmar Dam

6.3.2.2 Intermediate future time horizon

Yield-capacity analyses for the intermediate future time horizon were based on the adjusted long-term time series as derived from the short-term GCM-based sequences. A total of five GCMs were included in analyses for the intermediate future time horizon. The MAR estimates associated with each of the adapted five long-term sequences are indicated in **Table 6-3**. Yield-capacity curves are provided in **Figure 6.12**.

Figure 6.12 suggests that there are no major differences in reservoir yield characteristics between GCMs in the intermediate future (that is, when yield is expressed as % MAR, the yield characteristics at the specific dam site, as based on the various GCMs, corresponds). The small variation in yield estimates associated with a reservoir of size 1.25 MAR ranges from a yield of 67.51% of MAR (associated with GISS-ER) to 74.21% of MAR (associated with CGCM3.1). For smaller reservoirs (FSC < 1.25 MAR) there is even less variation in intermediate time horizon yield-estimates.

However, when taking into account the fact that the MAR associated with the GCM-based results vary between 221.70 Mm^3/a and 414.73 Mm^3/a, the actual expected yield for the intermediate future provides a different perspective on the results.

In **Figure 6.13** the intermediate future reservoir yield is expressed relative to the present time-horizon yield. Most notably, this graph indicates that GISS-ER and CNRM-CM3-based yield estimates for reservoirs with FSC less than 1 MAR are less than the present yield, while the remaining three GCMs indicate an expected increase in intermediate future yield. In fact, based on the results of the three latter GCMs for a reservoir of size 1.25 MAR, the intermediate future yield is expected to exceed 1.5 times the present yield.

This disagreement in yield results is as a result of disagreement in GCM-based runoff estimates and needs to be investigated further.

For reservoirs bigger than 2 MAR, all five GCMs indicated the expected yield to be more than present yield.

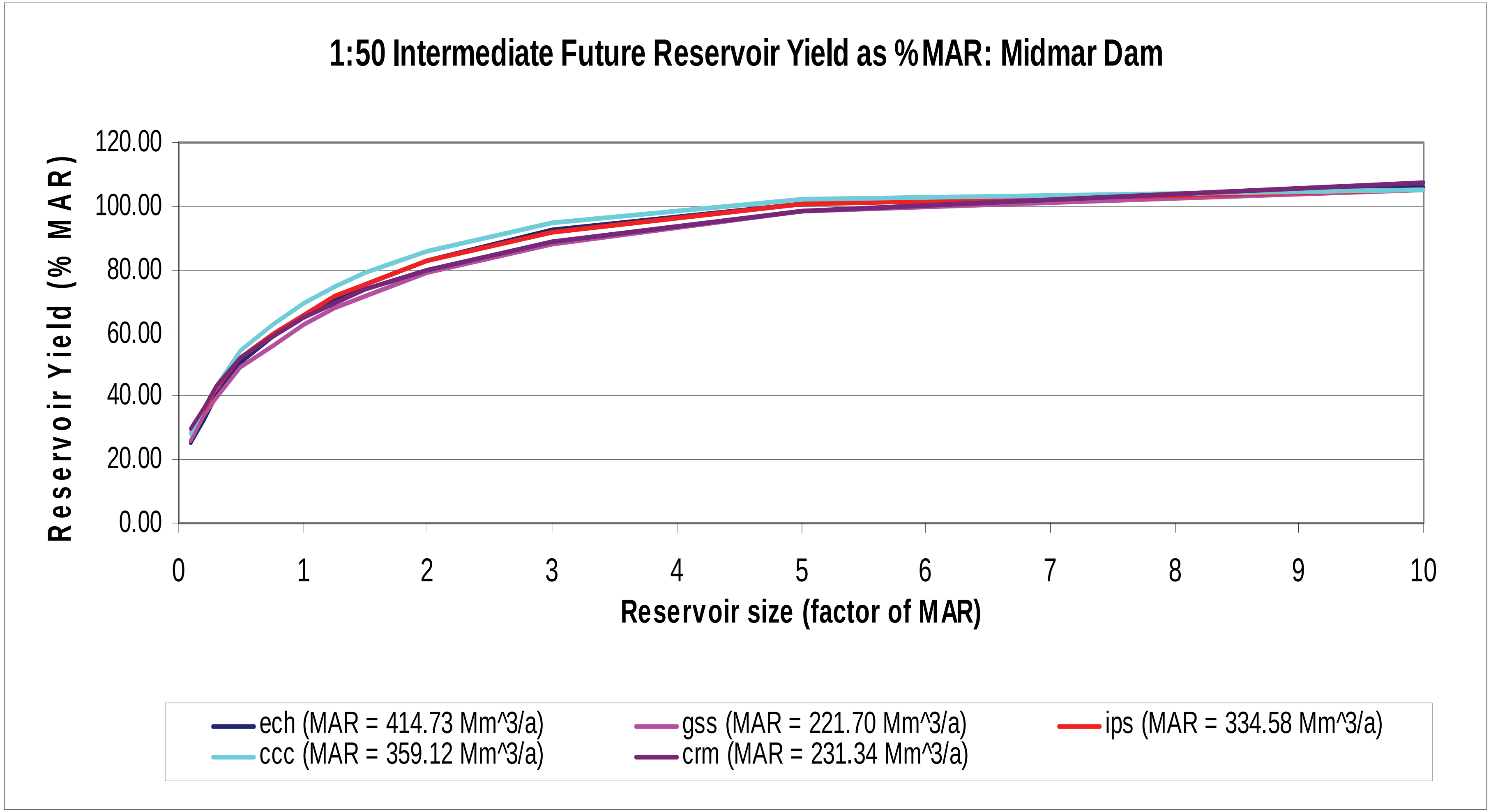


Figure 6.7: Yield-capacity (1:50) curves for the Intermediate Future time horizon: Midmar Dam

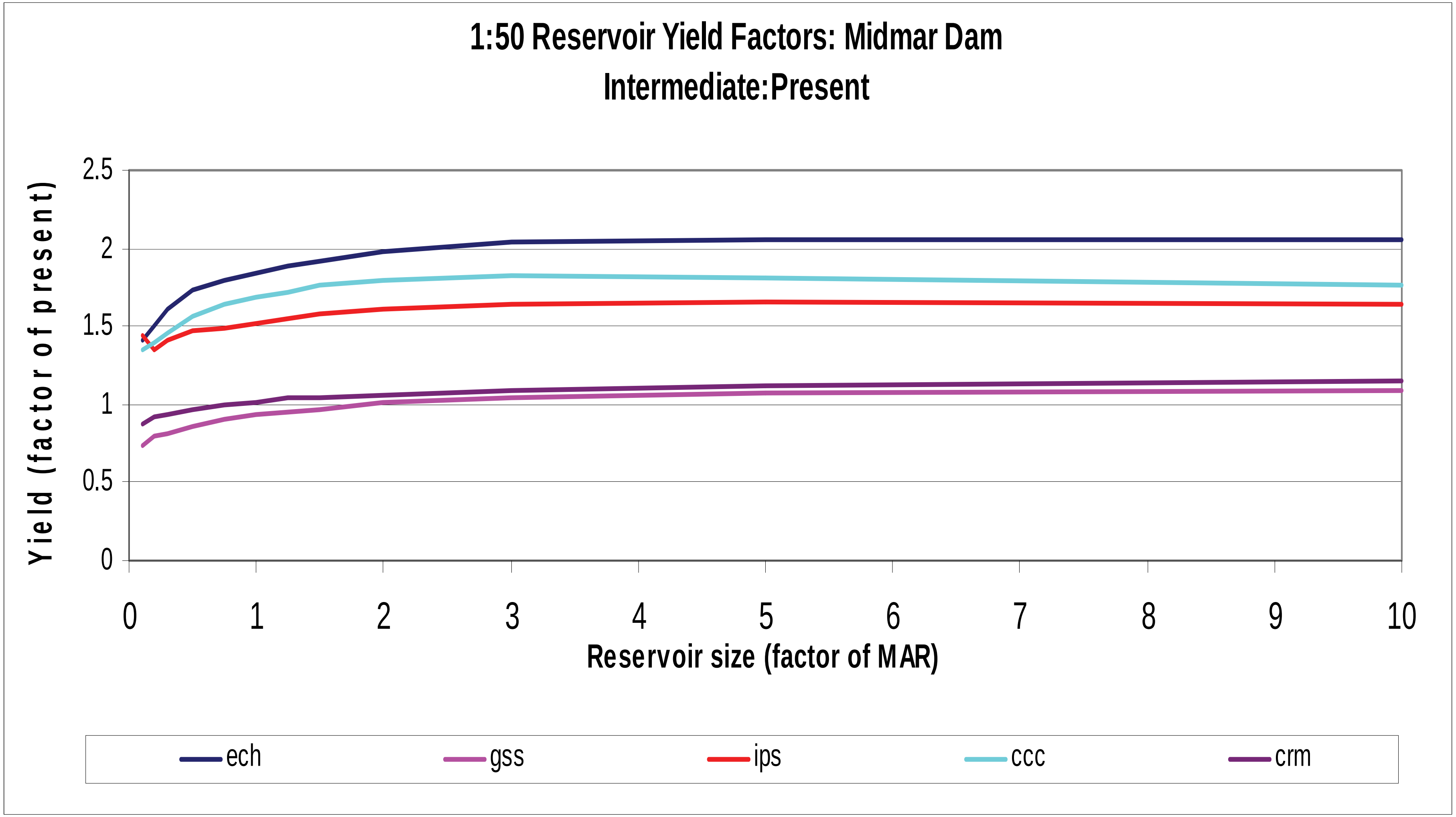


Figure 6.8: Intermediate Future Yield: Present Yield (1:50) (Midmar Dam)

6.3.2.3 Distant future time horizon

Yield-capacity analyses for the distant future time horizon were based on the adjusted long-term time series as derived from the short-term GCM-based sequences. A total of four GCMs were included in analyses. The MAR estimates associated with each of the four long-term sequences are indicated in **Table 6-3**. Yield-capacity curves are provided in **Figure 6.14**.

Figure 6.14 suggests that there are more notable differences in reservoir yield characteristics between GCMs in the distant future than in the intermediate future especially for reservoirs smaller than 4 MAR.

For reservoirs smaller than 4 MAR, IPSL-CM4 indicates a higher yield as proportion of MAR than the other GCMs, with an estimated yield of 81.44% of MAR associated with a 1.25 MAR size reservoir. The minimum yield-estimate relative to MAR for this size of reservoir is 62.42% of MAR (associated with CNRM-CM3 results).

However, when taking into account the fact that the MAR associated with the various GCMs vary between 221.19 Mm^3/a (GISS-ER) and 556.51 Mm^3/a (ECHAM5), the actual expected yield for the distant future provides a different perspective on the results.

In **Figure 6.15** the distant future reservoir yield is expressed relative to the present time-horizon yield. Most notably, this graph indicates that with the exception of GCM (GISS-ER), all GCMs considered in this study suggest expected distant future yield that exceeds present yield, irrespective of reservoir size. The actual relative difference in expected yield for a 1.25 MAR size reservoir ranges between 1 and 2.5 – indicating a wide range in GCM-results.

For reservoirs smaller than 1 MAR, GISS-ER-based yield estimates and expected decrease in the distant future.

This disagreement in yield results is as a result of disagreement in GCM-based runoff estimates and needs to be investigated further.

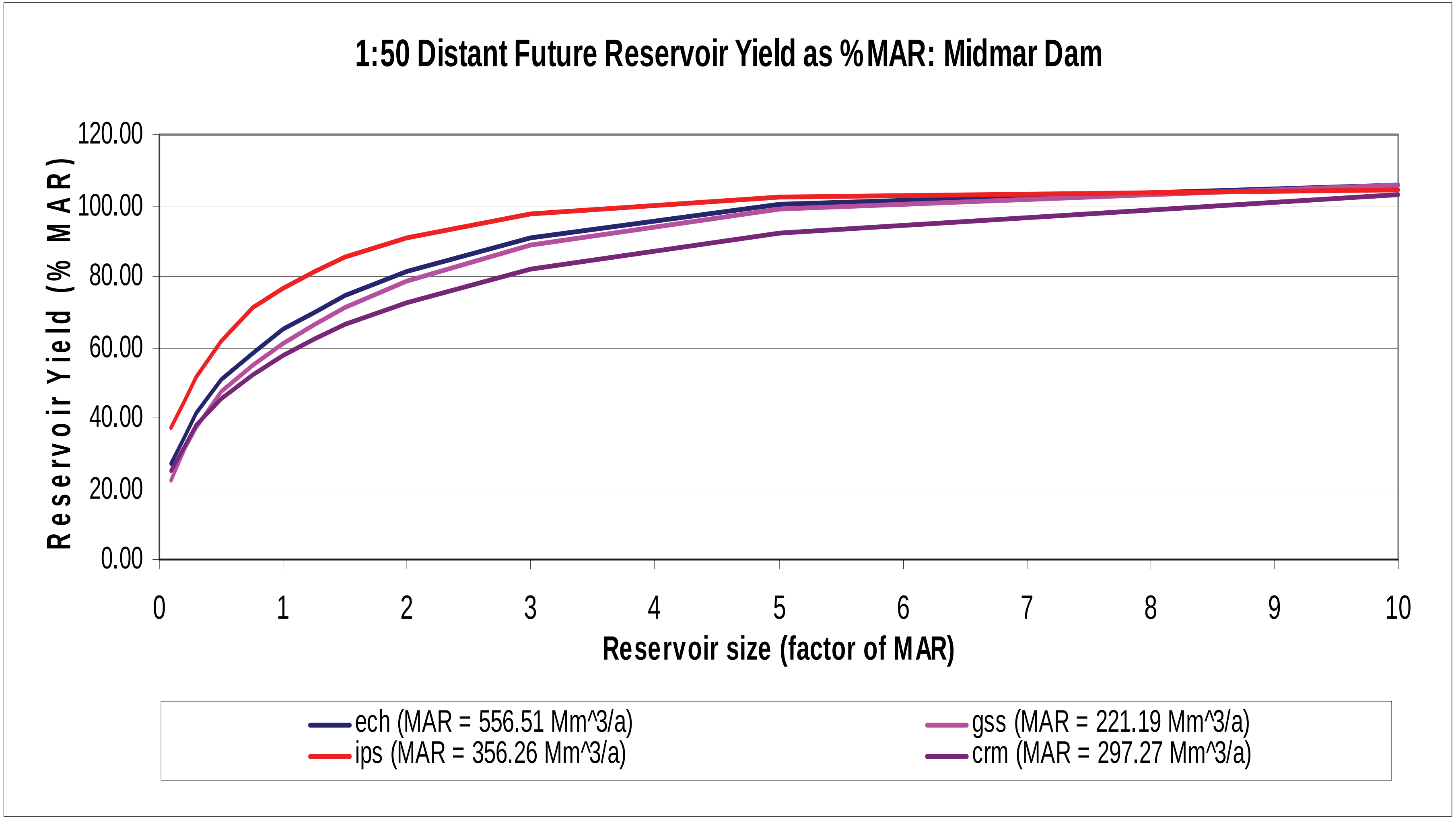


Figure 6.9: Yield-capacity (1:50) curves for the Distant Future time horizon: Midmar Dam

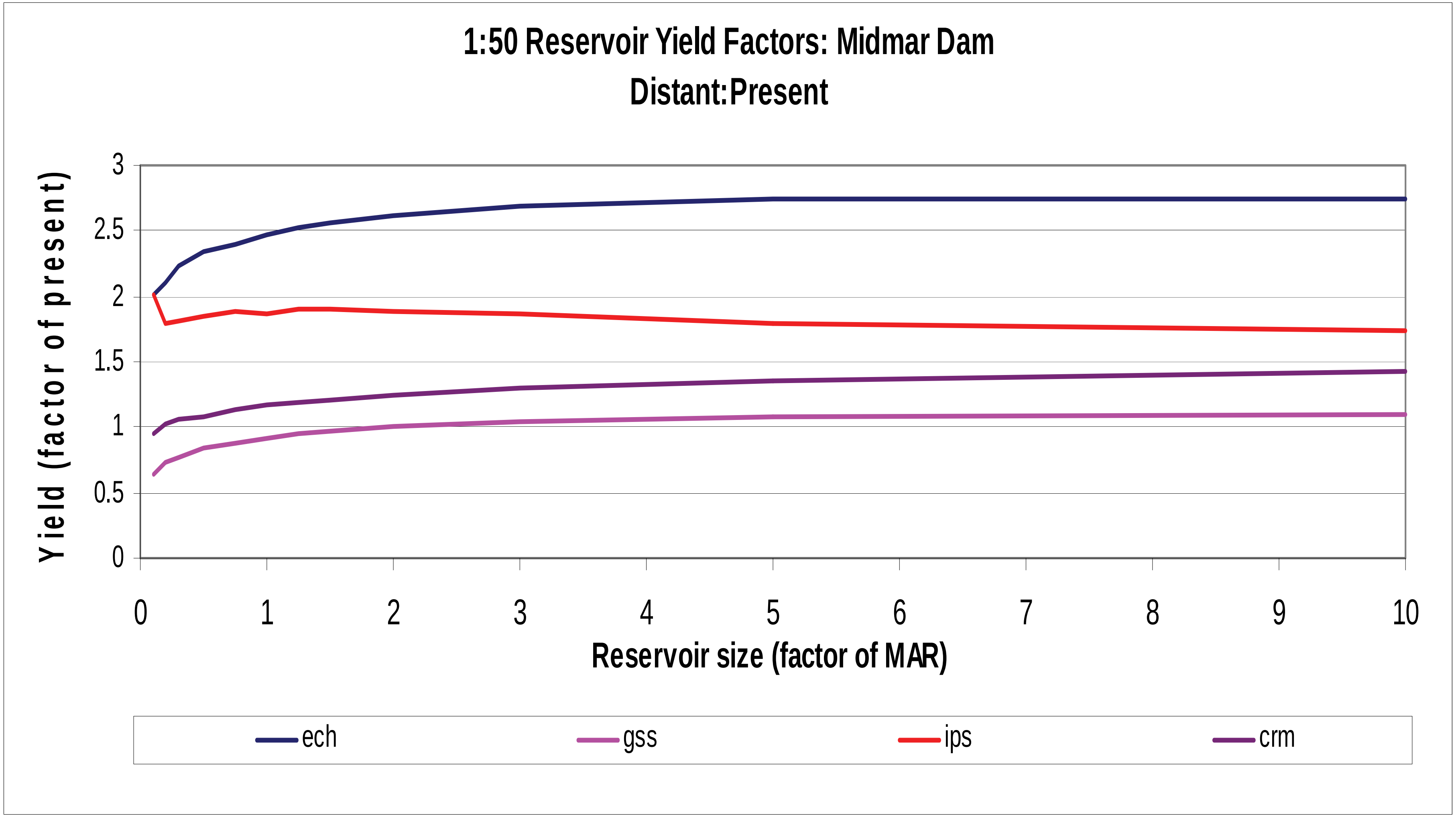


Figure 6.10: Distant Future Yield: Present Yield (1:50) (Midmar Dam)

6.3.3 Grootdraai Dam

Grootdraai Dam, situated in the upper reaches of the Vaal River catchment (quaternary catchment C11L), has a Gross FSC of 350.33 Mm^3 and a present time-horizon MAR of around 457.68Mm^3/a. Therefore the capacity of Grootdraai Dam translates to roughly **76% of MAR**.

6.3.3.1 Present time horizon

Analysis of present time horizon yield characteristics were based on the observation-based long-term present time horizon sequence with seasonality-adaptation as discussed above. The original observation-based sequence was included as a sixth sequence in this analysis. This procedure was followed in order to serve as a control to ensure that the present time horizon yield-characteristics of the five GCM-adapted sequences are in line with the actual present time horizon yield-characteristics. From the results it is clear that the GCM-based yield characteristics were very close to that of the actual present yield (**Figure 6.11**).

Note: The yield (Y-axis) on this graph is expressed as % MAR. For the present time horizon all analysed sequences indicate the same MAR of 457.31 Mm^3/a, so that the absolute yield values (and not just the yield expressed as % MAR) are near-equal.

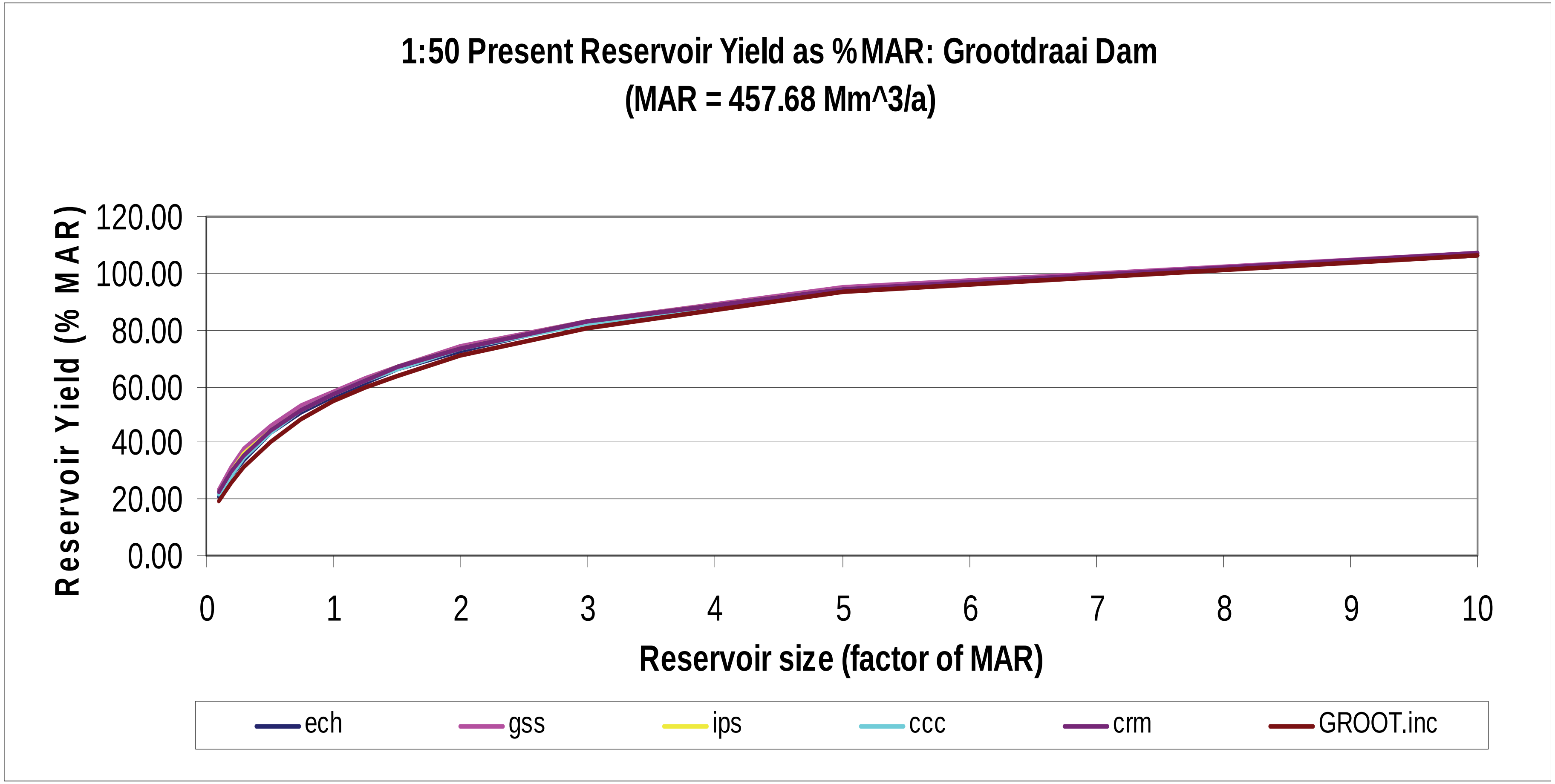


Figure 6.11: Yield-capacity (1:50) curves for the Present time horizon: Grootdraai Dam

6.3.3.2 Intermediate future time horizon

Yield-capacity analyses for the intermediate future time horizon were based on the adjusted long-term time series as derived from the short-term GCM-based sequences. A total of five GCMs were included in analyses for the intermediate future time horizon. The MAR estimates associated with each of the adapted five long-term sequences are indicated in **Table 6-3**. Yield-capacity curves are provided in **Figure 6.12**.

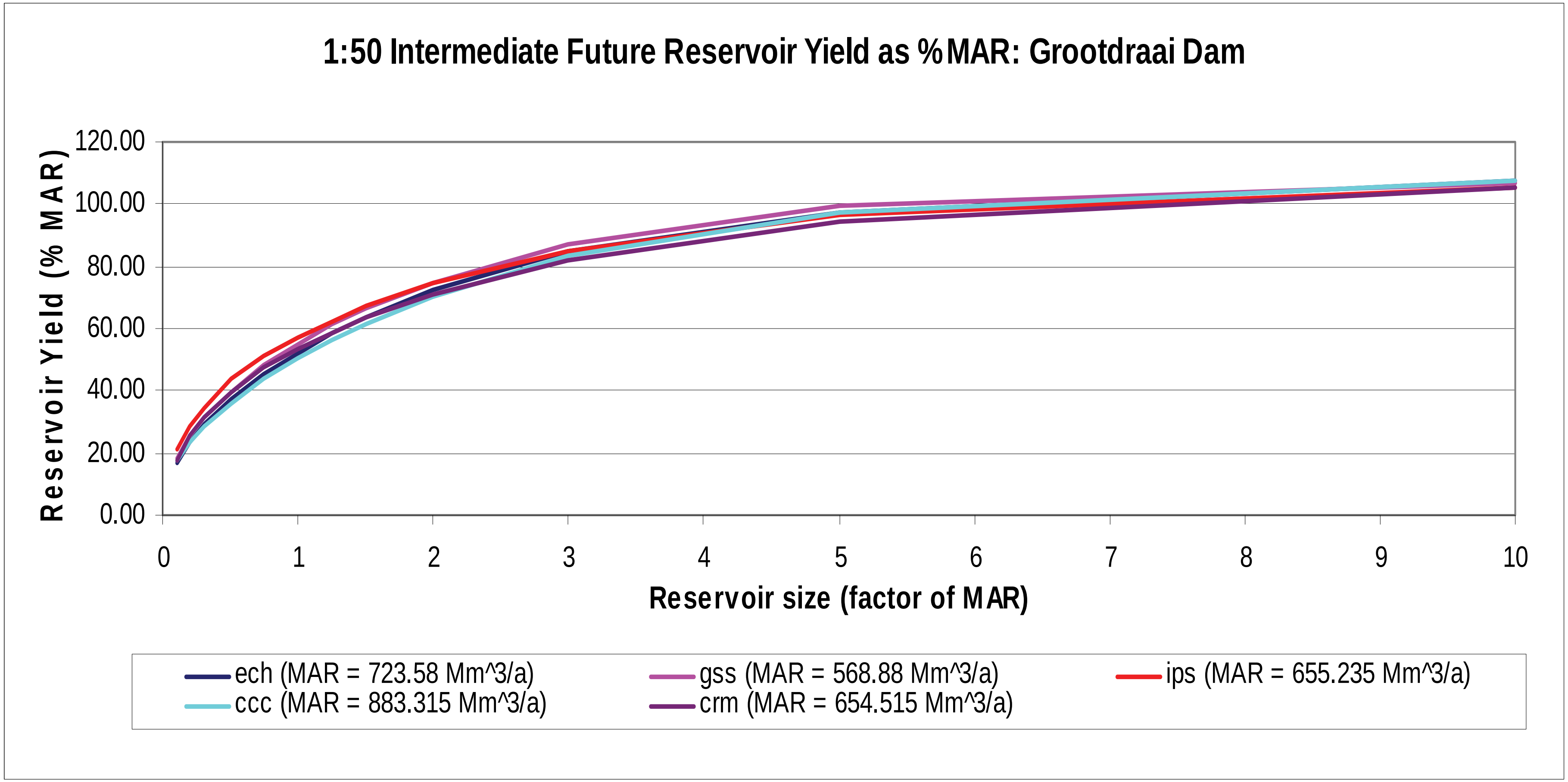


Figure 6.12: Yield-capacity (1:50) curves for the Intermediate Future time horizon: Grootdraai Dam

Figure 6.12 suggests that there are no major differences in reservoir yield characteristics between GCMs in the intermediate future (that is, when yield is expressed as % MAR, the yield characteristics at the specific dam site, as based on the various GCMs, corresponds).

For smaller reservoirs (FSC < 1.5 MAR) IPSL-CM4 indicates a slightly higher yield as proportion of MAR than the other GCMs. However, when taking into account the fact that the MAR associated with the IPSL-CM4-result is 655.235 Mm^3/a, which is considerably less than that of the CGCM3.1-result (883.315 Mm^3/a) and ECHAM5-result (723.58 Mm^3/a), the actual expected yield for the intermediate future provides a different perspective on the results.

In **Figure 6.13** the intermediate future reservoir yield is expressed relative to the present time-horizon yield. Most notably, this graph indicates that the expected intermediate future yield exceeds present yield, irrespective of reservoir size or GCM. Therefore, based on climate projections for the intermediate future for all the GCMs evaluated for Grootdraai Dam it indicates a increase in reservoir yield.

Furthermore, the graph indicates that it is in fact CGCM3.1 that suggests the most drastic increase in yield with a factor of around 1.7 for a reservoir of 0.76 MAR. The minimum increase based on GISS-ER-results reflects a yield increase-factor of roughly 1.14.

The maximum yield ratios for the various GCMs range between 1.298 and 1.948 and are expected for reservoirs from size 3 MAR to about 6 MAR.

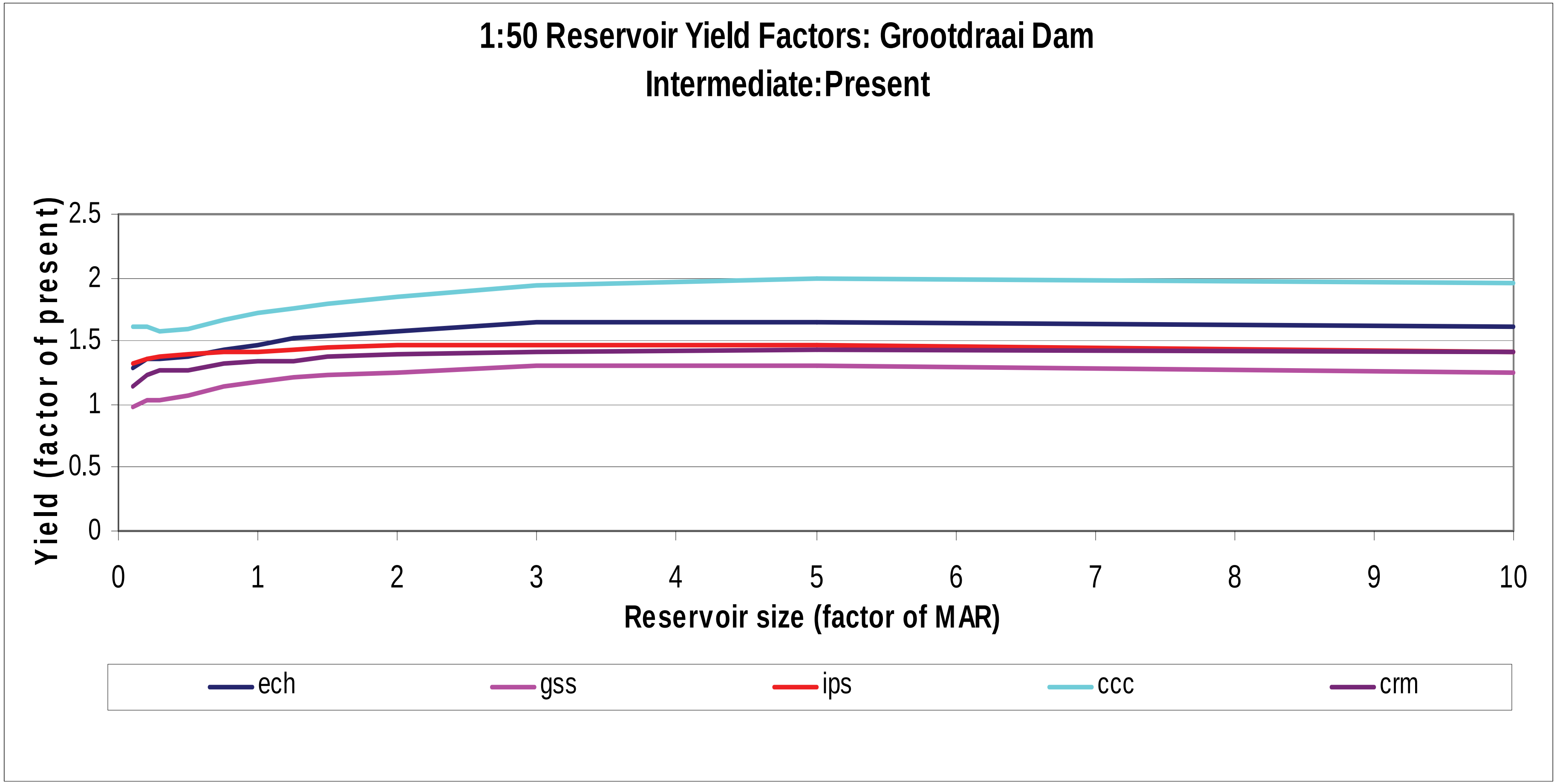


Figure 6.13: Intermediate Future Yield: Present Yield (1:50) (Grootdraai Dam)

6.3.3.3 Distant future time horizon

Yield-capacity analyses for the distant future time horizon were based on the adjusted long-term time series as derived from the short-term GCM-based sequences. A total of four GCMs were included in analyses. The MAR estimates associated with each of the four long-term sequences are indicated in **Table 6-3**. Yield-capacity curves are provided in **Figure 6.14**.

Figure 6.14 suggests that there are more notable differences in reservoir yield characteristics between GCMs in the distant future than in the intermediate future especially for reservoirs smaller than 4 MAR

For reservoirs smaller than 4 MAR, IPSL-CM4 indicates a higher yield as proportion of MAR than the other GCMs. However, when taking into account the fact that the MAR associated with IPSL-CM4 is 547.799 Mm^3/a, which is considerably less than that of the ECHAM5-result (1 218.44 Mm^3/a) and CNRM-CM3-result (858.459 Mm^3/a), the actual expected yield for the distant future provides a different perspective on the results.

In **Figure 6.15** the distant future reservoir yield is expressed relative to the present time-horizon yield. Most notably, this graph indicates that the expected distant future yield exceeds present yield, irrespective of reservoir size or GCM. Therefore, based on climate projections for the distant future for all the GCMs evaluated for Grootdraai Dam it indicates a increase in reservoir yield

Furthermore, the graph indicates that it is in fact ECHAM5 that suggests the most drastic increase in yield with a factor of around the 2.3 mark for a reservoir of 0.76 MAR. The minimum increase is based on GISS-ER-results and reflects a yield increase-factor of roughly 1.13.

The maximum yield ratios for the various GCMs range between 1.216 and 2.727 and are observed for reservoirs of various sizes, depending on the GCM under consideration.

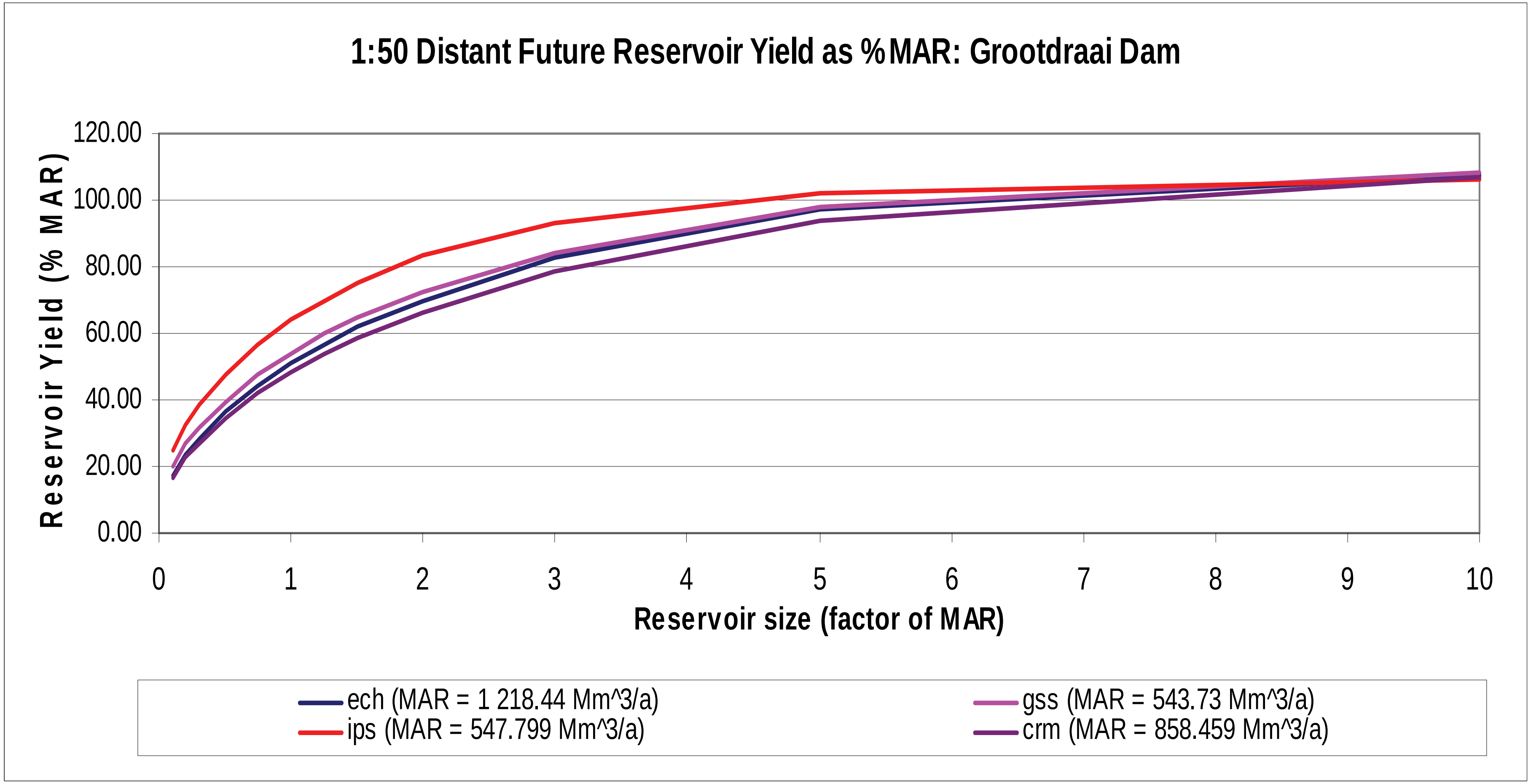


Figure 6.14: Yield-capacity (1:50) curves for the Distant Future time horizon: Grootdraai Dam

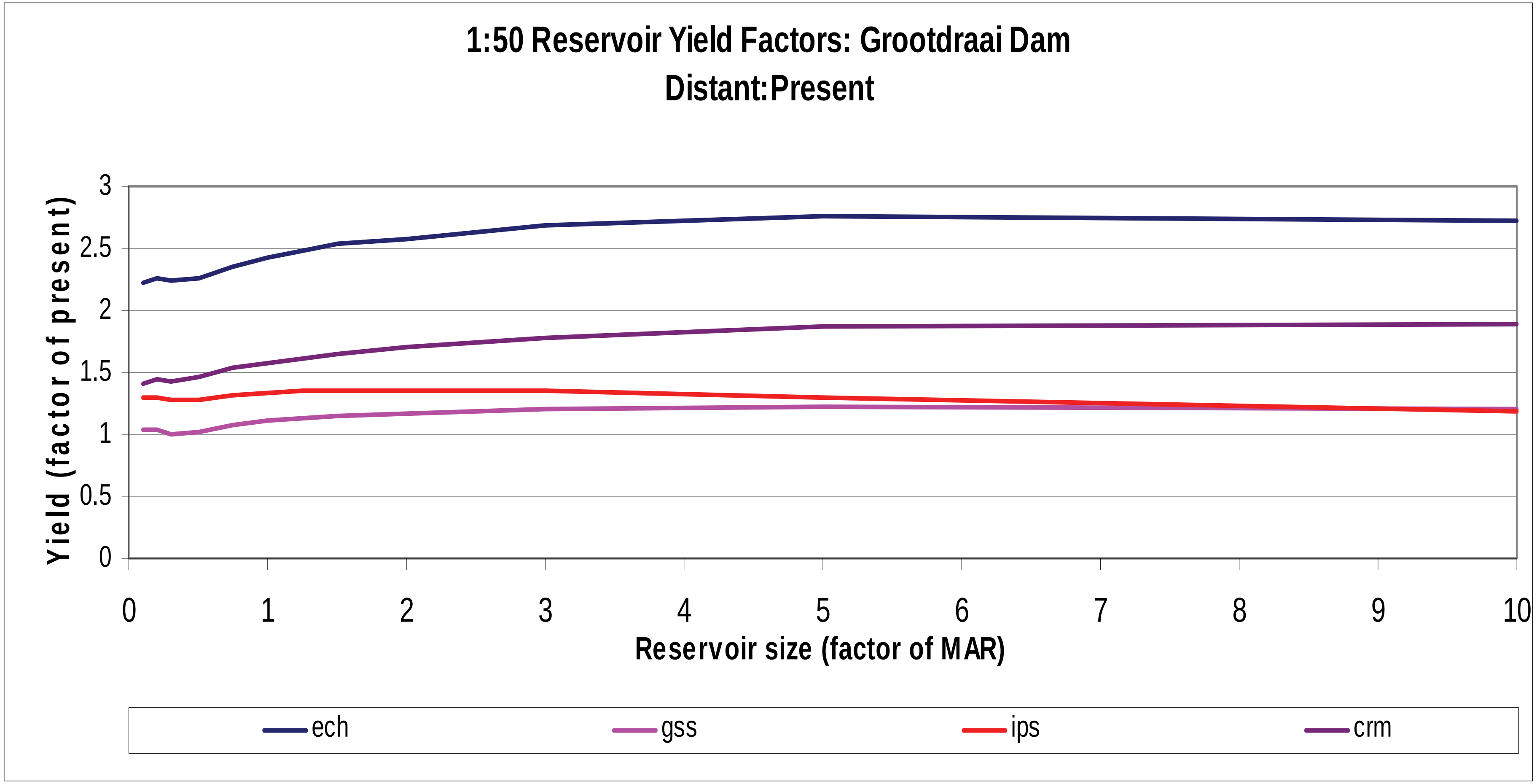


Figure 6.15: Distant Future Yield: Present Yield (1:50) (Grootdraai Dam)

7. Conclusion

(a) General

This research project resulted in the first substantial step towards the development of a practical methodology for assessing the potential impacts of climate change on long-term reservoir yields based on runoff time-series data derived from the downscaled results of *General Circulation Models* (GCMs) for various time-horizons.

(b) Methodology

Long-term yield analyses require that hydro-meteorological input data adhere to a number of pre-requisites, which include the following:

- Long records, typically 50 years or more in length, in order to ensure that at least one severe drought period is included and that all cyclic movements in the data can be accurately identified.
- Stationary records, i.e. the data should, except for the expected seasonality or other cyclic movement, not exhibit any long-term movement or change in variability.

However, runoff time-series data derived from downscaled GCM results generally cover short period lengths (such as 20 years) and, since they are based on varying greenhouse gas concentrations, are inherently non-stationary over the long-term. Furthermore, a comparison of GCM-based runoff characteristics for the *Present-day* time-horizon (1971 to 1990) highlighted another cause for concern since the various GCMs were found to differ significantly from one another, as well as from that of the observed naturalised historical runoffs for a particular catchment.

Therefore, in order to address these limitations, a simplistic statistically-based data pre-processing method was developed for generating long, stationary runoff data sets representative of each climate change scenario, which are also in line with observed runoff characteristics over the *Present-day* time-horizon. Although it is acknowledged that the method is crude and may be substantially refined through further research, it does provide a reasonable basis for applying available climate change scenario information in traditional long-term yield analysis methodologies and, as such, the means for identifying possible generalised future trends in yield characteristics.

(c) Analysis software

To facilitate the process of assessing the potential impacts of climate change on reservoir yields, a software utility was developed which automates the process of undertaking long-term yield analyses based on (1) alternative runoff data time-series, including both historical- and climate change scenario-based data sets and (2) a range of possible reservoir storage volumes. The utility, referred to as *SDFPrep*, incorporates the existing *Stochastic Model of South Africa* (STOMSA) software for stochastic streamflow analysis and generation, although the possibility of including alternative stochastic generators may be investigated in future. Results are presented graphically in the form of so-called *storage-draft-frequency* (SDF) curves, providing a useful interpretation tool for comparing projected and present-day yield characteristics, as well as results from various climate models.

(d) Analysis results

In order to test the above data-processing method and analysis software they were applied in the long-term yield analysis of three existing major dams in South Africa, i.e. the Berg River Dam in the Western Cape, Midmar Dam in the KwaZulu-Natal Midlands and Grootdraai Dam on the Eastern Highveld.

The dams in question were selected at a Reference Group meeting based on the fact that the dams are located in climatically diverse areas with varying expected climate change impacts.

Results from the analyses can be summarised as follows:

- The projected impacts of climate change on long-term reservoir yields vary significantly from certain climatic region to others and also depend largely on the climate model used.
- A total of four GCMs were included for the analysis of Berg River Dam. Results for the *Intermediate Future* (2046 to 2065) time-horizon are inconsistent but suggest a significant possible decrease in yield for the *Distant Future* (2081 to 2100).
- In the case of Midmar Dam, five GCMs were included in the analysis and results suggest a significant possible increase in yield for both the *Intermediate Future* and *Distant Future* time-horizons.
- As above, five GCMs were included in the analysis of Grootdraai Dam and results suggest a significant possible increase in yield for both the *Intermediate Future* and *Distant Future* time-horizons.

8. Recommendations

While the research project resulted in a practical methodology for assessing the potential impacts of climate change on reservoir yields based on existing climate change scenario information, the methods applied are crude and further research in this regard is considered to be essential. Within this context, the following specific recommendations are made:

- Improved communication channels should be established between water resource planners and climate change researchers in order to ensure that research outputs are better aligned with the requirements of water resource planning tools. Of particular concern is the apparent discrepancy between runoff characteristics derived from downscaled GCM information for the *Present-day* time-horizon and that of observed naturalised historical runoffs.
- While a statistically-based data pre-processing method was developed for generating long, stationary runoff data sets from available climate change scenario information for application in traditional long-term yield analysis methodologies, the validity of the method remains essentially untested. Other approaches should therefore be actively considered including the possibility of developing alternative yield analysis methodologies that accommodate the inherent non-stationarity of a changing climate.
- The SDFPrep software utility should be applied in a national study aimed at providing broad-scale information to the water resources planning community on possible future climate change impacts. Results can be presented on a quaternary catchment scale and in the form of colour-coded maps showing indices representing the possible impacts on reservoir yields for a range of reservoir storage sizes and assurances of supply.
- Methodologies developed for assessing climate change impacts on yield should also be tested and applied in an integrated water resources system context using more sophisticated yield assessment tools such as the *Water Resources Yield Model* (WRYM).
- Runoff time-series data applied in this project were developed by simulation using the daily time-step ACRU agro-hydrological model.

  The possibility should, however, be investigated of using other hydrological models for this purpose (e.g. the monthly-time step WRSM2000 rainfall-runoff model) as this may provide opportunities for the improved alignment of results with other studies, such as those undertaken for planning purposes by the Department of Water Affairs (DWA).
- Climate modelling methodologies are continually improved upon and refined and in order to enhance the credibility of climate change impact assessment methodologies and results, assessments should be extended to include results obtained from a larger number of GCMs, greenhouse gas emission scenarios and alternative downscaling methods.

- For the purpose of simplicity, the modelling undertaken in this research project focused on the potential impacts of climate change on catchment runoff and ignored other factors that were considered to be of secondary importance. These include climate change-related changes in natural vegetation, land use, migration patterns, socio-economic activities, as well as rainfall directly onto and evaporation directly from the exposed surface area of the reservoir. These aspects could impact on yield in varying degrees depending on the system in question and requires further research.
- Possibly the most significant challenge regarding climate change impact assessments is the incorporation of results into the mainstream water resources planning process. Specifically, research is required for the development of a framework to guide the practical response to projected climate change impacts, including, for example:
  - The need for and timely implementation of additional augmentation in cases where projections indicate a possible decrease in runoff and reservoir yields.
  - The possible deferment of planned augmentation schemes in cases where projections indicate a possible increase in yield.
  - The possible adaptation of flood emergency plans, flood design parameters and sediment management plans in cases where the frequency and severity of flood flows are projected to change.
  - Managing impacts on water quality resulting from higher air and water temperatures, sediment loads, etc.
  - Assessing the credibility of climate change impact projections and also the associated risk of their consideration in the implementation of planning decisions.

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APPENDIX A: Detailed discussion on time series adjustment methodology

Yield analysis requires the runoff data (or naturalised inflow time series) to adhere to a number of pre-requisites. These include

1. Long-term records (typically 50 hydrological years or more) to ensure that the record period includes at least one severe drought and to ensure that all cyclic movements in the data can be identified as such.
2. Stationary records (i.e. the data should, except for the expected seasonality or other cyclic movement, not exhibit any long-term movement or change in variability)

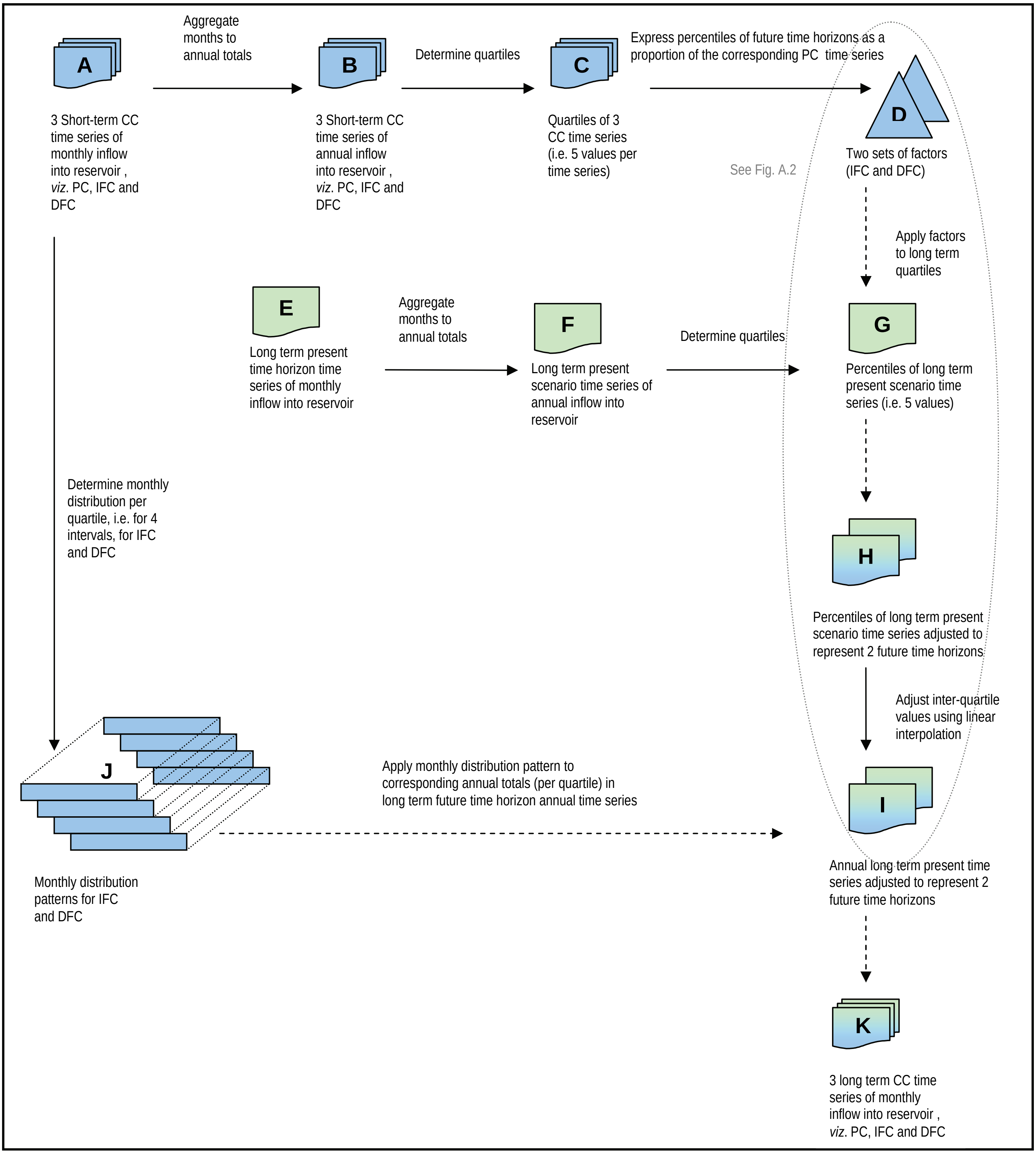
The time series provided fail in both of these assumptions. Indeed, the time series obtained from the GCMs and thus also from the Hydrological model, only spans 19 hydrological years. Secondly, since a key input to the GCMs are the changes in atmospheric aerosol and greenhouse gas concentrations, the resulting climatic output is defined to be non-stationary over the long-term. The downscaling method and hydrological model that follows only carries forward the non-stationary nature of the data, so that the resulting runoff data is also non-stationary.

After discussions with climate experts, it was agreed that the relatively short 19 year intervals of climatic data can be assumed to be stationary (purely on the basis that it covers a short time period). However, the problem of inadequate record length still remained.

The study team developed a methodology whereby long-term time series, representative of future time horizon runoff, are derived. Additional to the generation of longer time series, the method also artificially imposes stationarity on the dataset.

Figure A1 below provides a diagrammatic representation of the methodology developed, with discussions following the individual items on the diagram in alphabetical order. Items A to D as well as item J deals with the GCM-simulated short-term time series, whilst items E- G deal with a long-term present time horizon runoff time series (1947-2008) simulated separately from the climate change simulations, using a calibration-type hydrological rainfall-runoff model.

Figure A1: Diagram of methodology of creating long-term stationary CC scenario time series



A: This is representative of the three short-term surface water runoff time series data simulated by a GCM and downscaled. The 3 time series represent the cumulative natural runoff that enters a reservoir, for each the 3 time horizons as modelled by the specific GCM. These are the present state (referred to as 'PC' in the diagram), the intermediate future scenario (referred to as 'IFC' in the diagram) and the distant future scenario (referred to as 'DFC' in the diagram). The 2 latter time series (i.e. IFC and DFC) represent the projected future runoff at different time intervals, assuming a specific scenario (A2 in this case), whilst the PC time series represents runoff as modelled for current conditions. The time series provide monthly total surface water runoff volumes for consecutive hydrological years. In particular, the time intervals represented by the three time horizons are:

- present climate (PC): 1971-1989,
- intermediate future climate (IFC): 2046-2064,
- distant future climate (DFC): 2081-2099

The monthly total runoff volumes in a hydrological year are added, to produce total annual runoff volumes for the above-mentioned time horizons; that is, 19 consecutive values for each of the three time horizons. This is what is represented by item **B** in **Figure A1**.

B: This is representative of three short-term surface water runoff time series data, given in annual total flow volumes. As described above, each of the three time series consist of 19 values. These values are ranked in ascending order and five percentile values are determined for each time series. These are:

- 0^{th} percentile (or minimum)
- 25^{th} percentile (or 1^{st} quartile)
- 50^{th} percentile (or median or 2^{nd} quartile)
- 75^{th} percentile (or 3^{rd} quartile)
- 100^{th} percentile (or maximum or 4^{th} quartile)

This results in five statistical descriptive values for each of the three short-term annual time series and leads to item **C** in **Figure A1**.

C: This is representative of the five percentiles, describing the bounds of the quartile intervals, for each of the three short-term annual runoff time series. There are four such intervals, *viz*. [0^{th}-25^{th}), [25^{th}-50^{th}), [50^{th}-75) and [75^{th}-100^{th}].

In order to compute the two sets of quartile-adjustment factors in item D, let's say that the five percentiles for time interval PC are given by $\{p_{0,\ PC}, p_{25,\ PC}, p_{50,\ PC}, p_{75,\ PC}, p_{100,\ PC}\}$. Furthermore, assuming that the corresponding percentiles for the two future time intervals are given by {$p_{0,\ IFC}$, $p_{25,\ IFC}$ …} and {$p_{0.\ DFC}$, $p_{25,\ DFC}$ …}, compute the future percentiles relative to the present, i.e.

$$f_{i,\ IFC} = p_{i,\ IFC} / p_{i,\ PC}$$

and

$$f_{i,\ DFC} = p_{i,\ DFC} / p_{i,\ PC}$$

for $i \in \{0, 25, 50, 75, 100\}$

The result is two sets of factors, one representative of the conversion of present time (PC) interval percentiles to intermediate future (IFC) percentiles and the other representative of the conversion of present time (pr3) interval percentiles to distant future (DFC) percentiles, as represented by item **D** in **Figure A1**.

D: This is representative of two sets of conversion factors that are applied to the percentile values derived from the long-term present time horizon runoff time series (see items **E** and **F**). These factors, once applied to the percentiles of the long-term record, gives the 0^{th}, 25^{th} 50^{th}, 75^{th} and 100^{th} percentiles of the new long-term runoff time series that will represent the two future time horizon runoff time series (item **H** in **Figure A1**).

E: This is representative of a long-term monthly runoff record that represents the natural runoff that enters a specific reservoir, based on present climatic conditions. This long-term time series is calibrated against an observed runoff time series, taking into account various land use and human development aspects and rainfall is derived from long-term observed records, and is statistically stationary. This stationarity is preserved throughout the procedures that follow.

The monthly total runoff volumes in a hydrological year are added, to produce total annual runoff volumes for the above-mentioned present condition time horizon. This is what is represented by item **F** in **Figure A1**.

F: This is representative of the long-term present condition surface water runoff time series data, given in annual total flow volumes. As described above, the time series consists of 62 values. These values are ranked in ascending order and 5 percentile values are determined for each time series. These are:

- 0^{th} percentile (or minimum)
- 25^{th} percentile (or 1^{st} quartile)
- 50^{th} percentile (or median or 2^{nd} quartile)
- 75^{th} percentile (or 3^{rd} percentile)
- 100^{th} percentile (or maximum or 4^{th} quartile)

This results in five statistical descriptive values that represent the long-term annual time series and leads to item **G** in **Figure A1**.

G: This is representative of the five percentiles, describing the bounds of the quartile intervals, for each of the long-term annual runoff time series. There are four such intervals, *viz*. [0^{th}-25^{th}), [25^{th}-50^{th}), [50^{th}-75) and [75^{th}-100^{th}].

These percentiles are adjusted using the two sets of adjustment factors described for item **C** above, representing the intermediate future (IFC) and distant future (DFC) time horizons, respectively.

The adjustment is done by multiplying each of the long-term percentiles with the corresponding adjustment factor. This gives rise to two new sets of percentiles that represent the long-term intermediate and long-term distant future time horizons, respectively (item **H** in **Figure A1**).

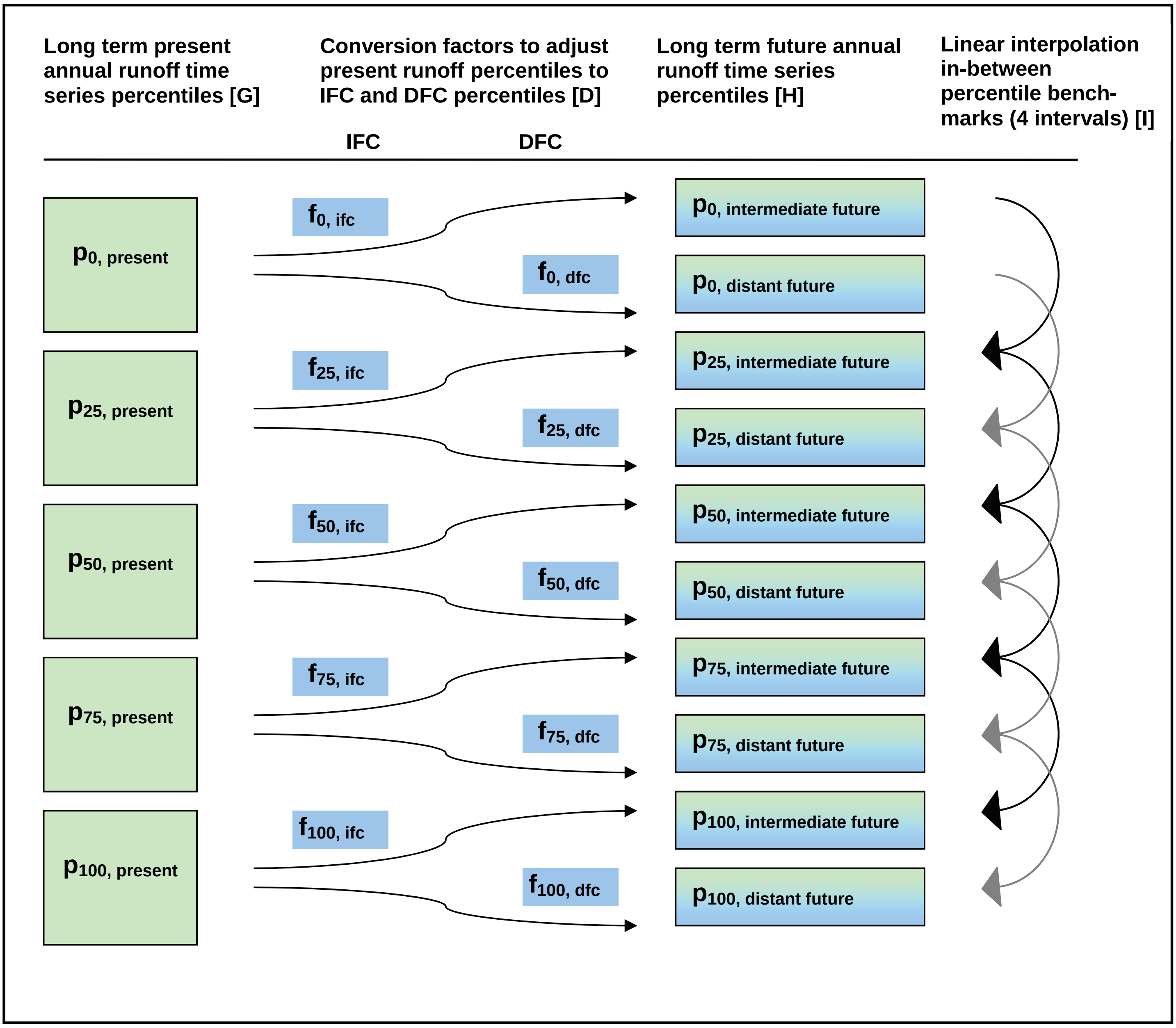
The adjustment procedure is presented as a diagram in **Figure A2**. Corresponding items in **Figure A1** are indicated in [square brackets].

As can be seen from the **Figure A2**, the five percentiles for the two new long time series have now been computed. These will serve as 'benchmarks' in the computation of the remaining annual total values (i.e. the values that lie 'in-between' the percentile benchmarks) and are represented by item **H** in **Figure A1**.

H: This is representative of the five benchmark percentiles of the intermediate and distant future long-term annual total runoff time series, calculated as described in the above description. The remaining total annual flow volumes in the long-term present conditions time series are converted to the future time horizon by means of linear interpolation between the five percentile benchmarks, as indicated in **Figure A2**. This gives rise to item **I** in **Figure A1**.

I This is representative of the two long-term future time horizon-based annual runoff volume time series. As described above, these time series are derived by first adjusting the five percentile values and secondly, by linear interpolation of annual totals that are situated in-between these percentile benchmarks.

Figure A2: Adjustment of long-term present percentiles to reflect long-term future time horizon percentiles



In order to perform yield analyses on these time series, the annual totals need to be disaggregated into monthly values, allowing for the seasonality (wet and dry seasons) to be characterised in the time series. This is represented by item **K** in **Figure A1**.

This is done by making use of the seasonal distributions derived from the two short-term future time horizon monthly time series in item **A**. The four quartile-intervals described under item **C**, are viewed as four groups of data-sets, each having a set of flow values for months 1 to 12. The average value for each month in each of the four data-sets is computed and expressed as a proportion of the average total annual flow for that data-set. Thus resulting in four sets of monthly distribution patterns for each of the two future time horizon time series. This is represented by item **J** in **Figure A1**.

J: This is representative of the monthly distribution patterns of annual flows, as per short-term time series. The distribution pattern changes as the total annual flow volume changes by associating a specific distribution pattern with each of the four percentile-intervals (i.e. [0^{th}-25^{th}), [25^{th}-50^{th}), [50^{th}-75^{th}) and [75^{th}-100]). Therefore there are four distribution patterns associated with each of the two future time horizon time series.

These distribution patterns are applied to the long-term total annual flow volume time series represented by item **I** in order to produce the long-term monthly flow volume time series represented by item **K** in **Figure A1**.

K: This is representative of three long-term monthly runoff time series, representing the present, intermediate future and distant future time horizons respectively. These time series are stationary and can be used in reservoir yield analyses.

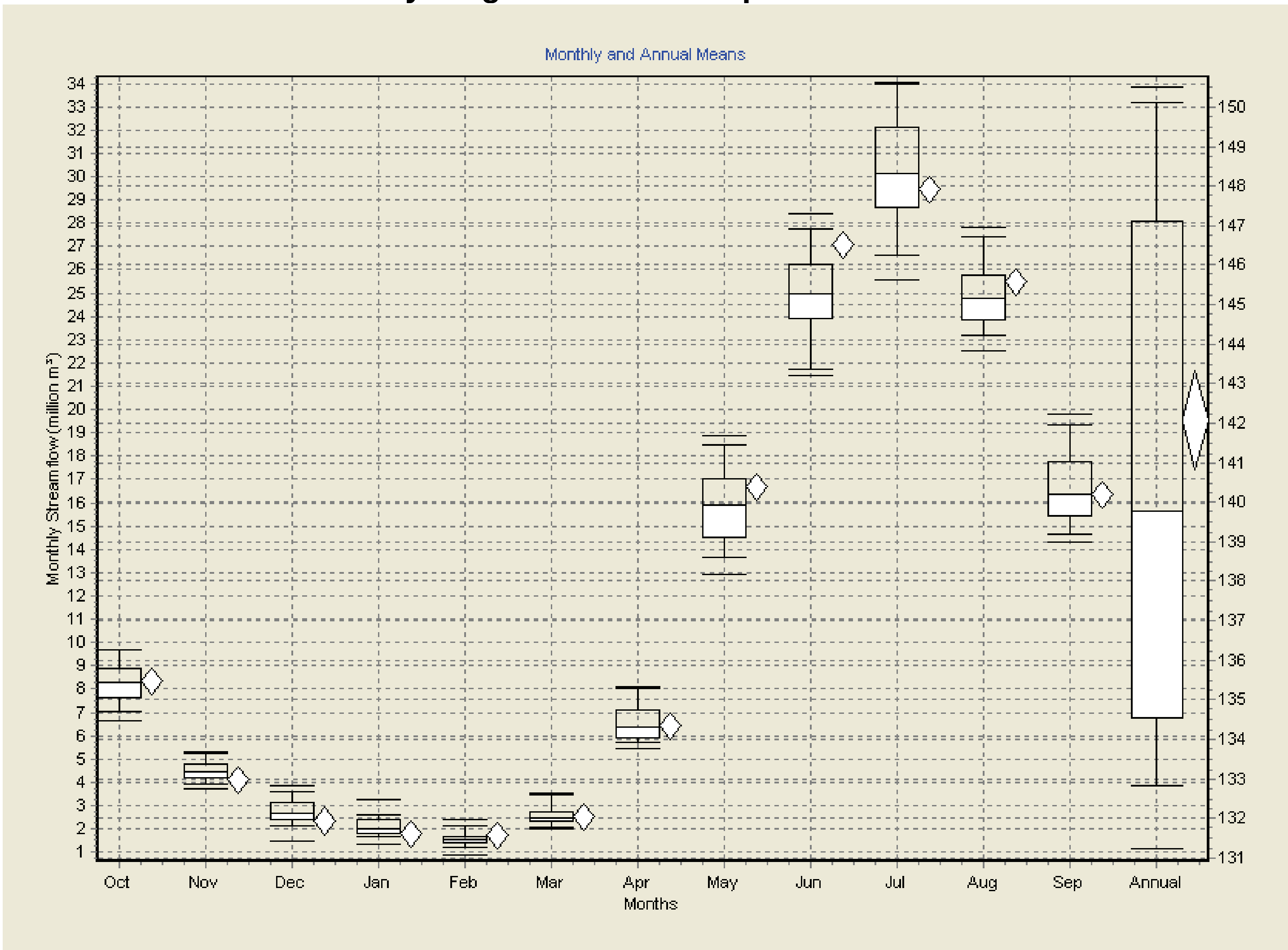
Upon investigation, the research team found that the seasonality (i.e. the monthly distribution of annual total flows) in the GCM-based time series differed significantly from that of the long-term present time horison sequence. In order to facilitate the comparison of yield results between the different time horison results of the GCM-based simulated sequences, the long-term present runoff sequence was adjusted to reflect a seasonal distribution similar to that of the short-term GCM-based present time horizon sequence. This was done in a similar fashion as the monthly breakdown performed for the future time horizon sequences. In particular, the long-term total annual flow volumes were computed and this annual sequence was characterised in terms of the 0^{th}, 25^{th}, 50^{th}, 75^{th} and 100^{th} percentiles. The mean monthly distribution (per quartile – as for the future time horizons) of the short-term present time horizon sequence was also determined. Having characterised both the long- and the short-term sequences, the short-term-based monthly distributions were then used to disaggregate the total annual flow volumes in the long-term sequence, using mean monthly distributions pertaining to each particular quartile.

This resulted in a new long-term present time horizon sequence that has the same MAR as the original long-term sequence, but with a seasonal distribution similar to that of the GCM-based short-term present time horizon sequence.

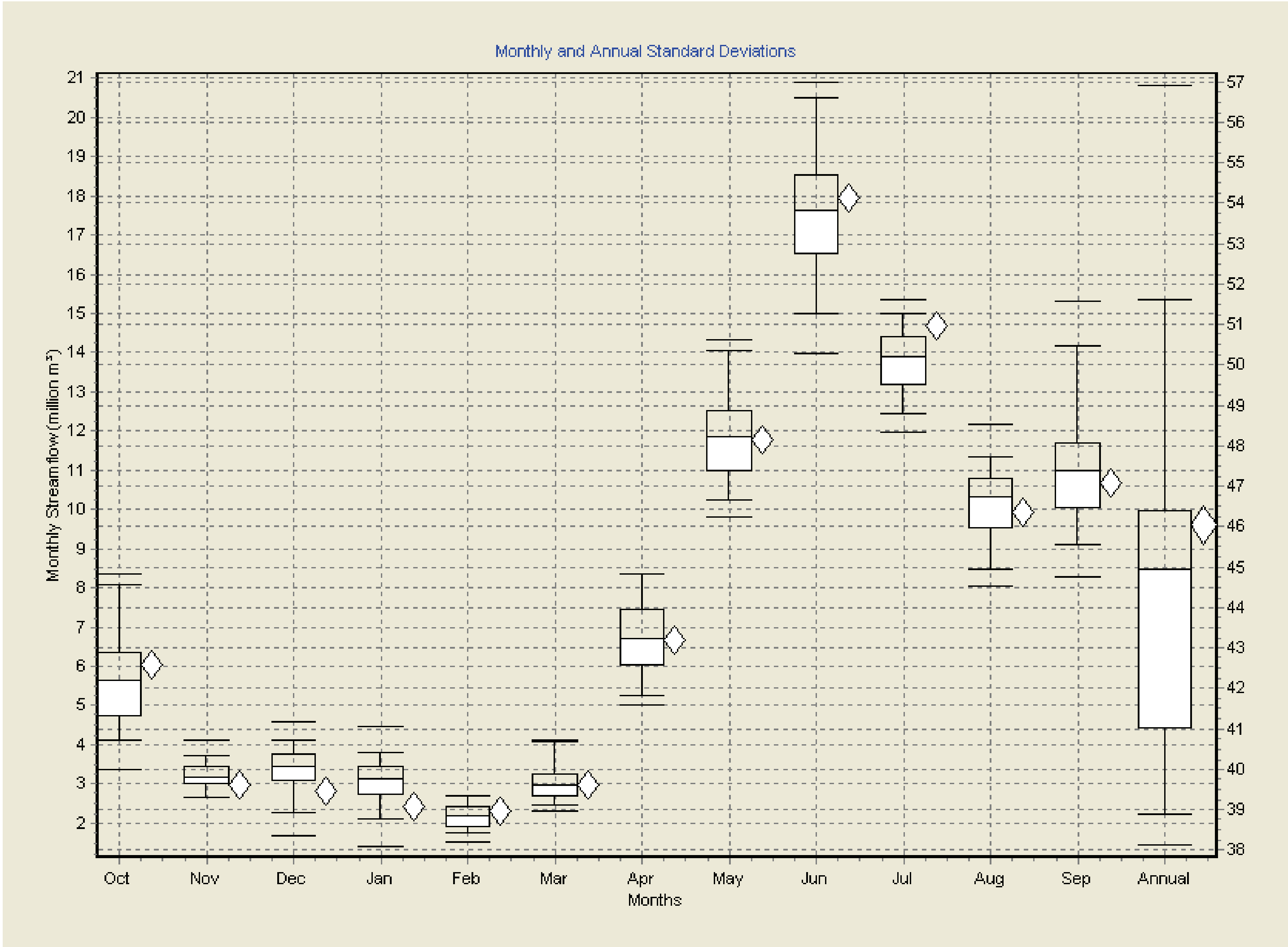
APPENDIX B: Verification and validation of stochastic sequences

Appendix B.1: BERG RIVER DAM

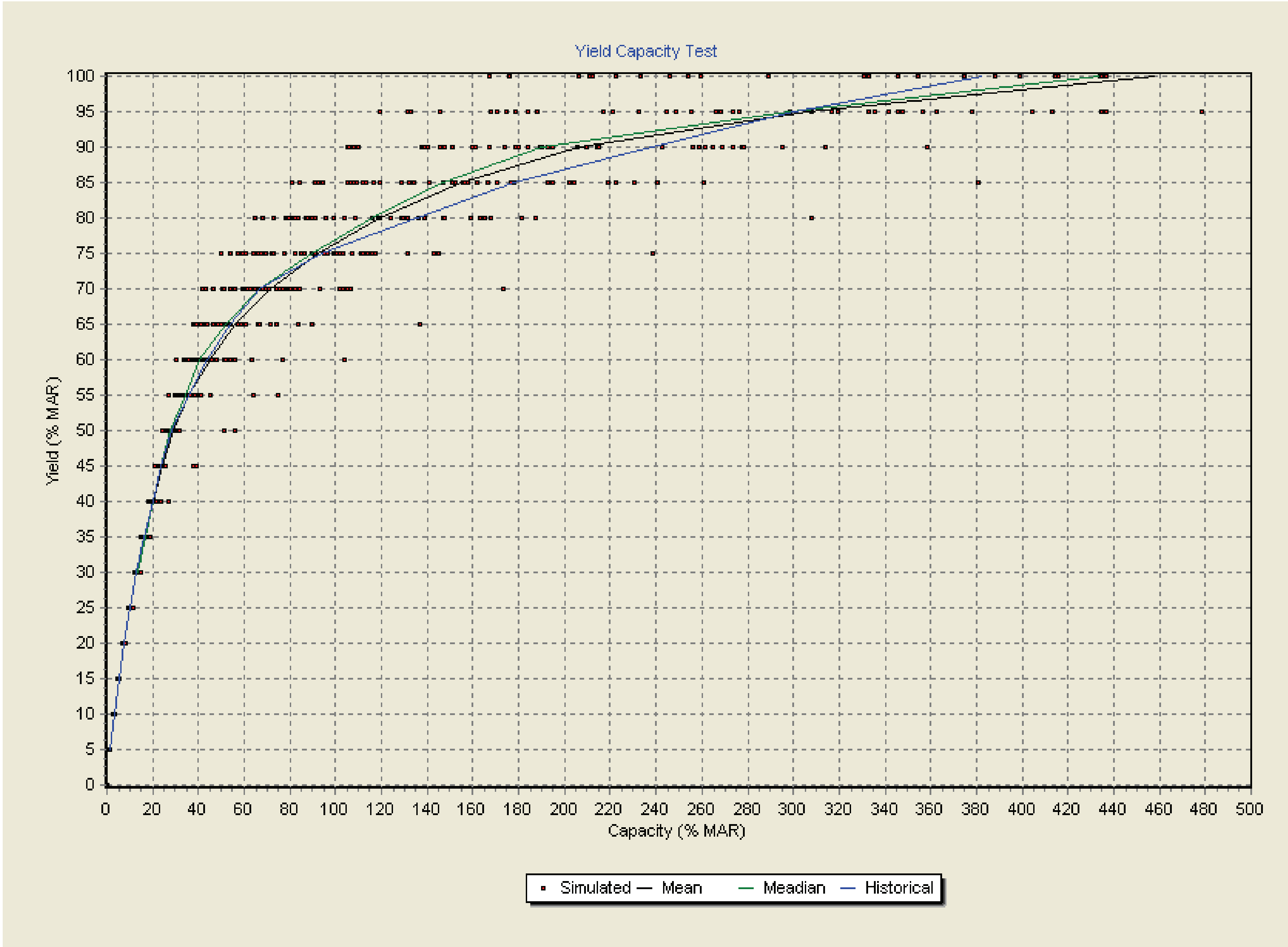
BERG RIVER DAM: Detailed Study long-term runoff sequence



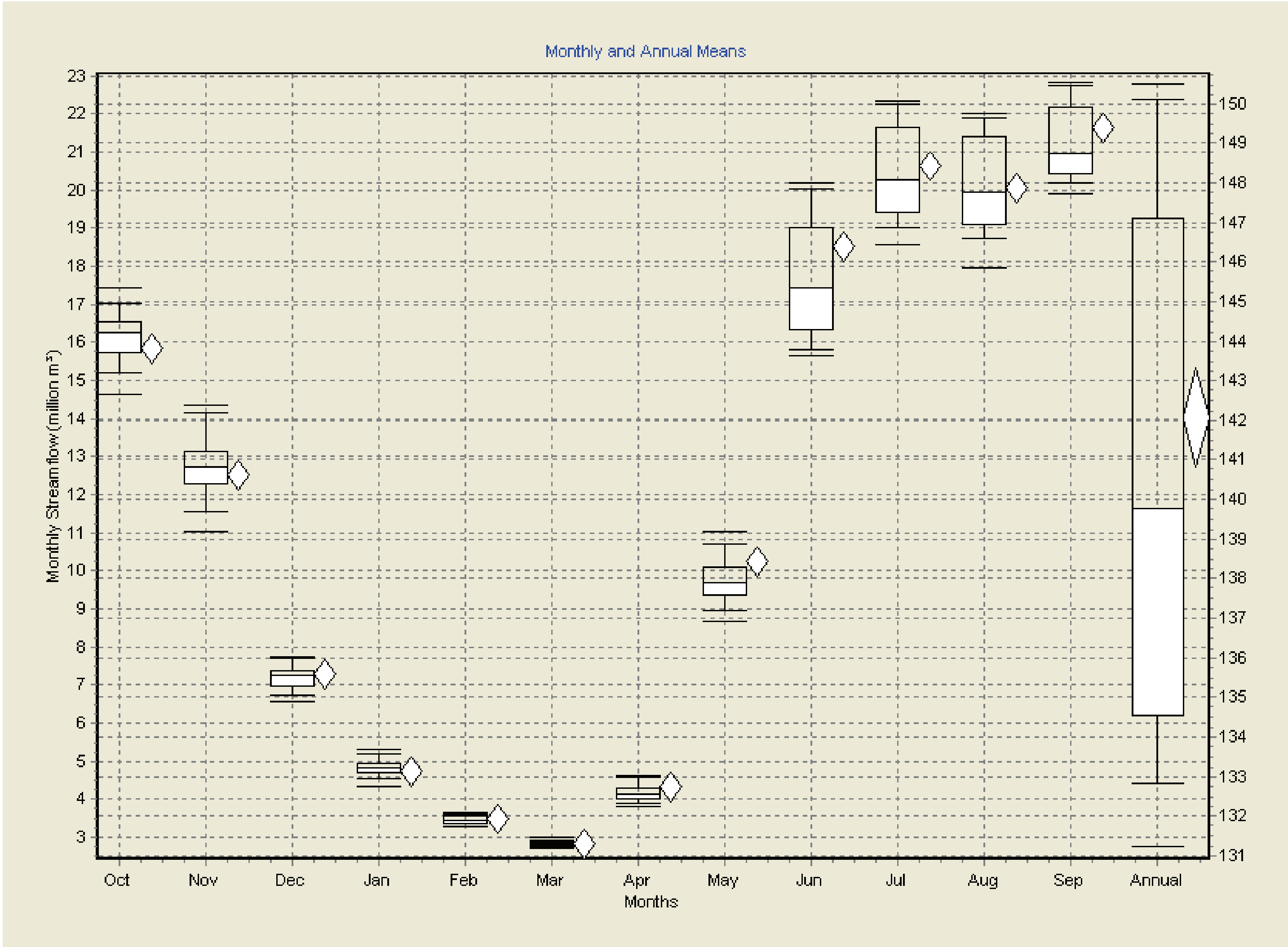
BERG RIVER DAM: Detailed Study long-term runoff sequence



BERG RIVER DAM: Detailed Study long-term runoff sequence



BERG RIVER DAM: ECHAM 5: Present



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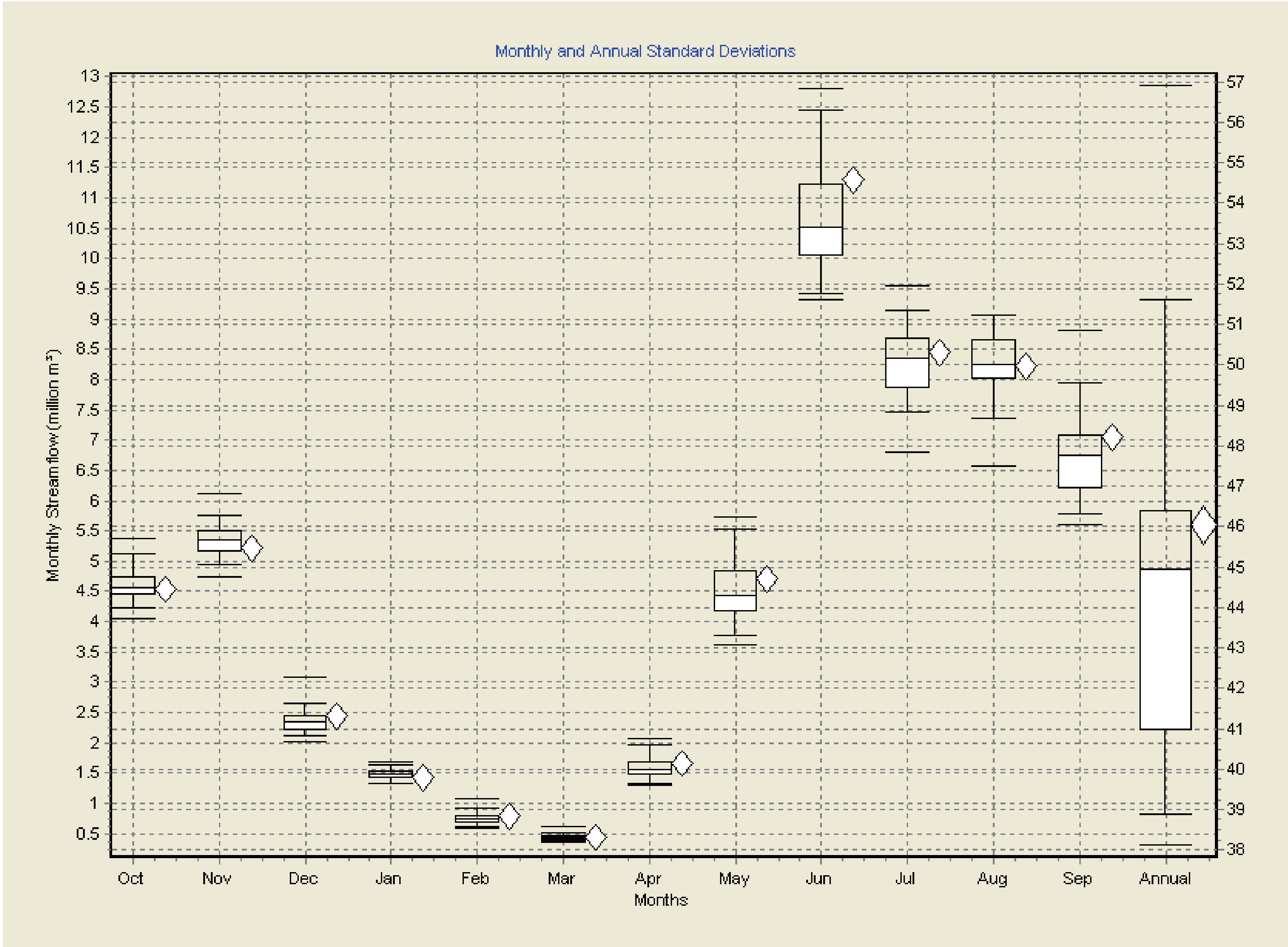

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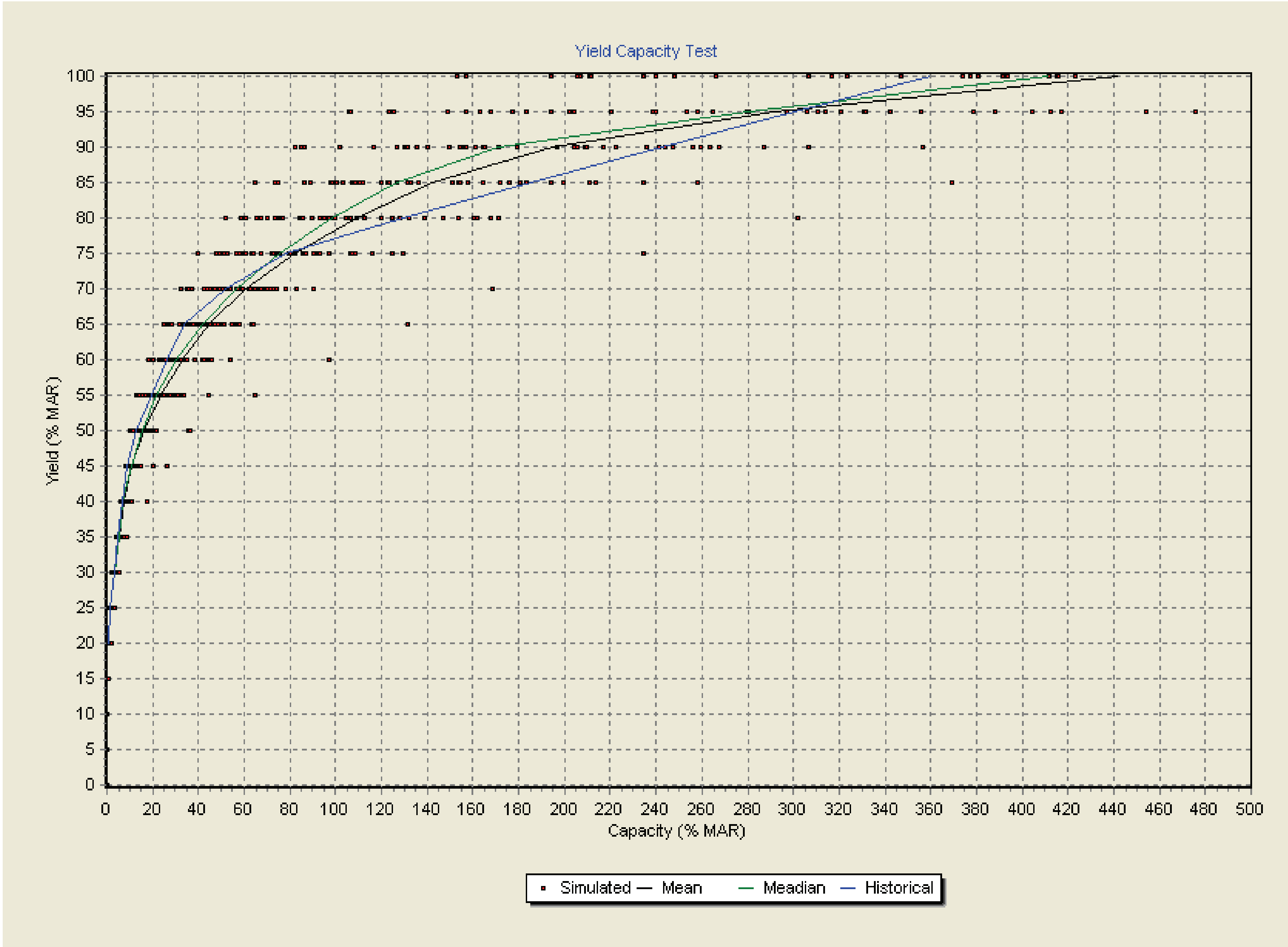
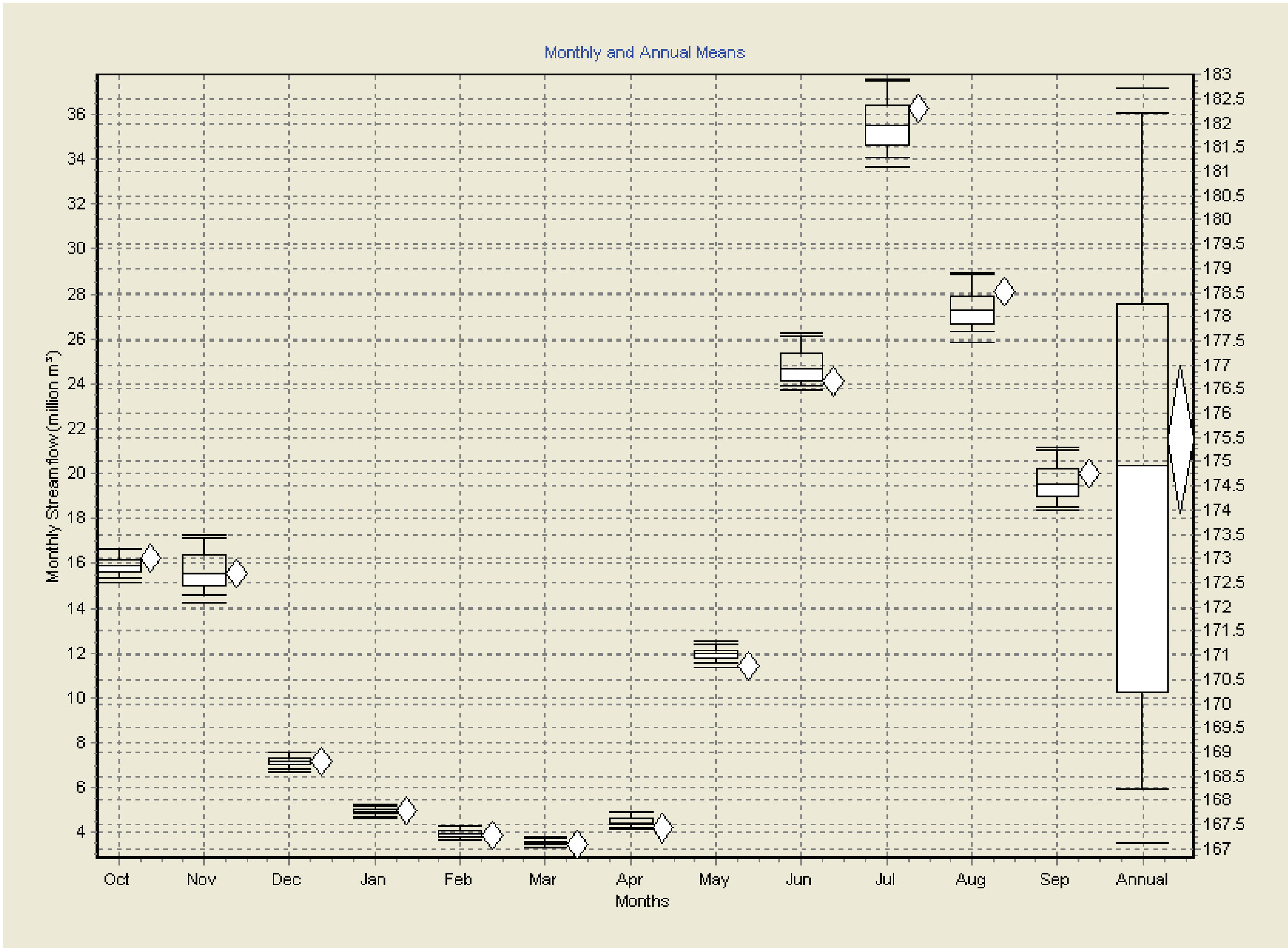


BERG RIVER DAM: ECHAM 5: Intermediate Future



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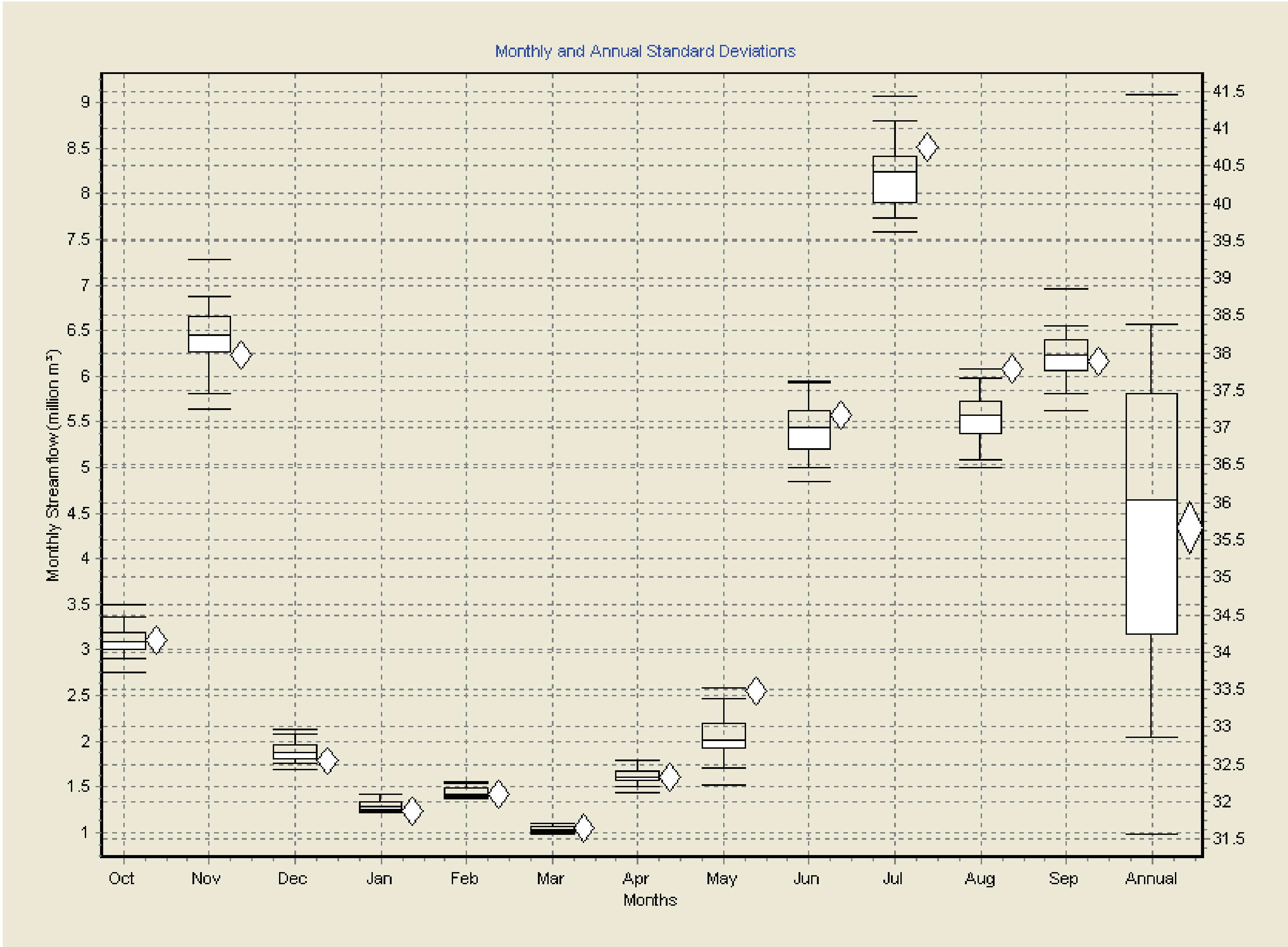

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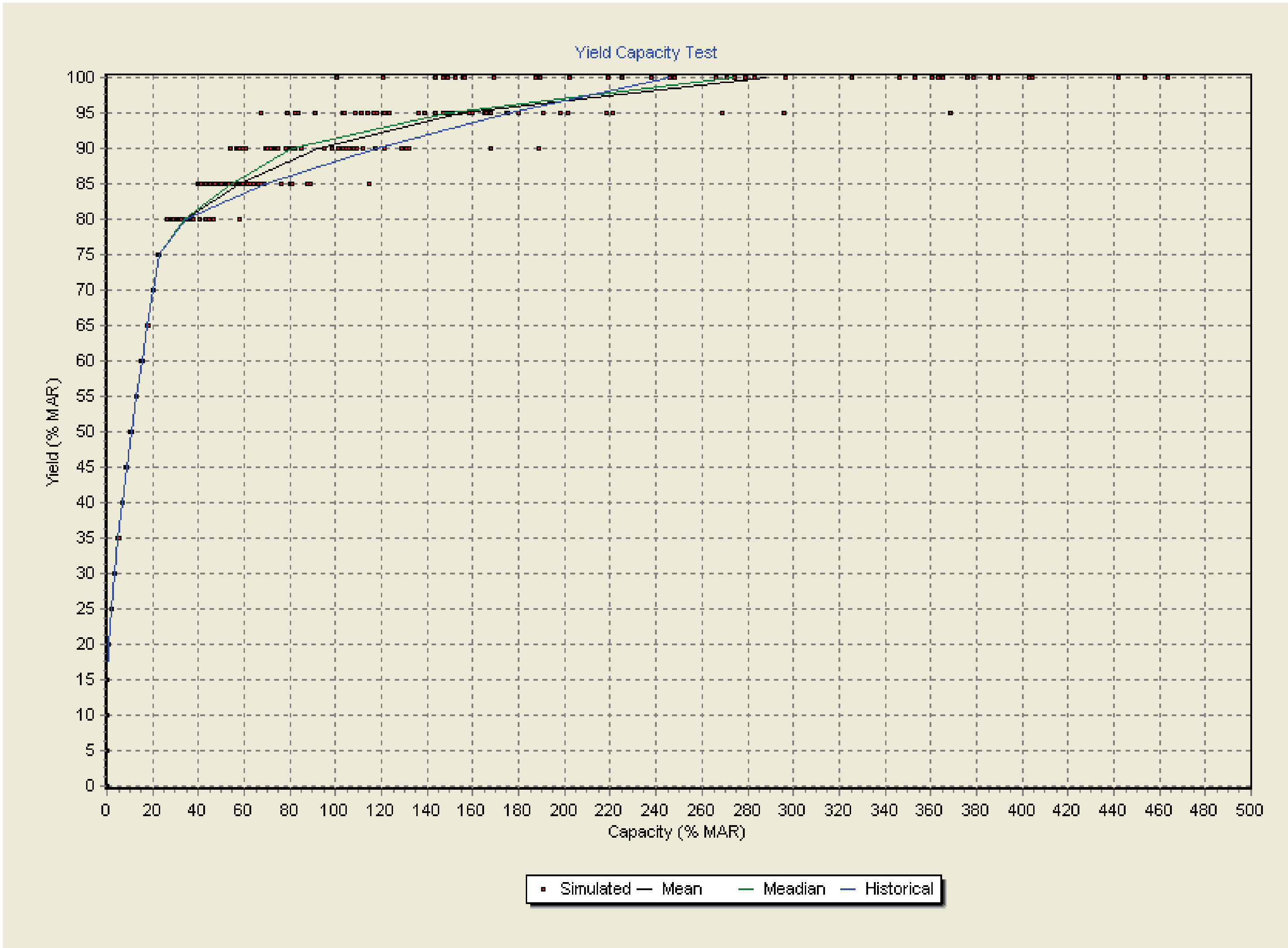

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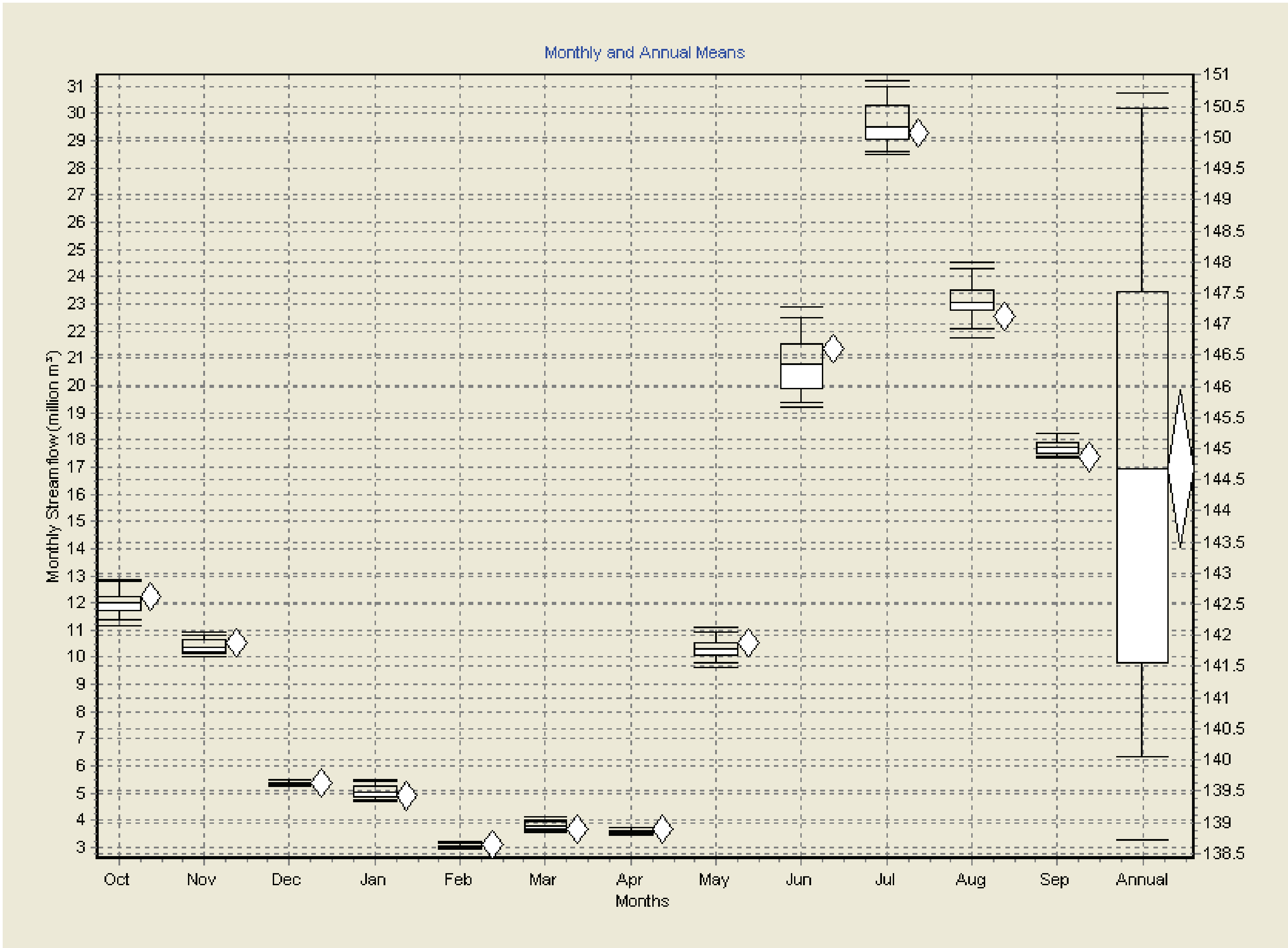

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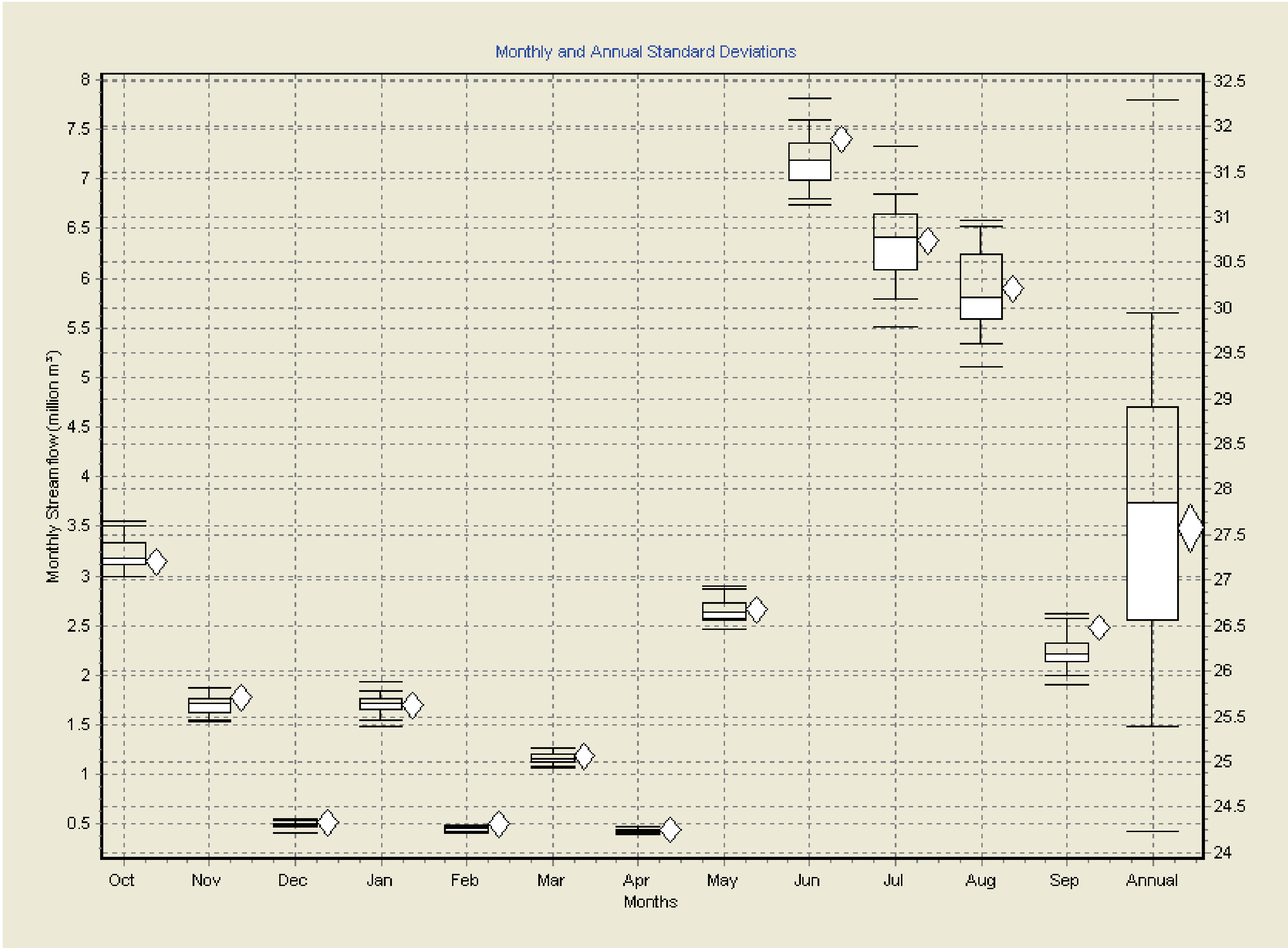

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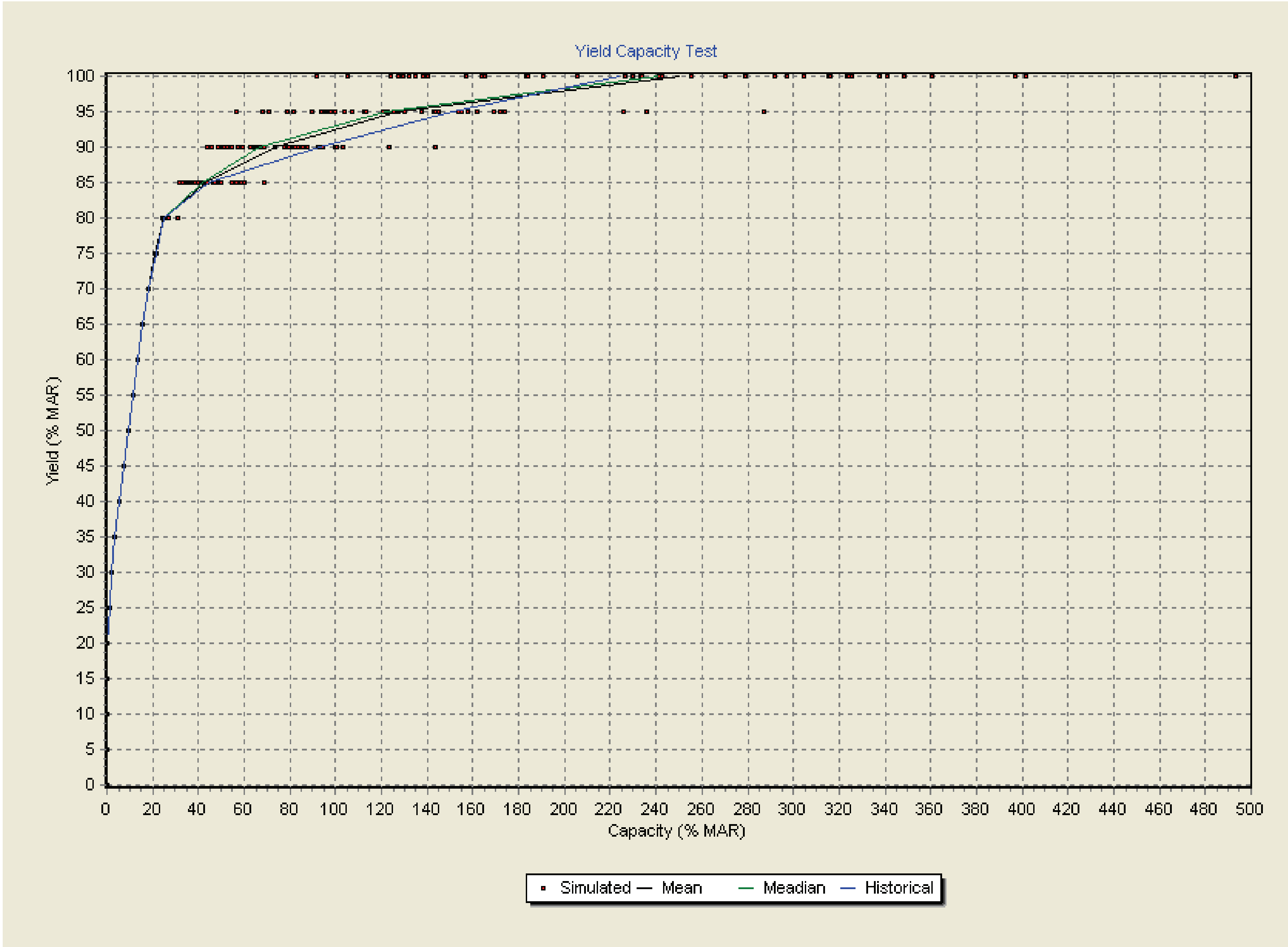

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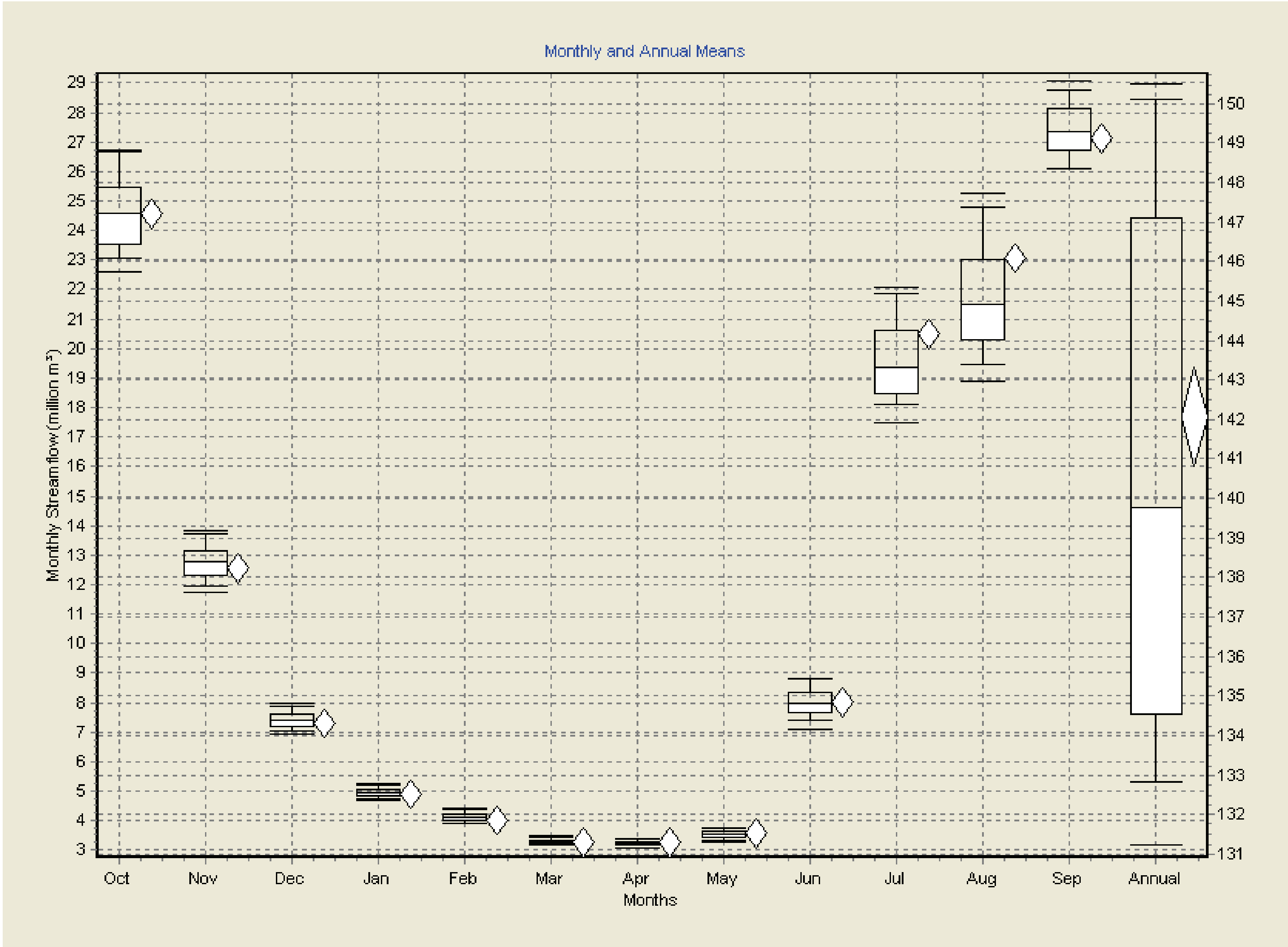

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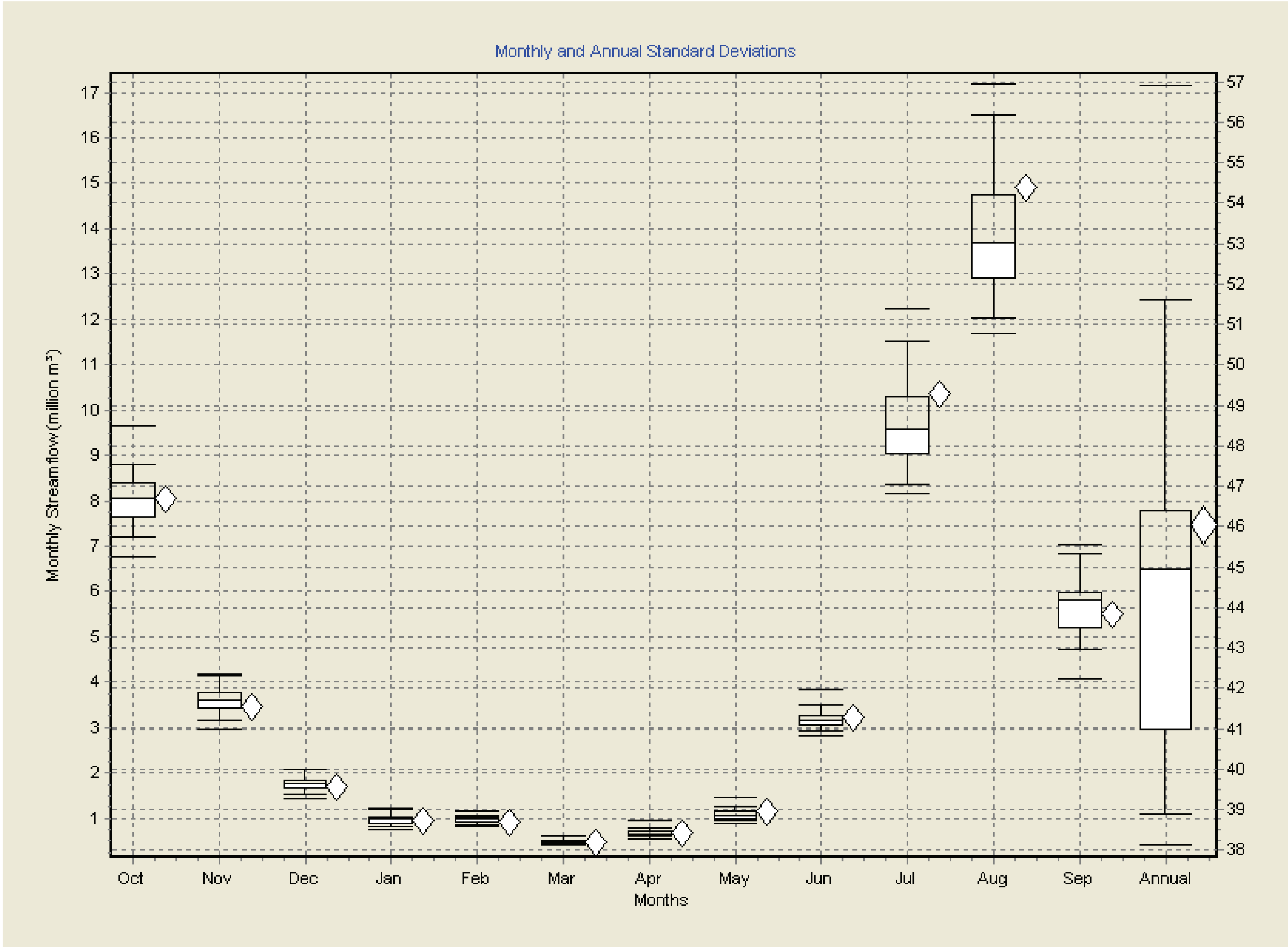

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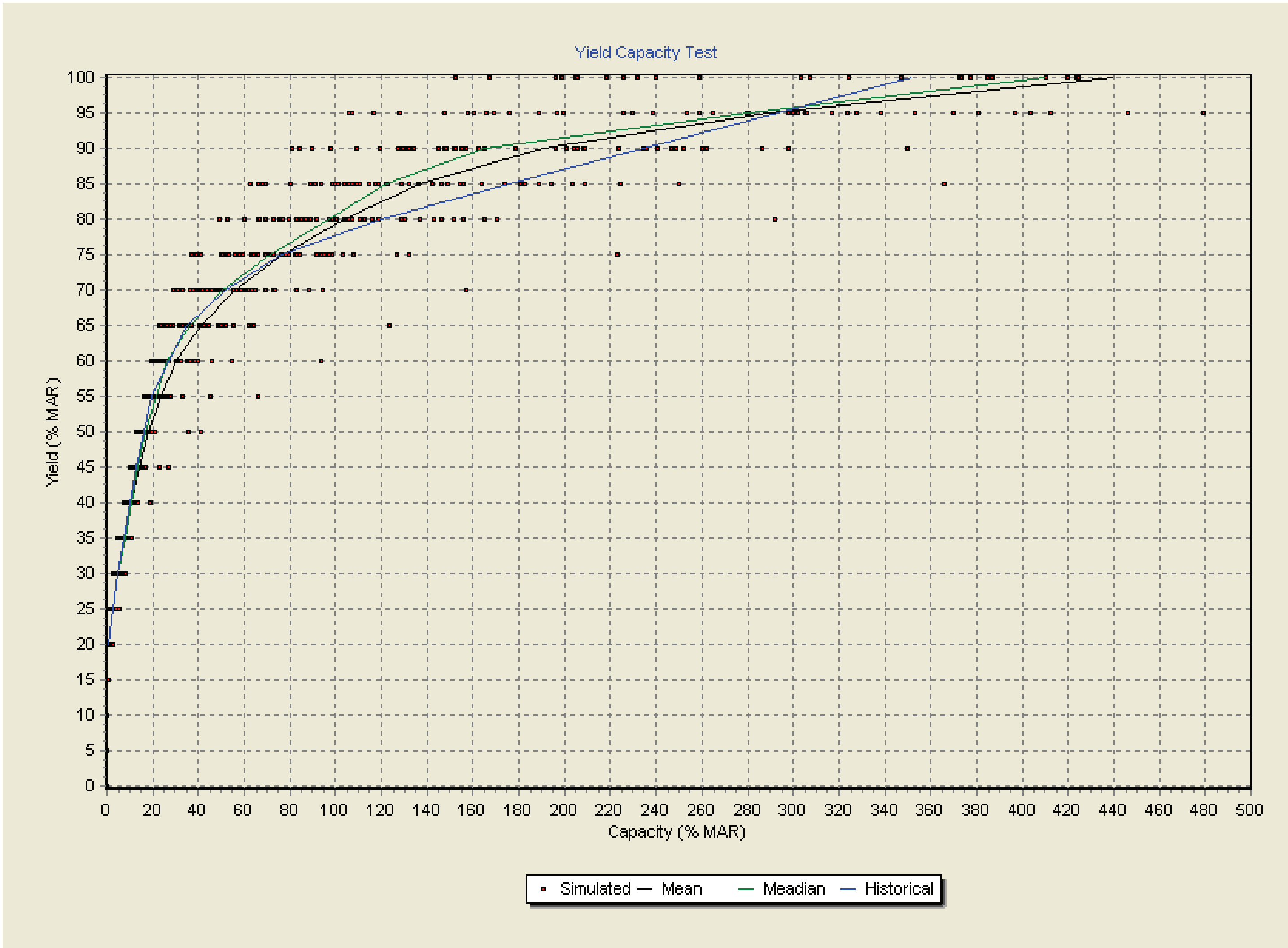

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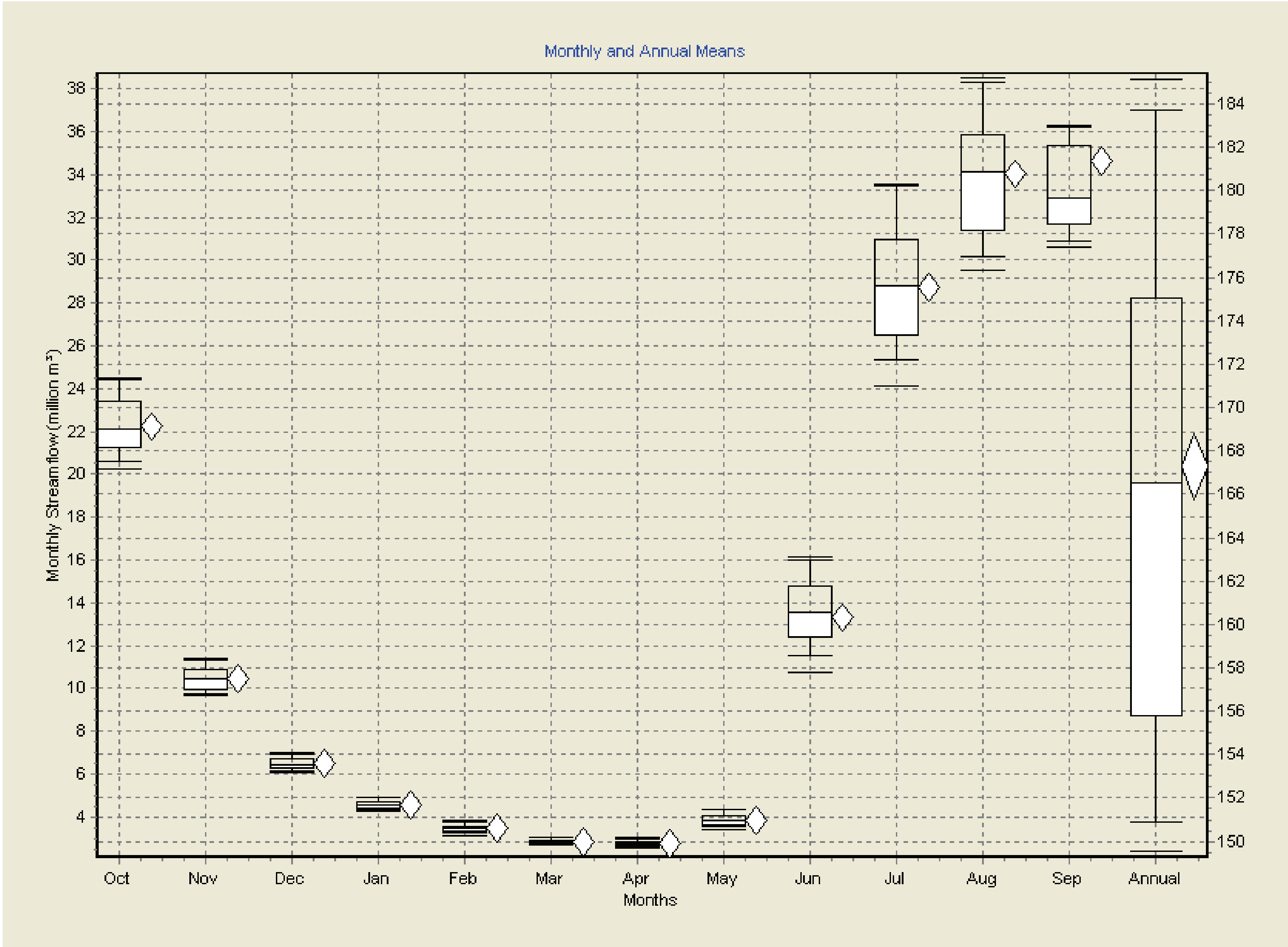

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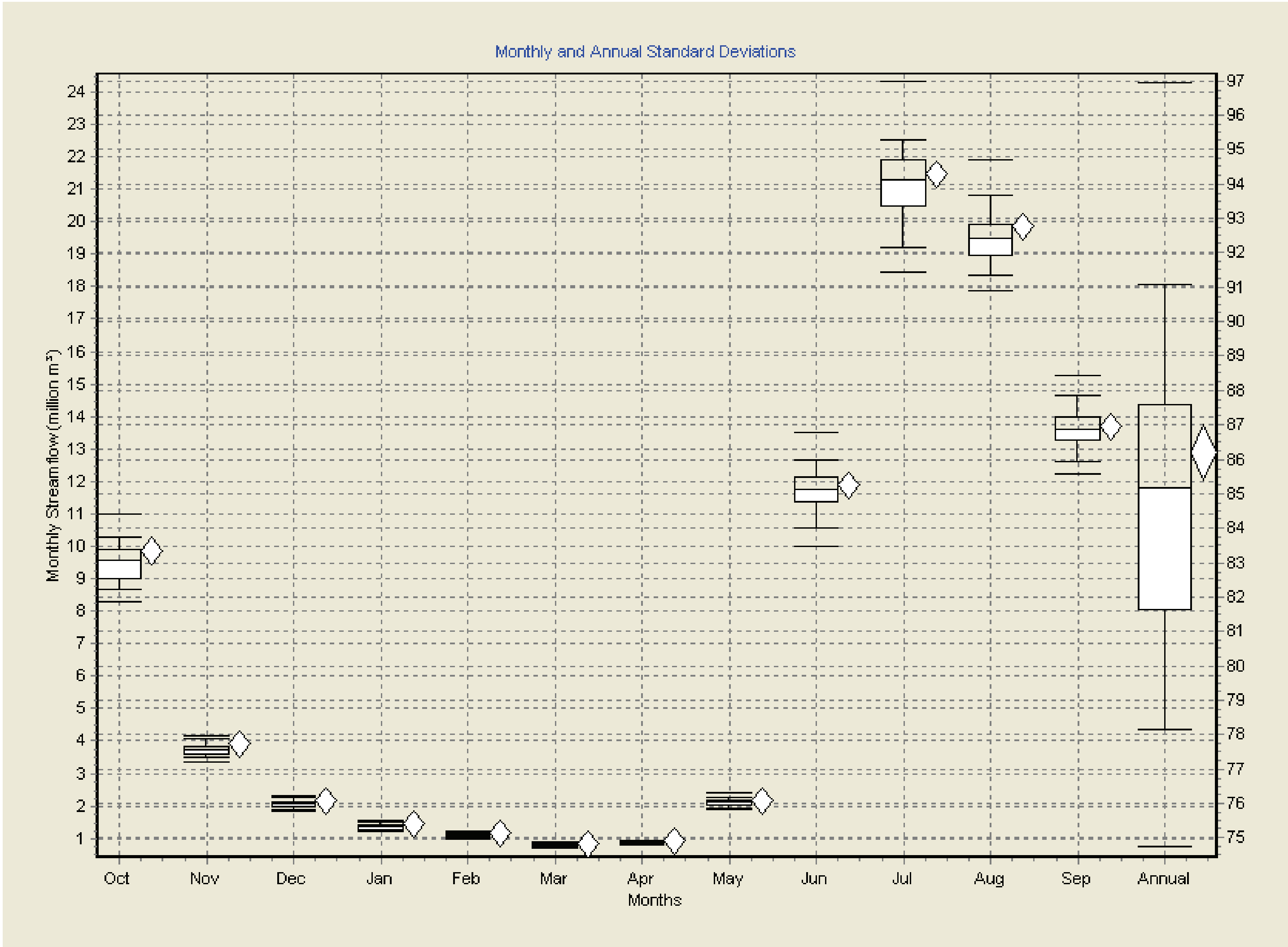

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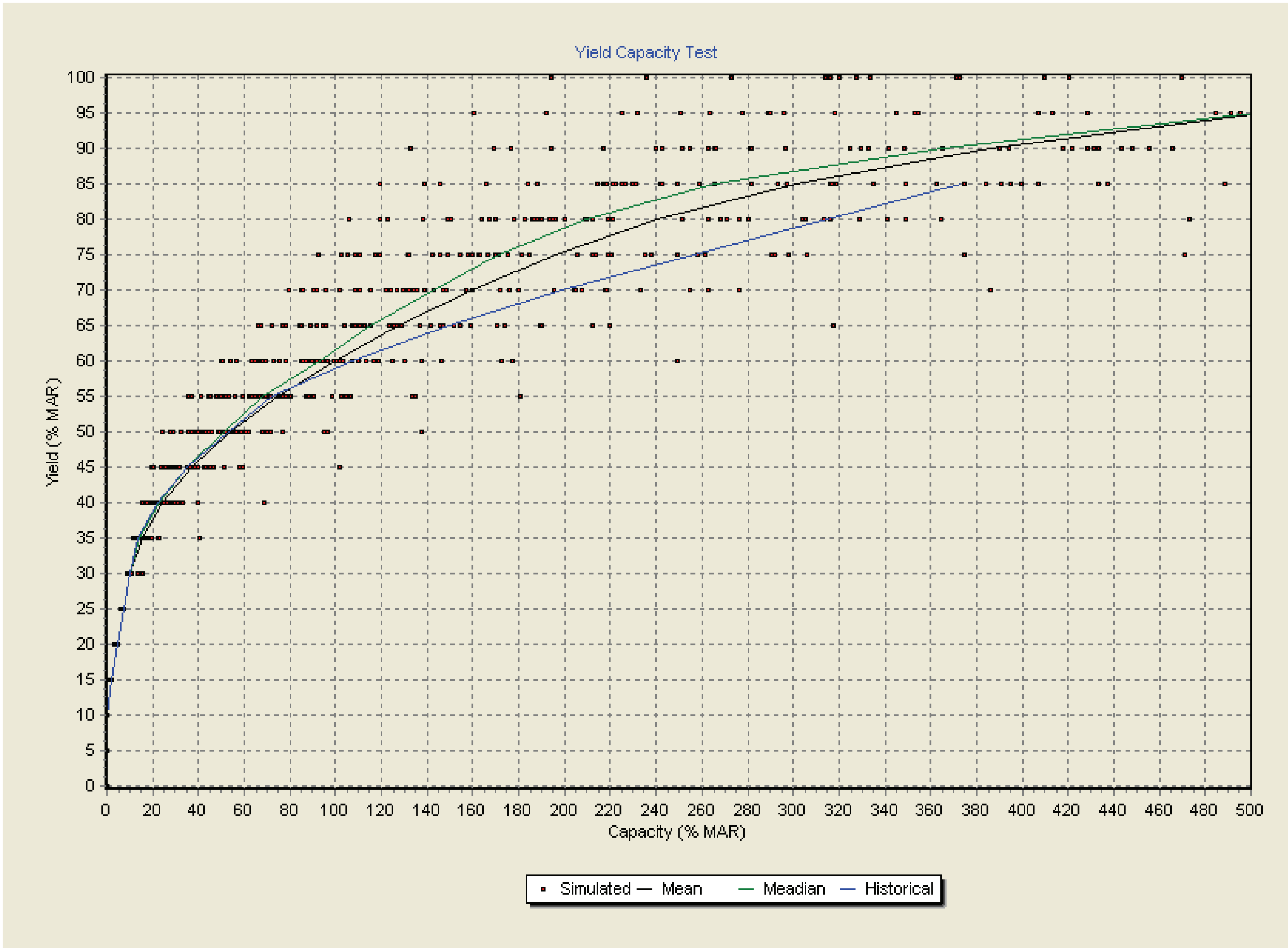

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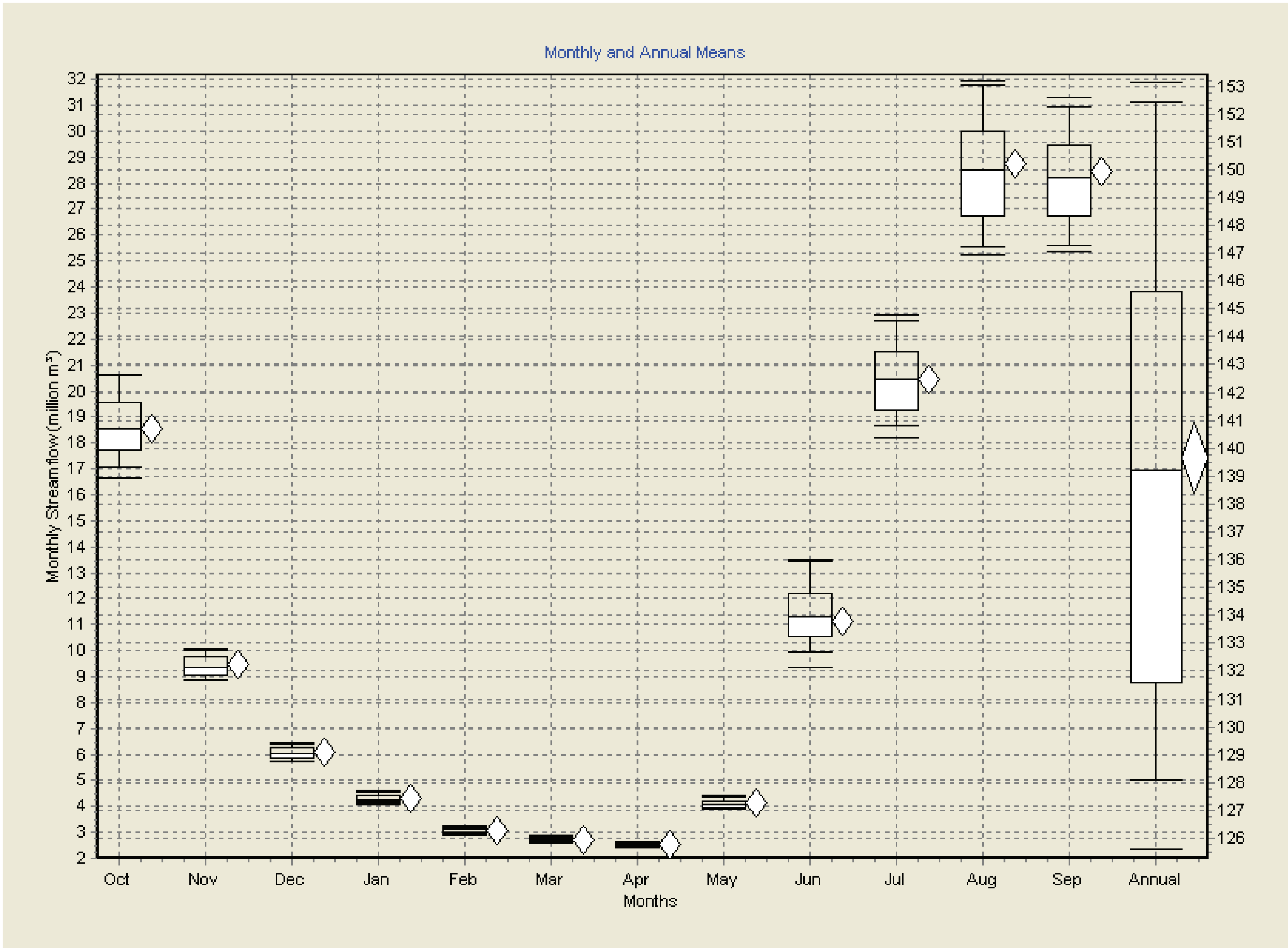

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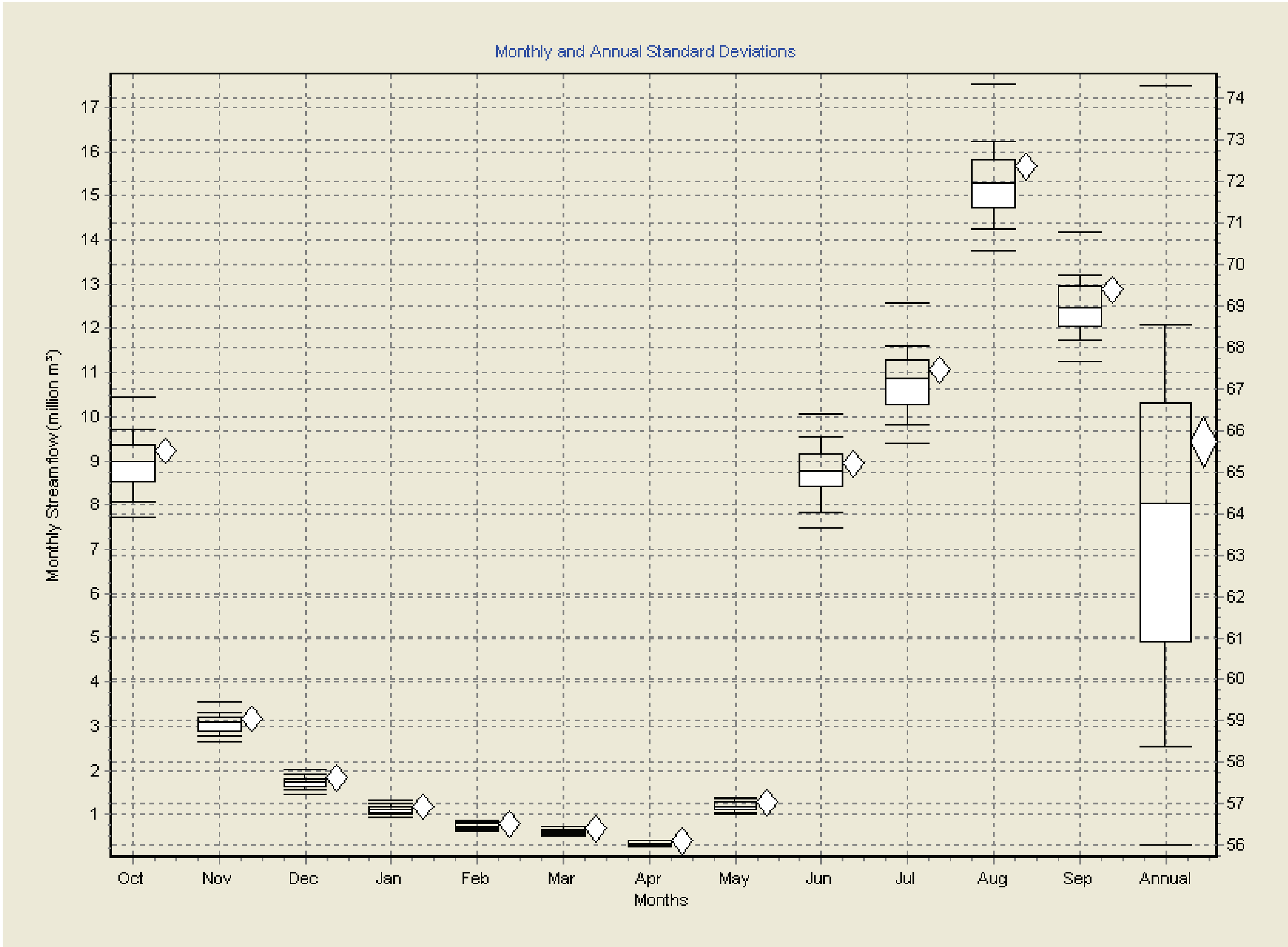

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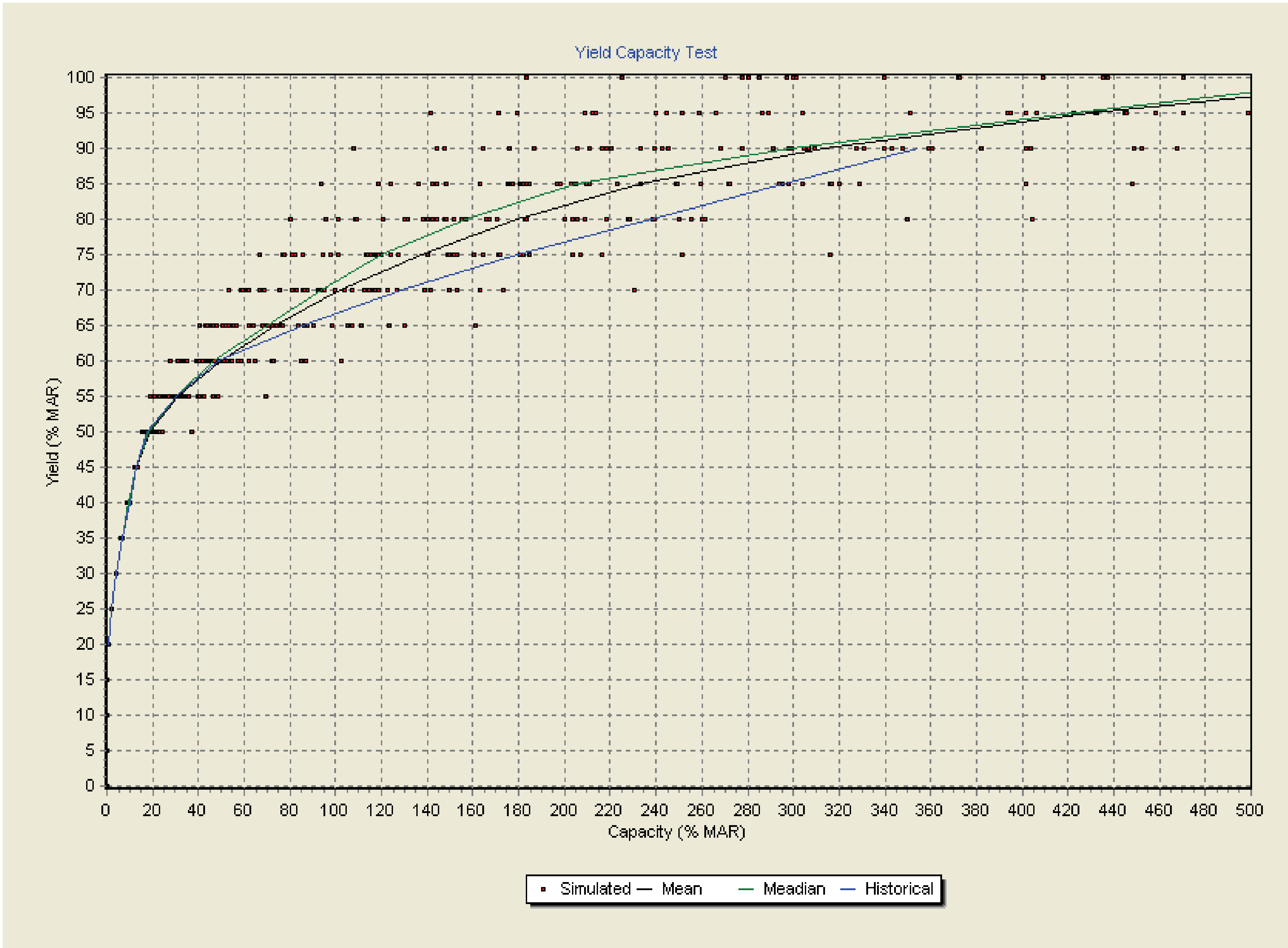

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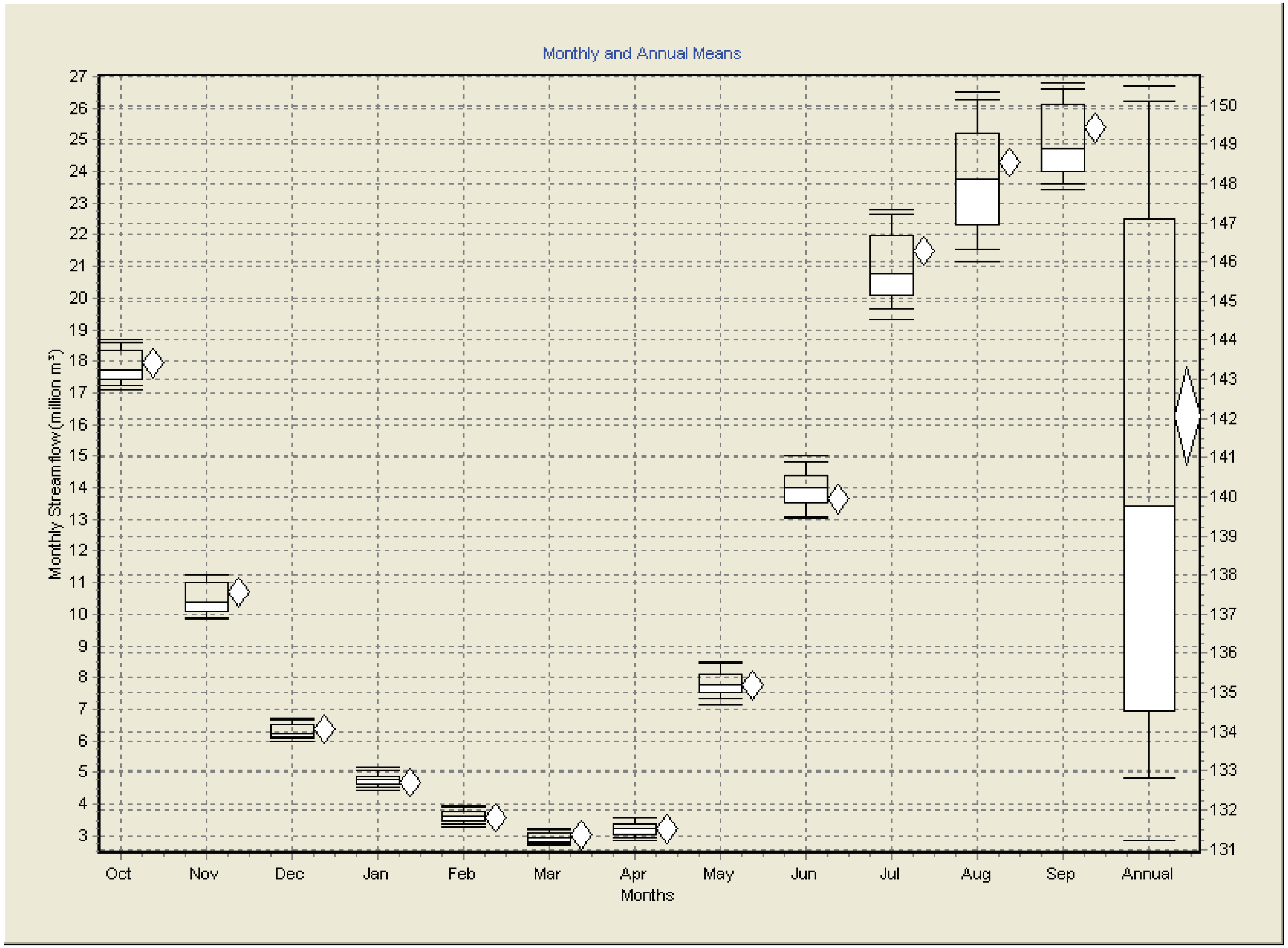

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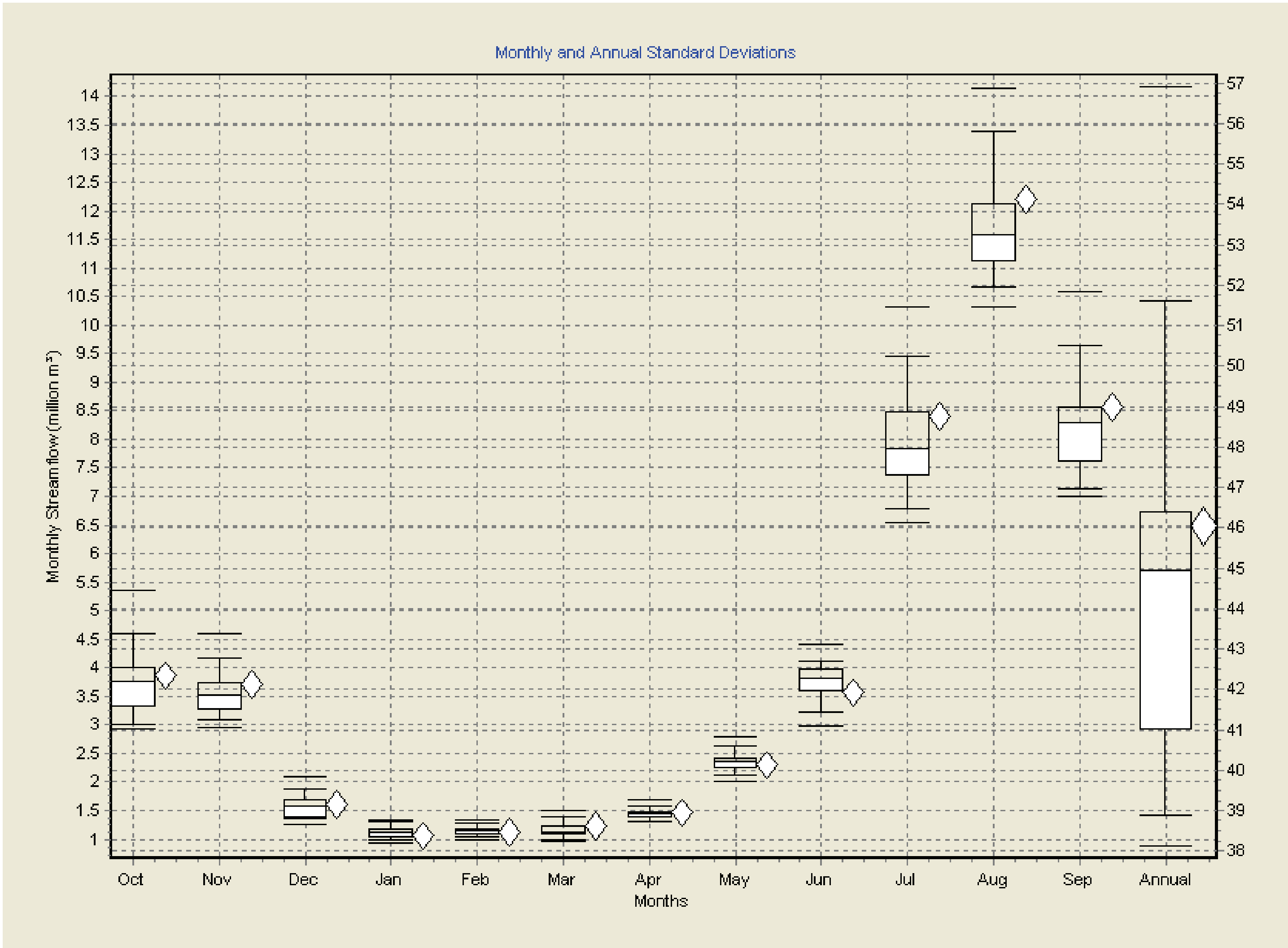

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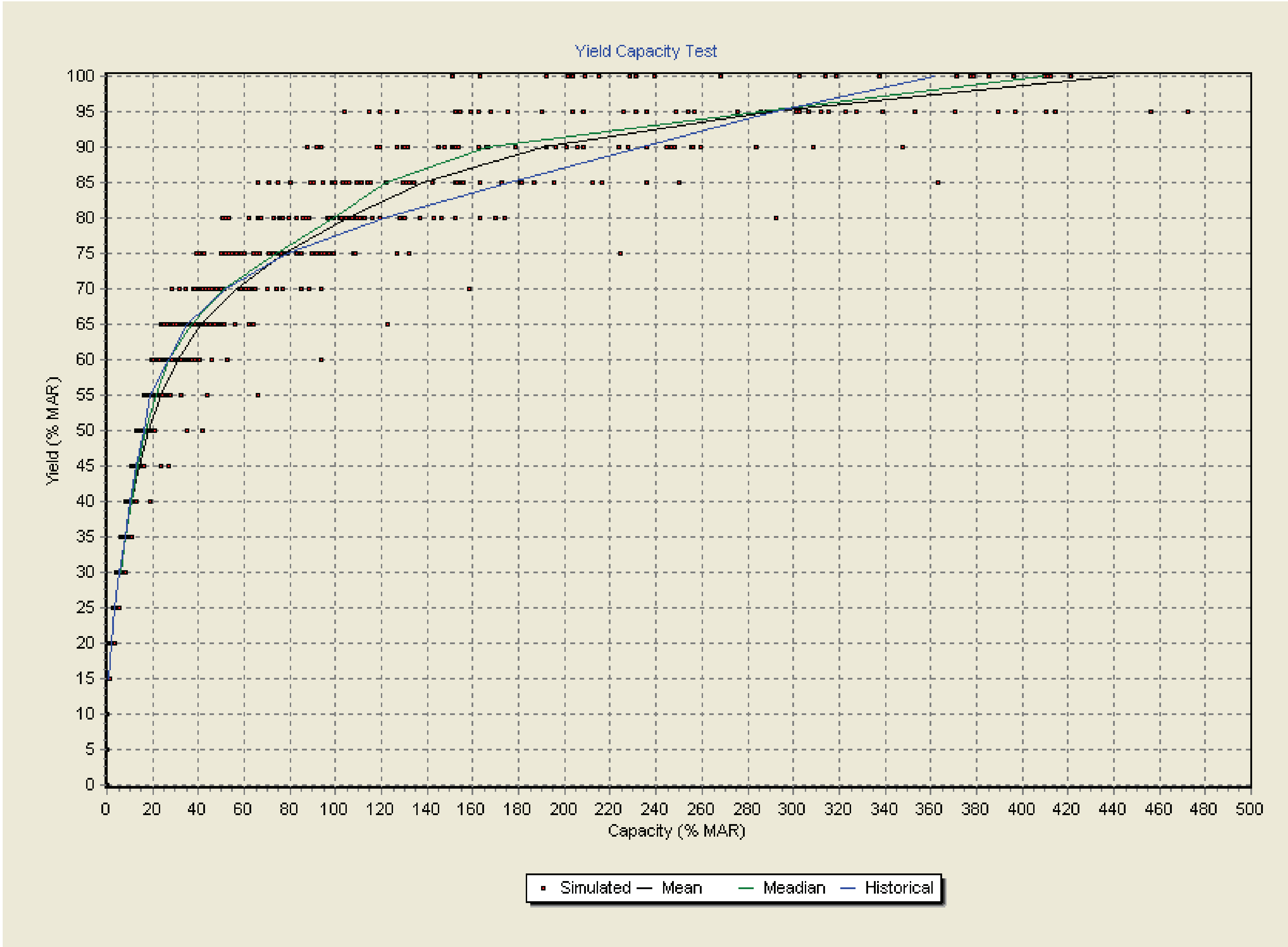

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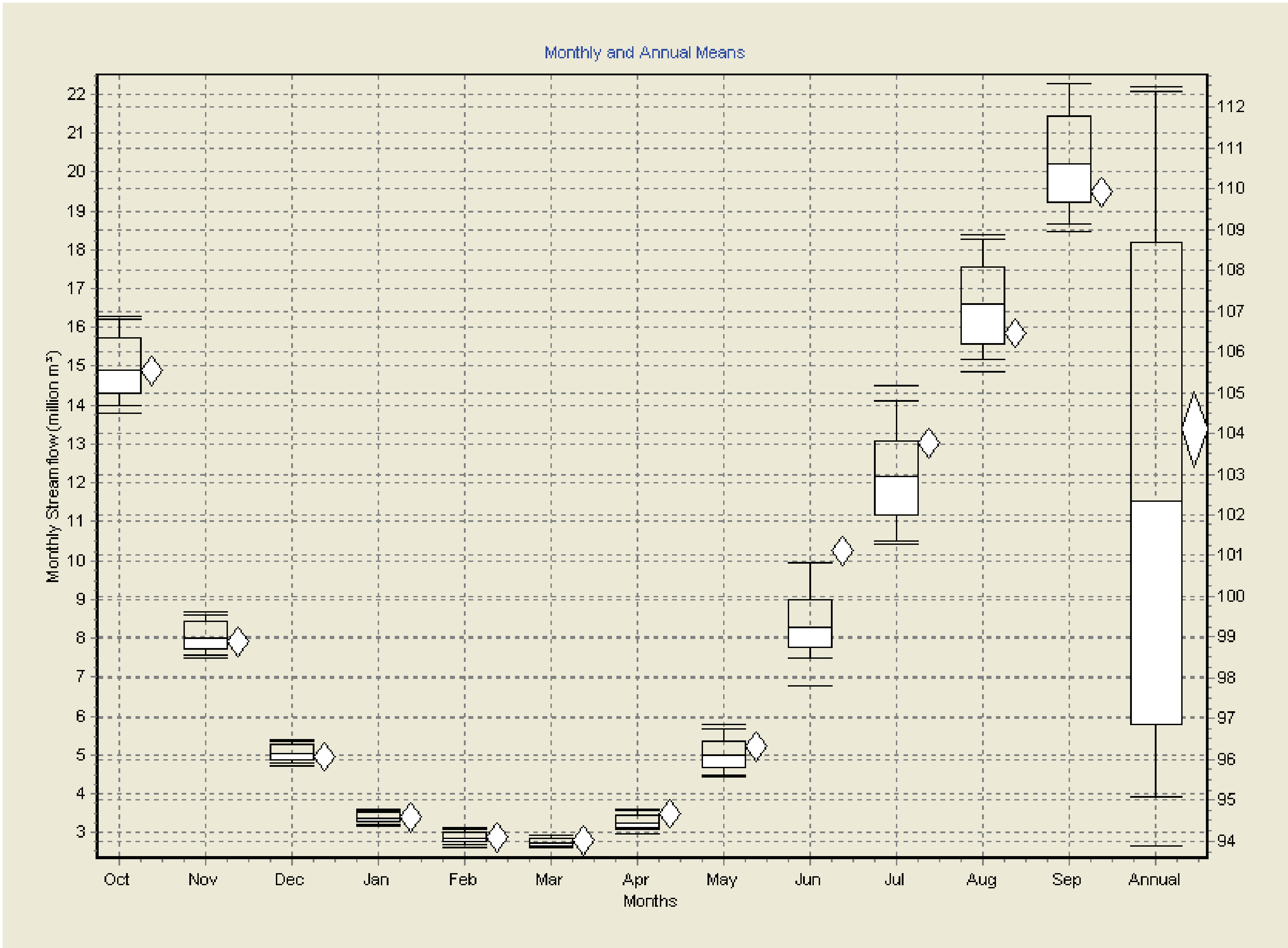

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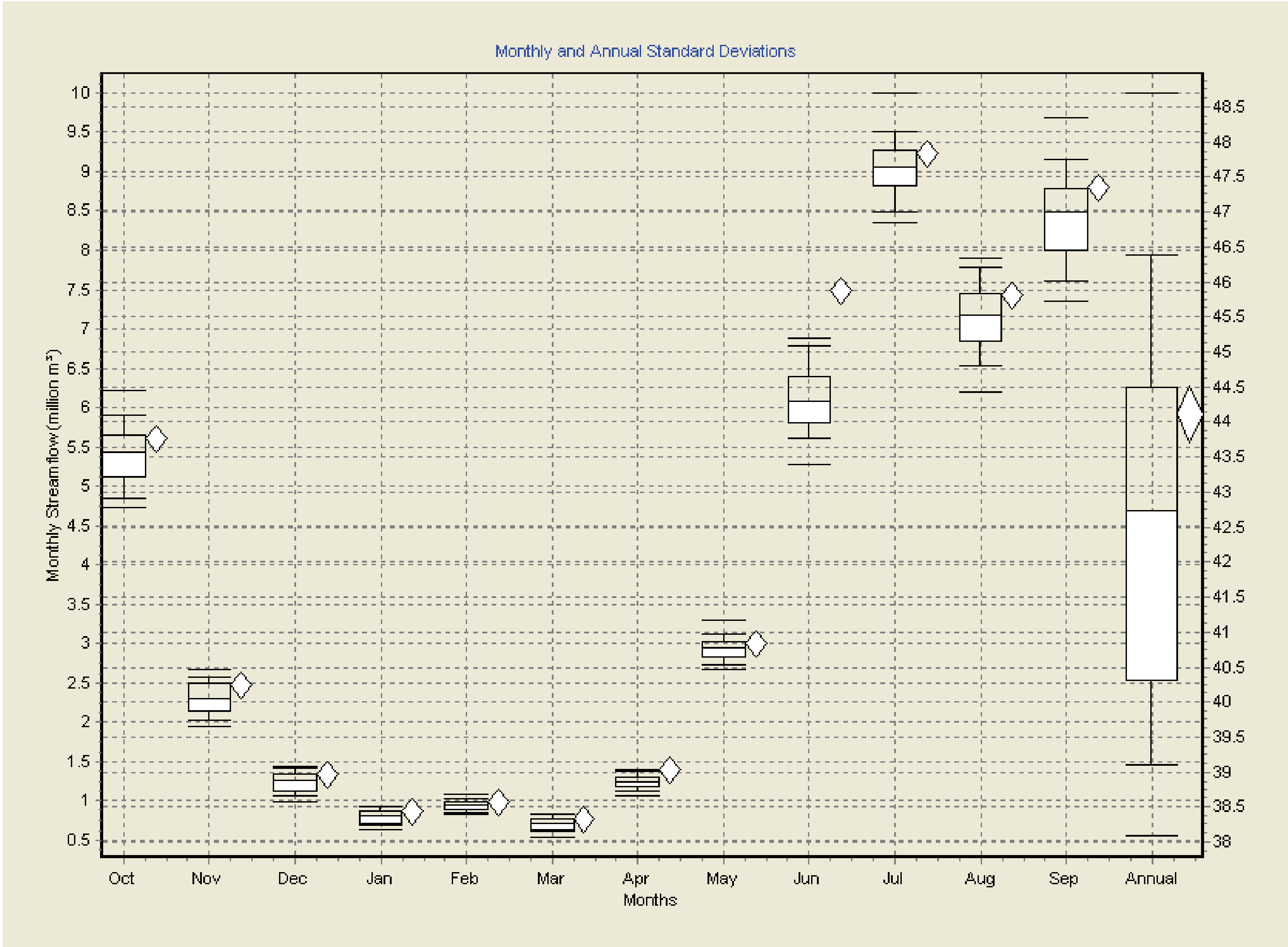

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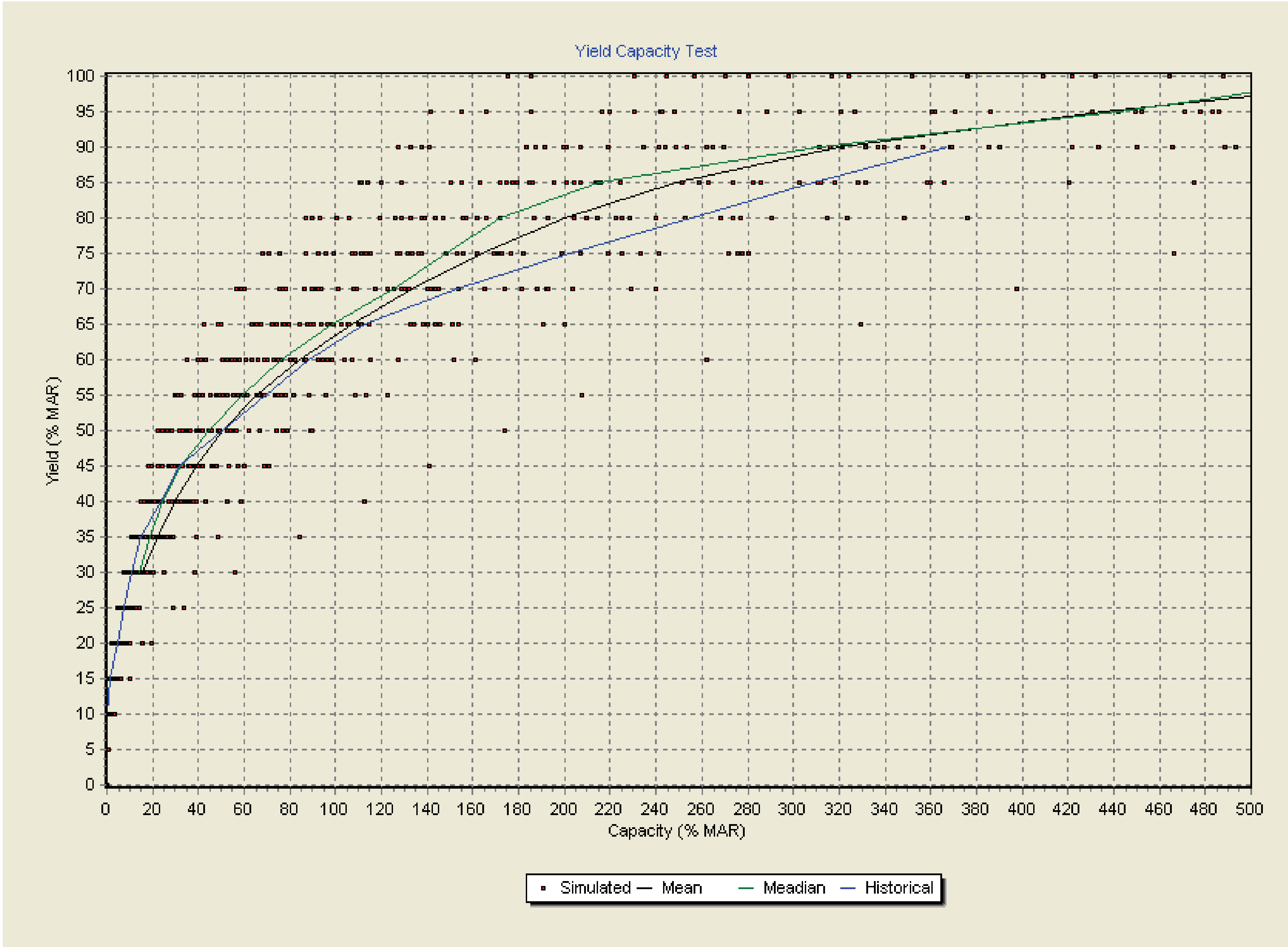

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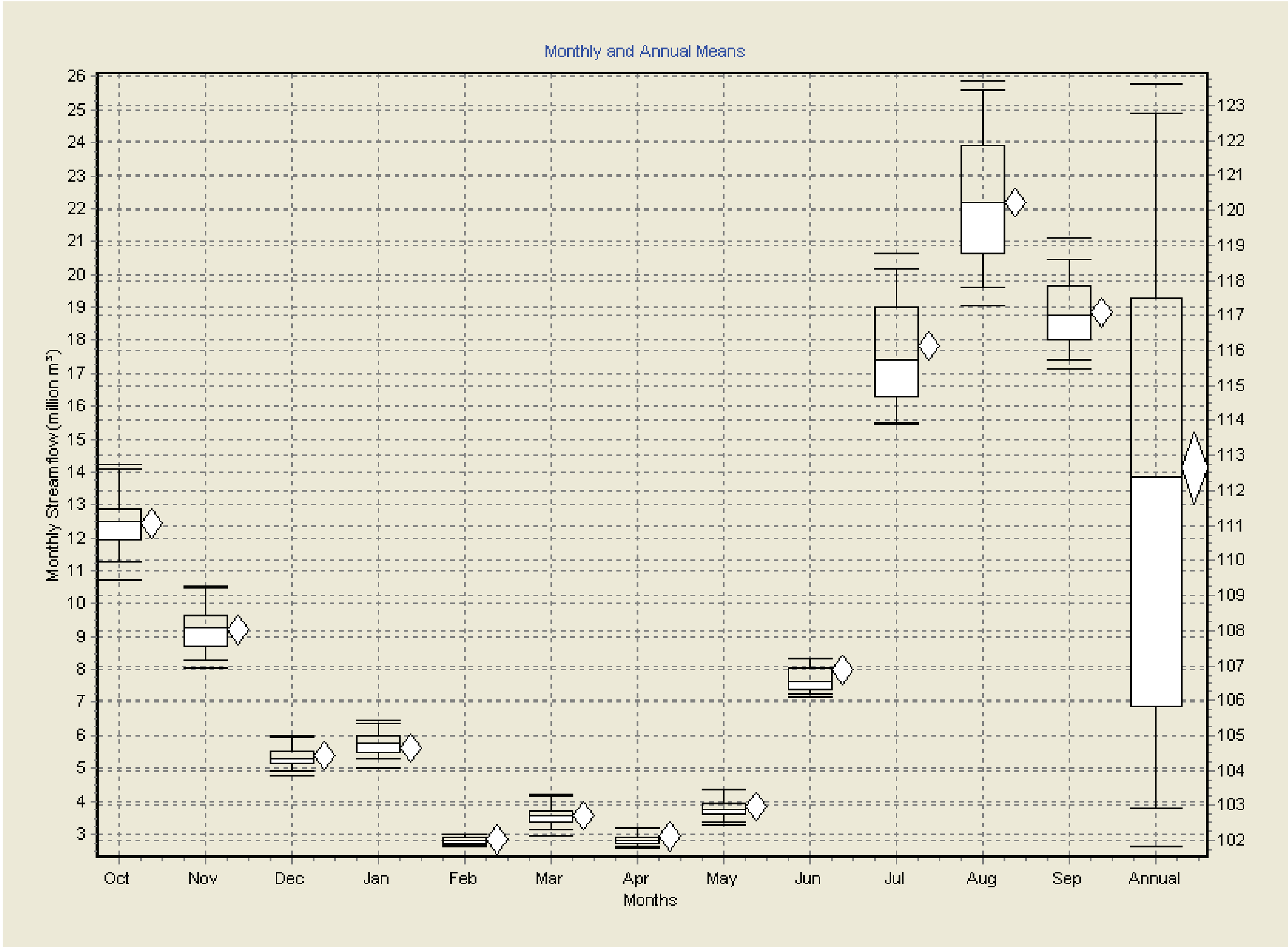

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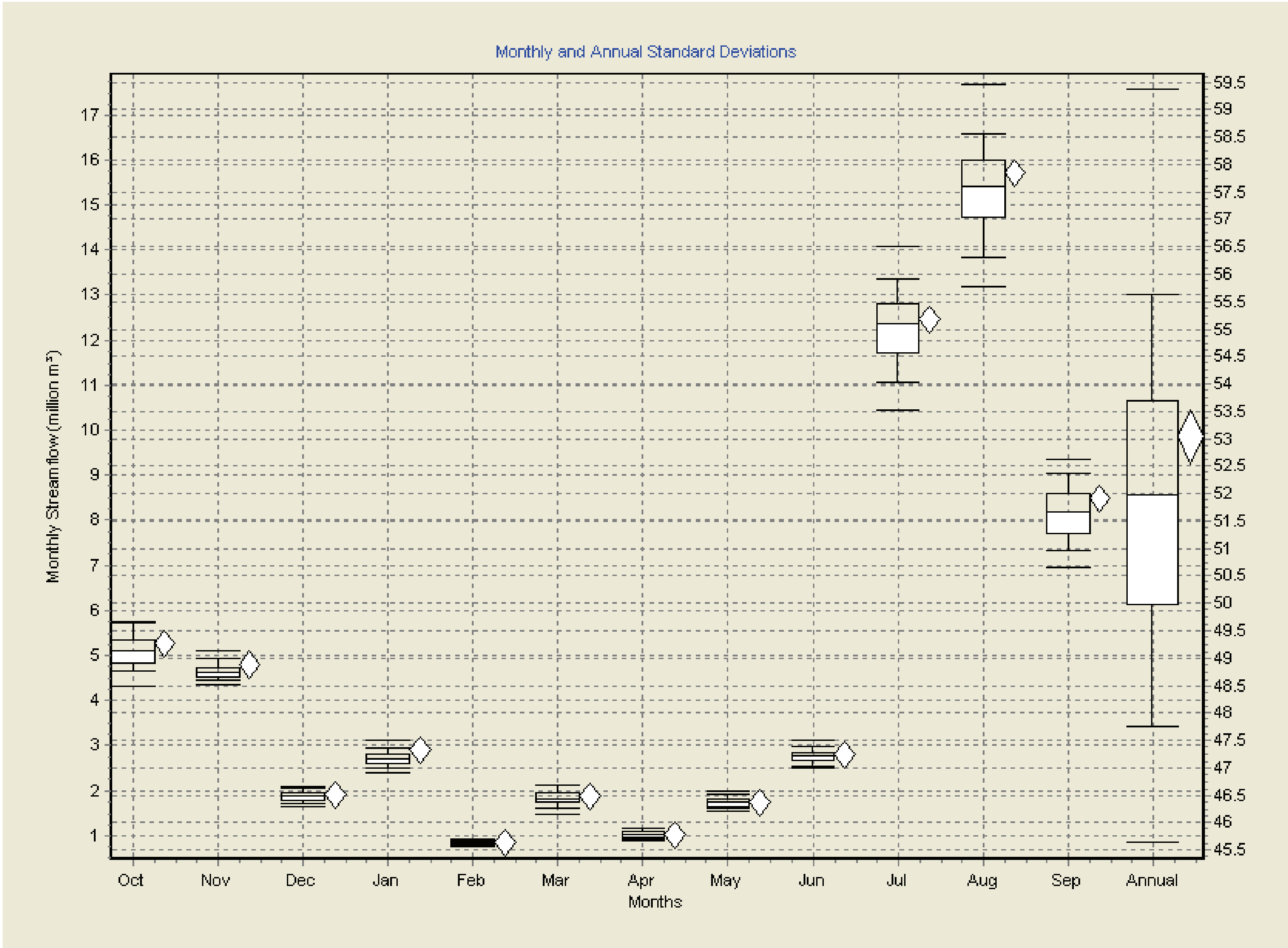
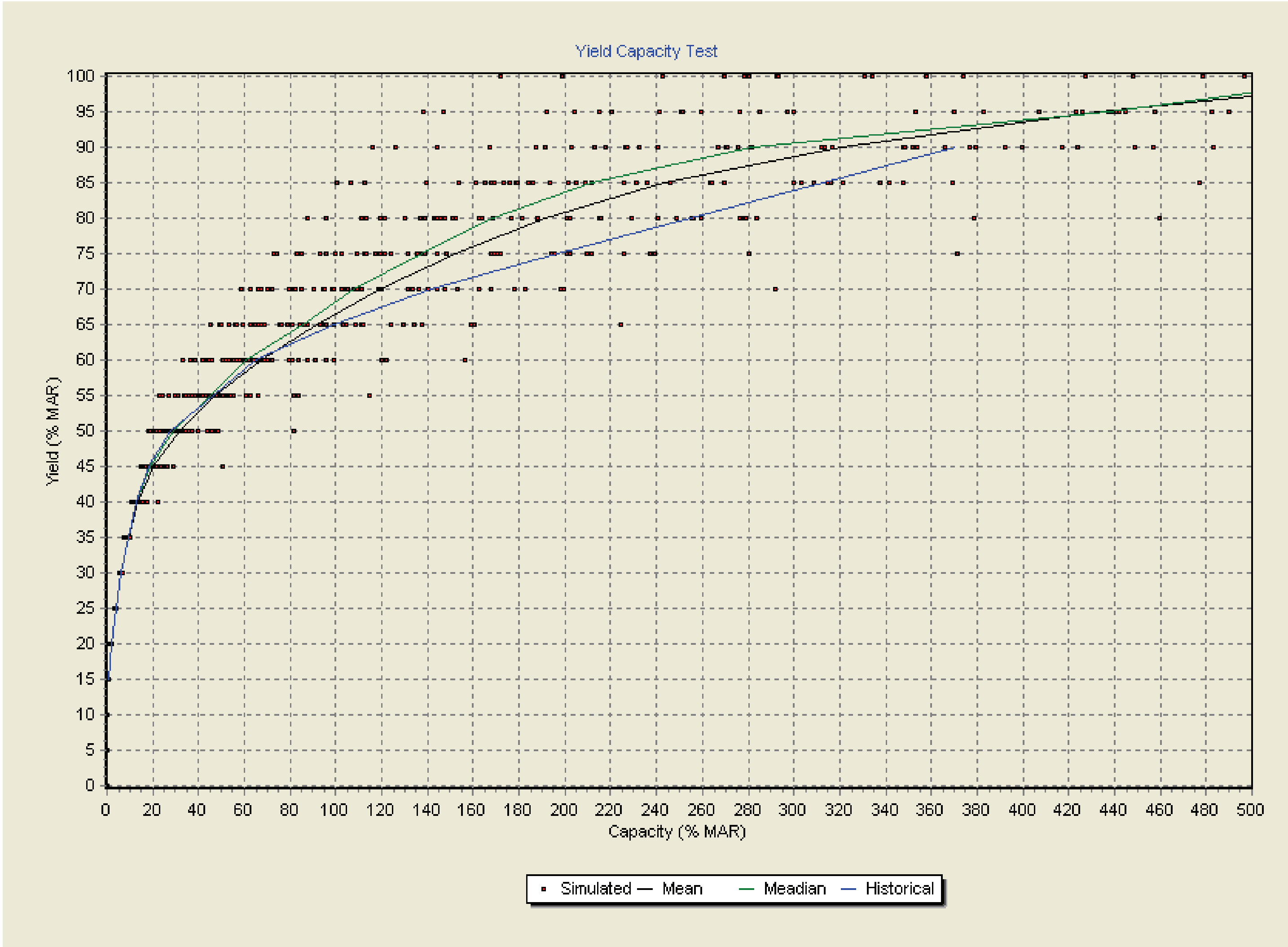


BERG RIVER DAM: IPSL-CM4: Distant Future



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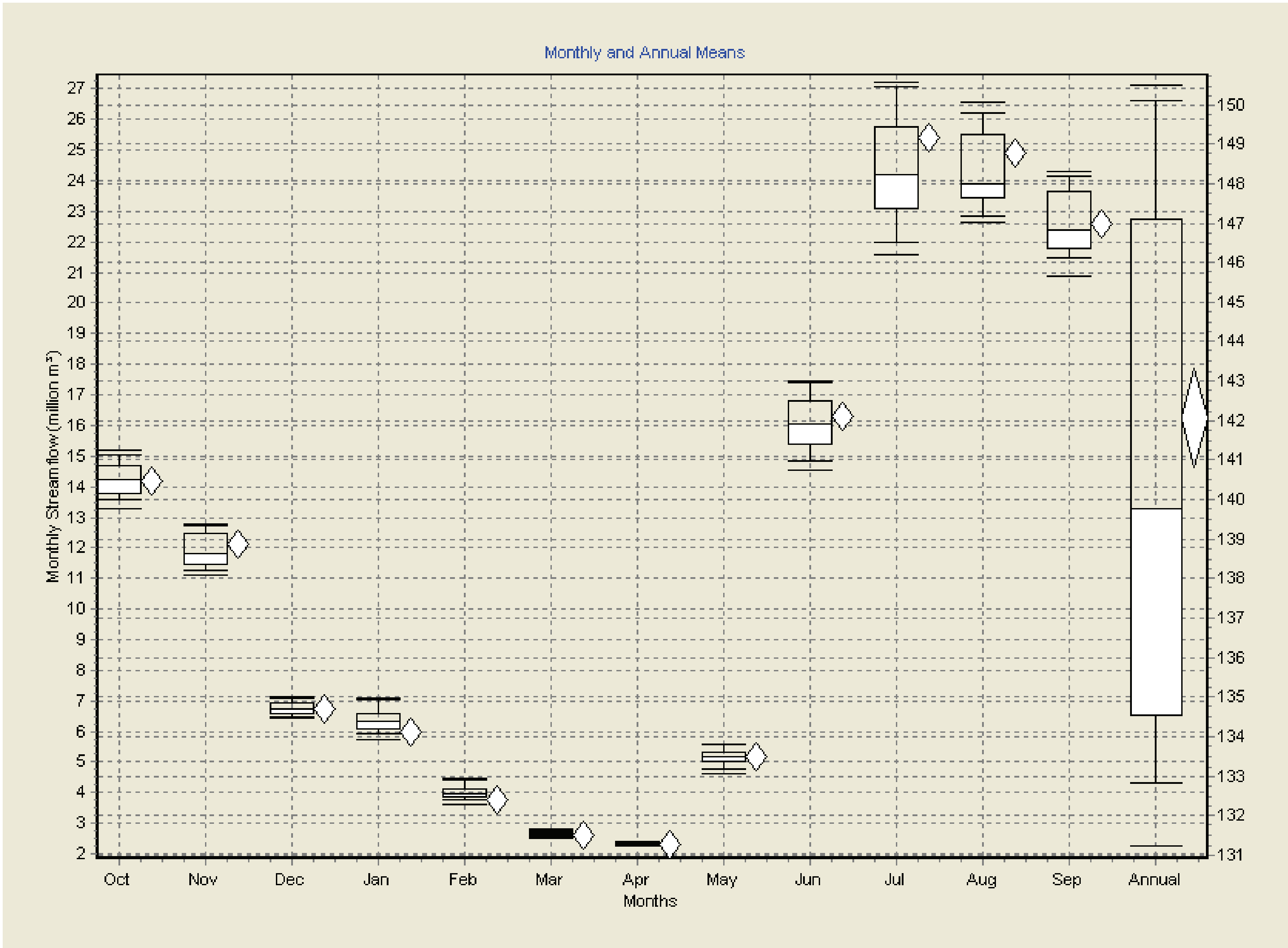

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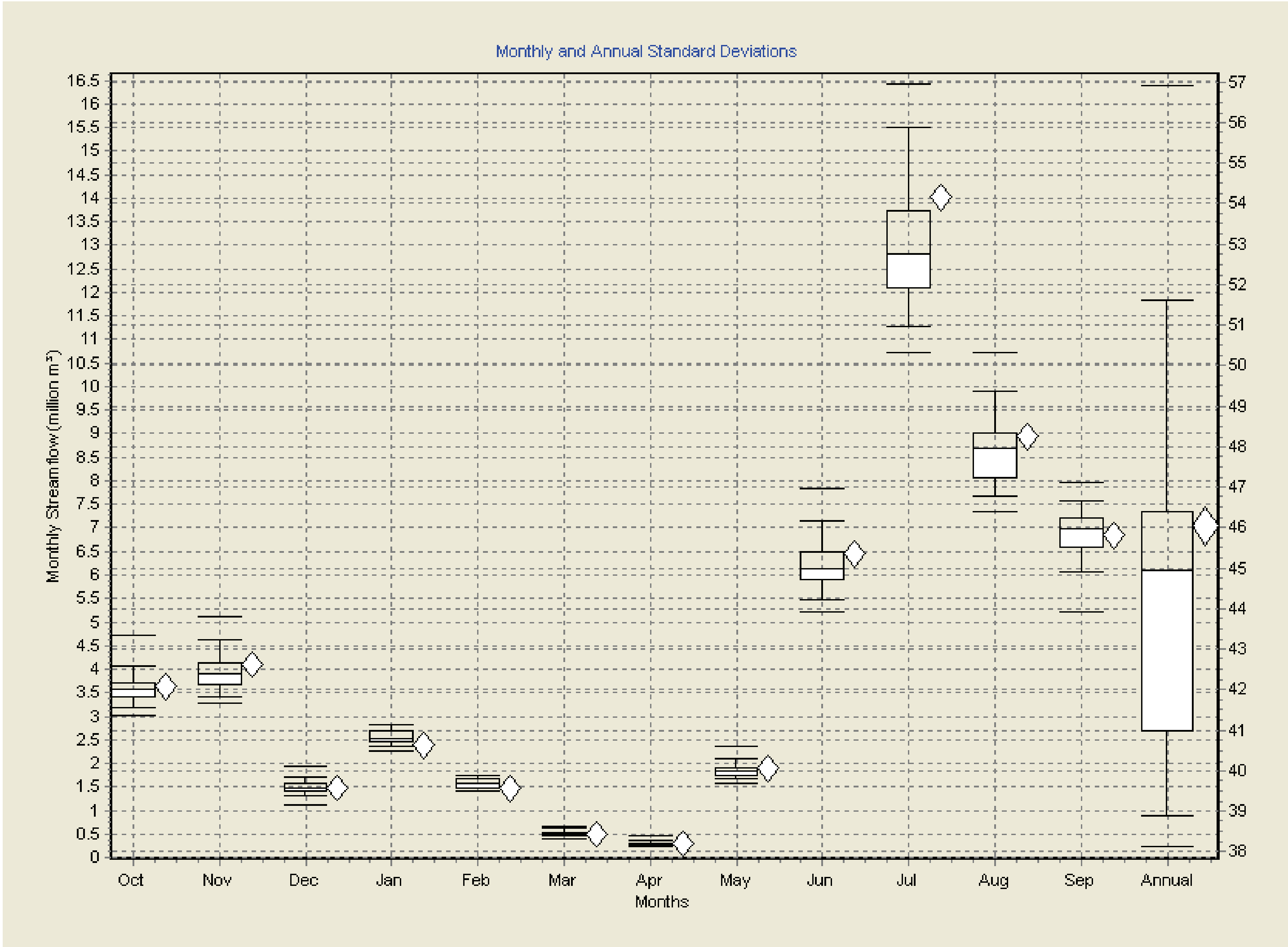

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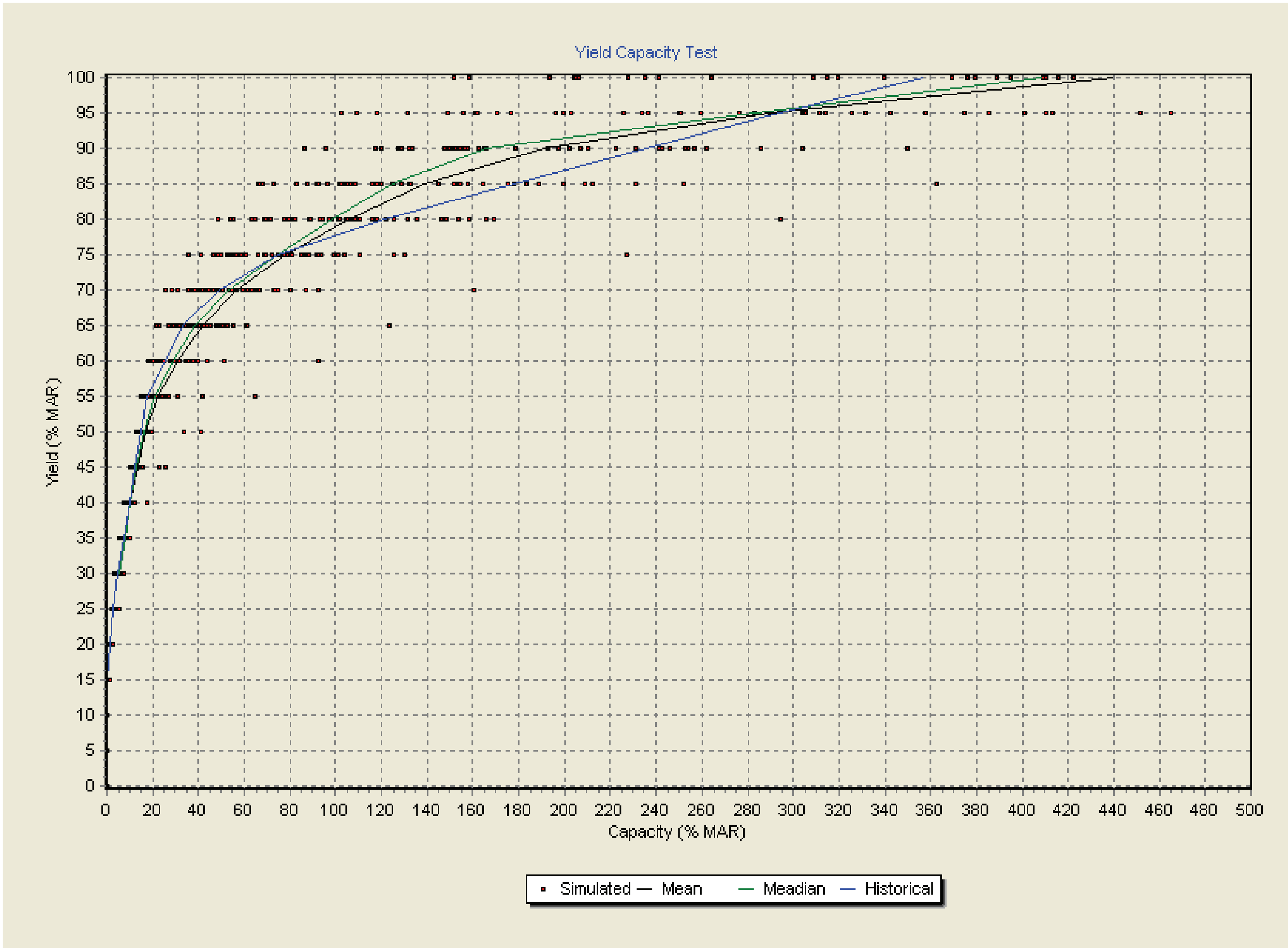

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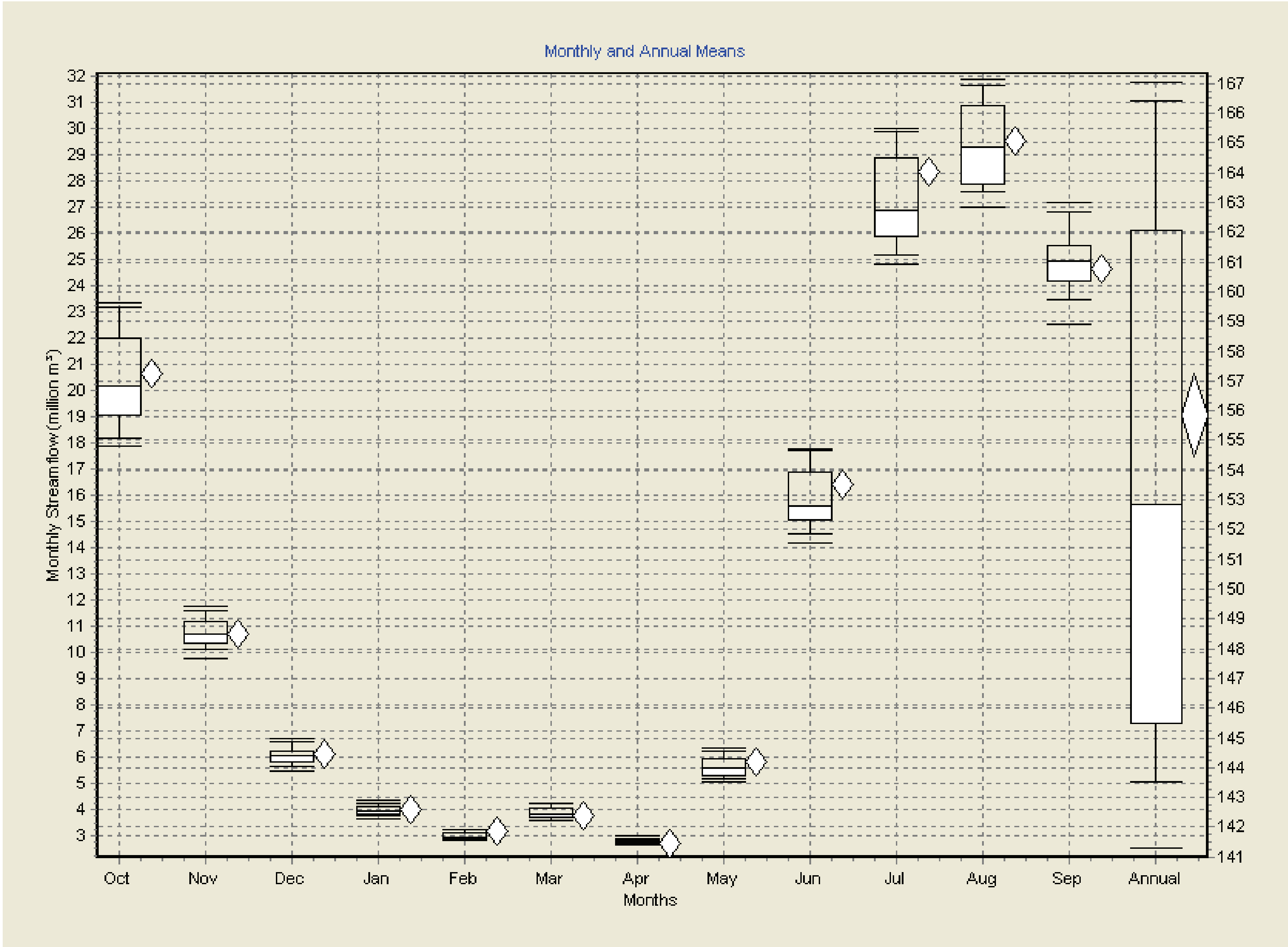

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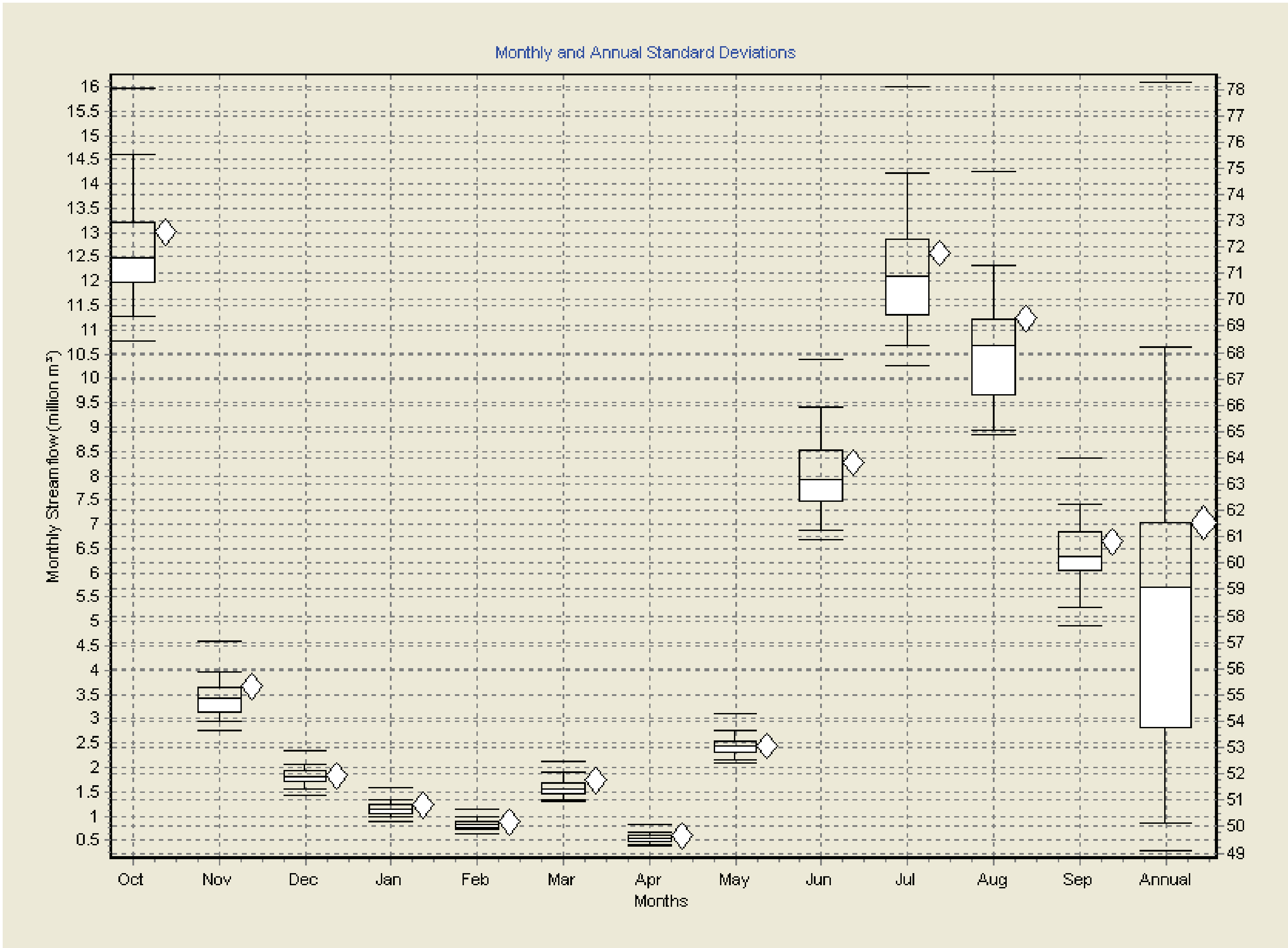

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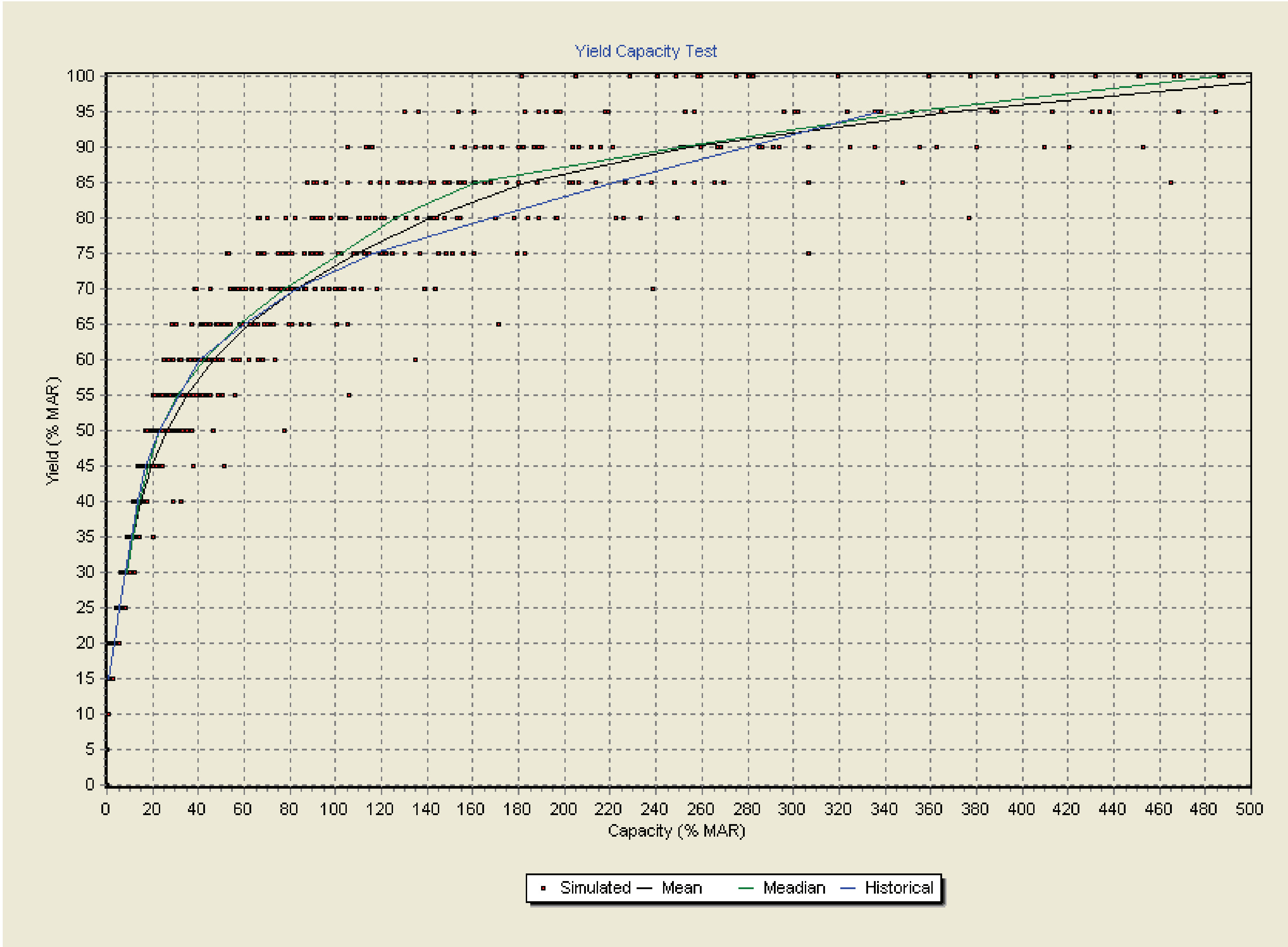

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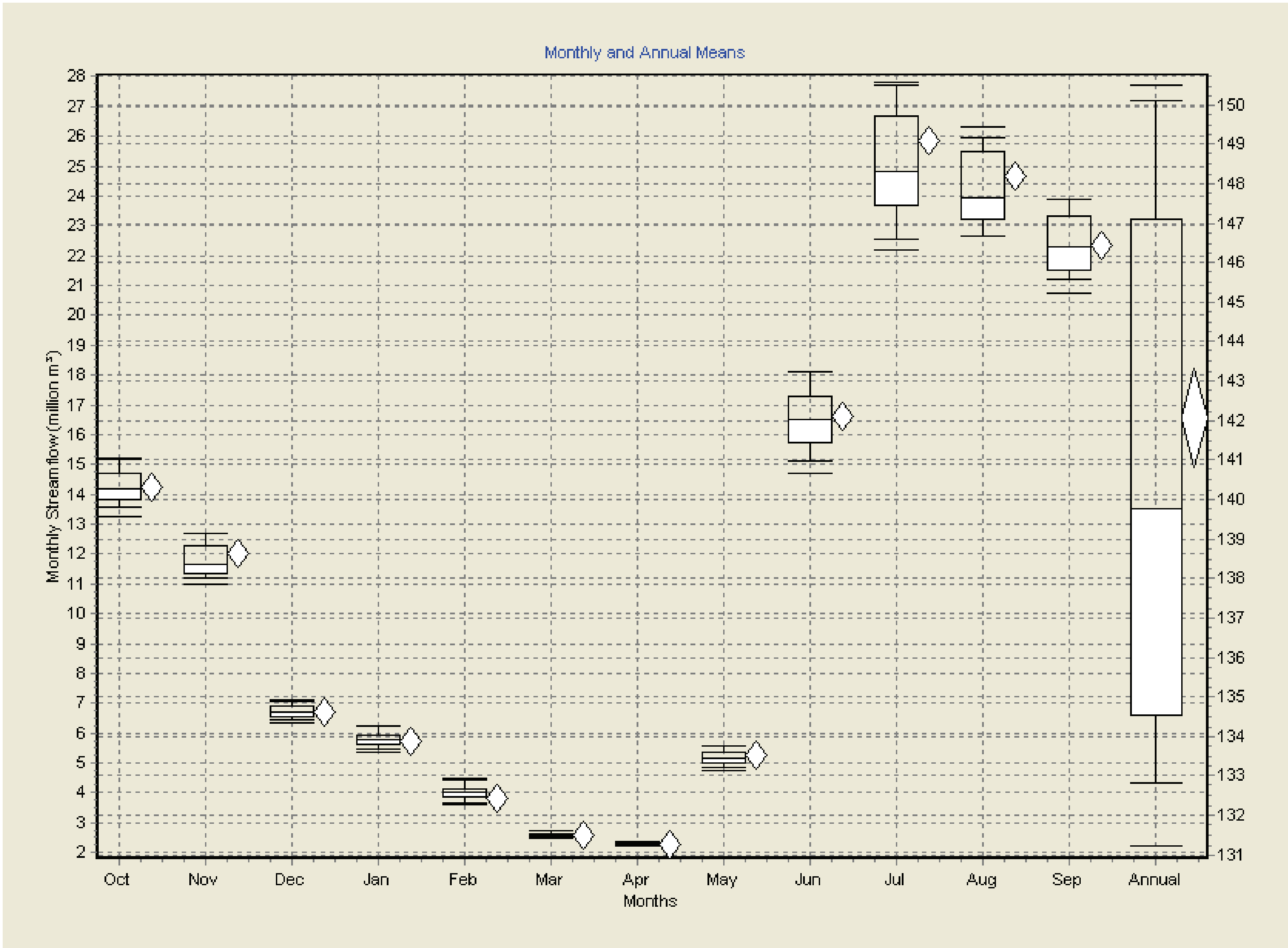

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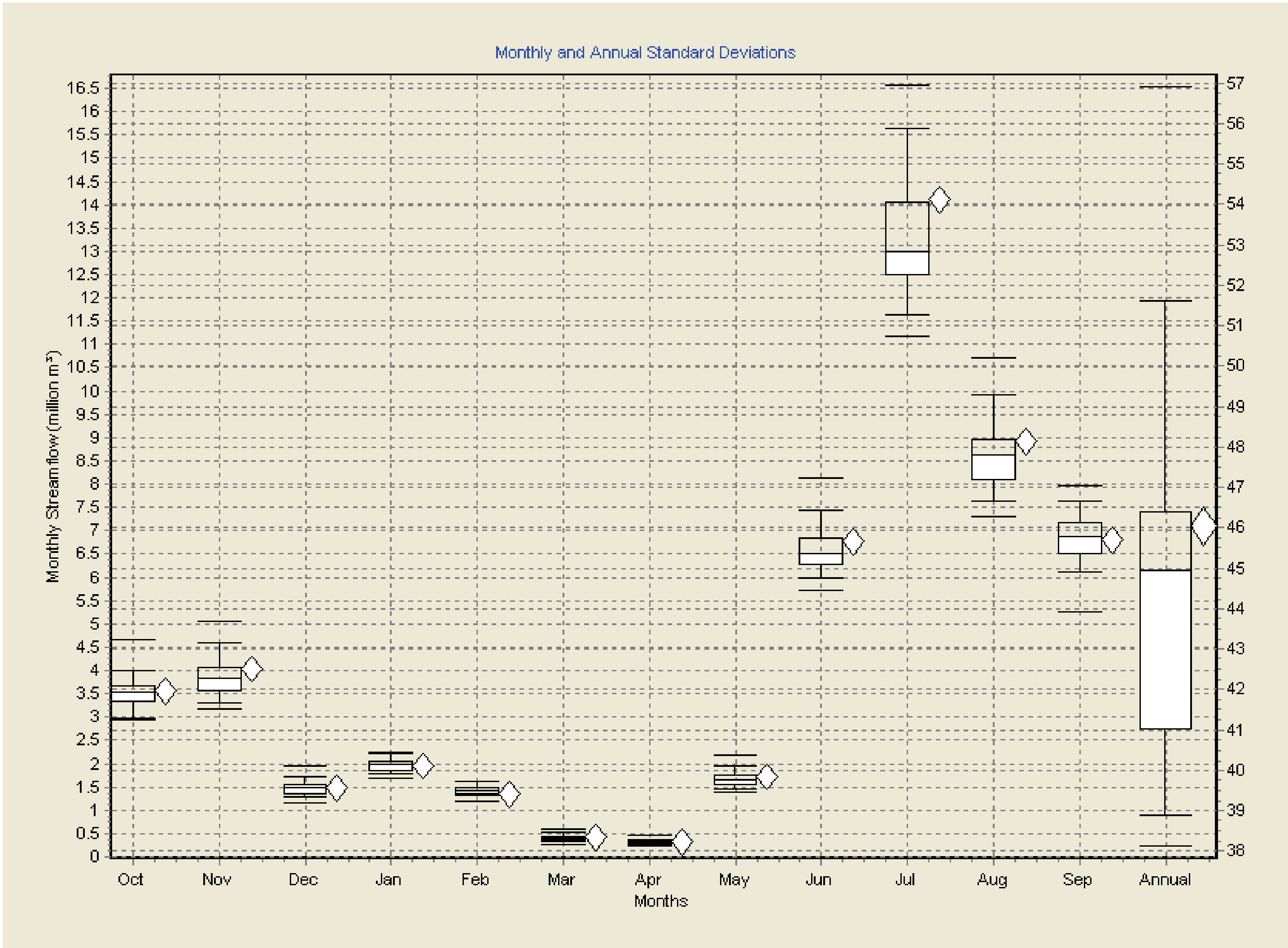

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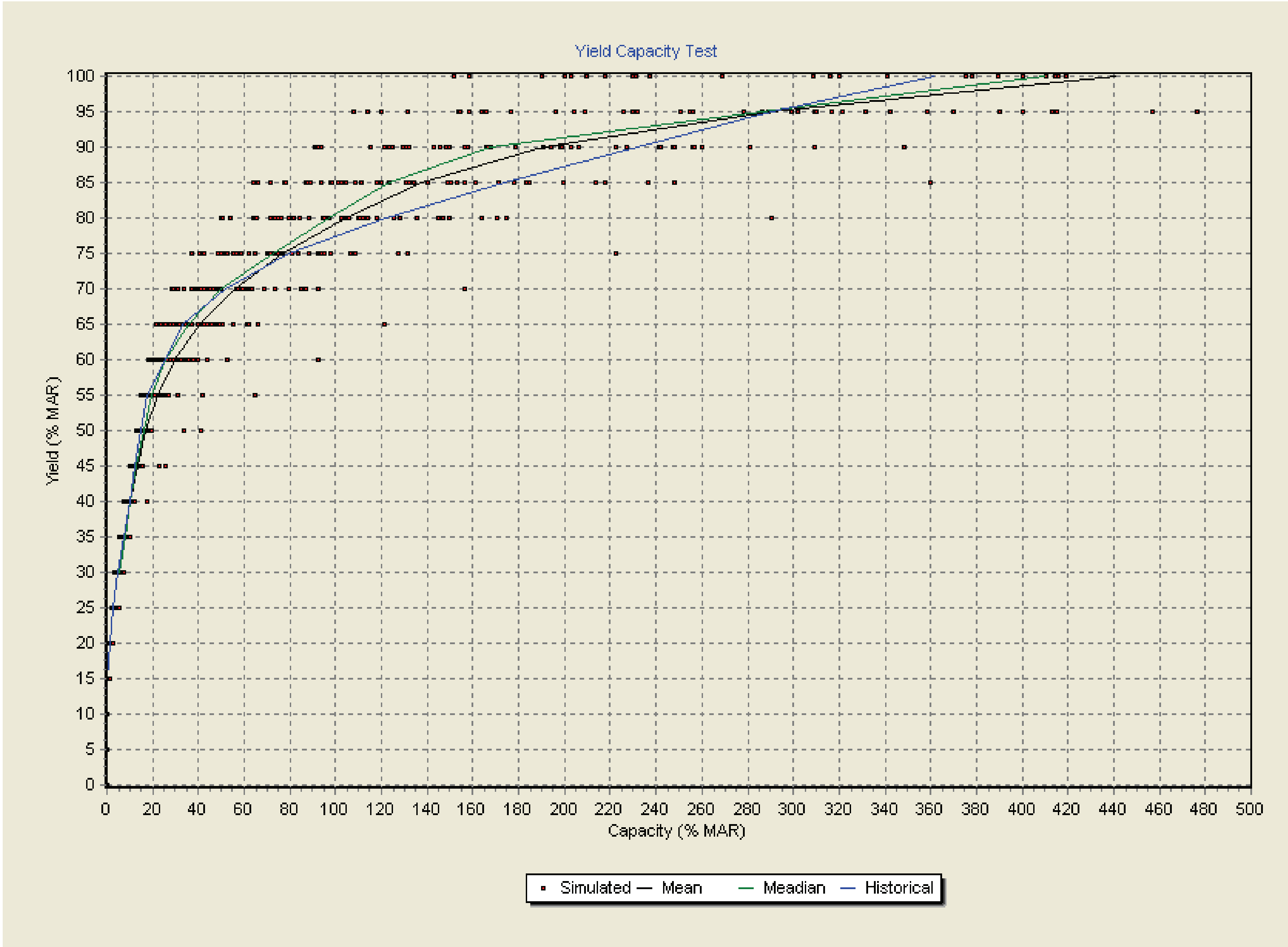

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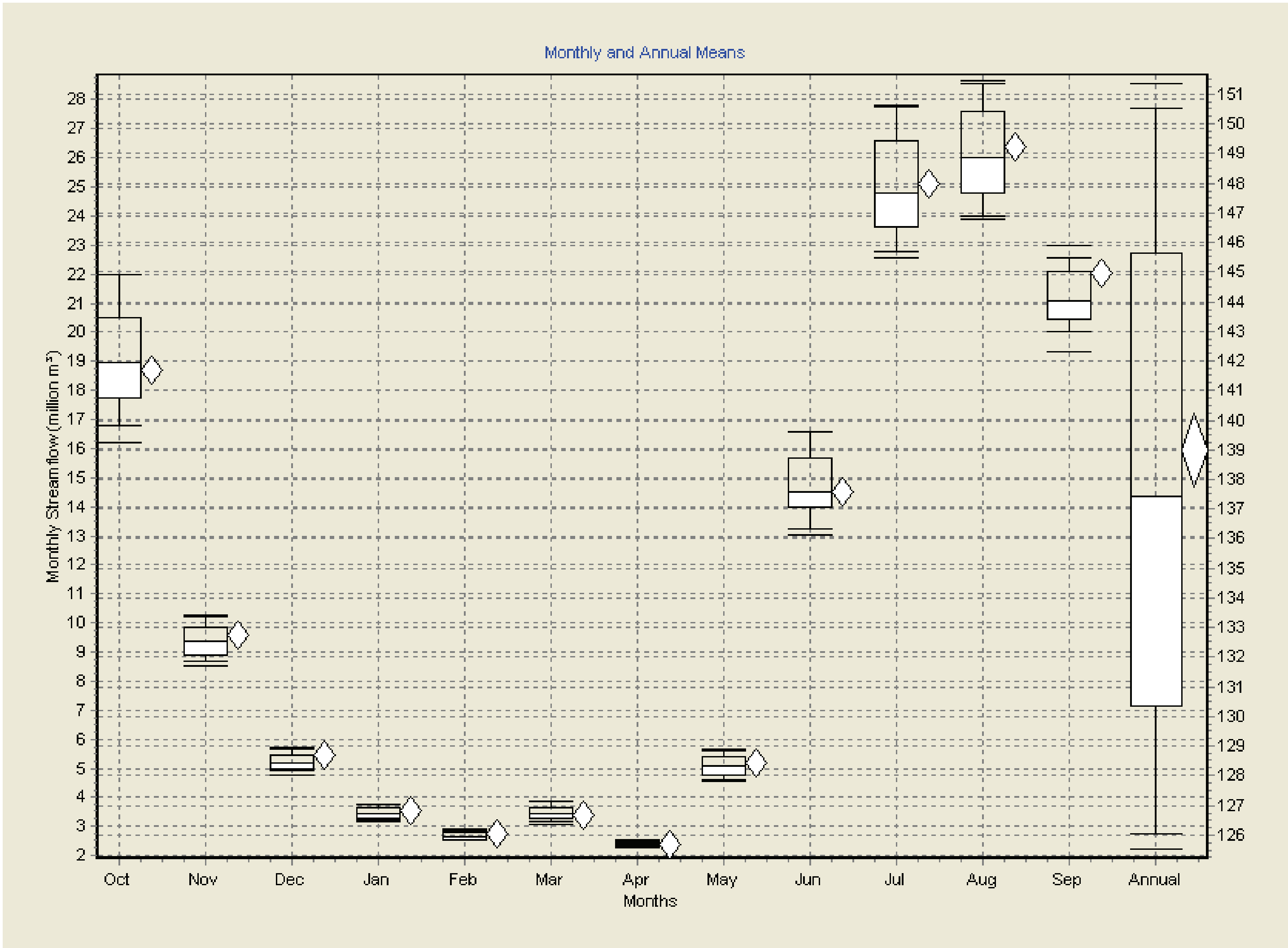

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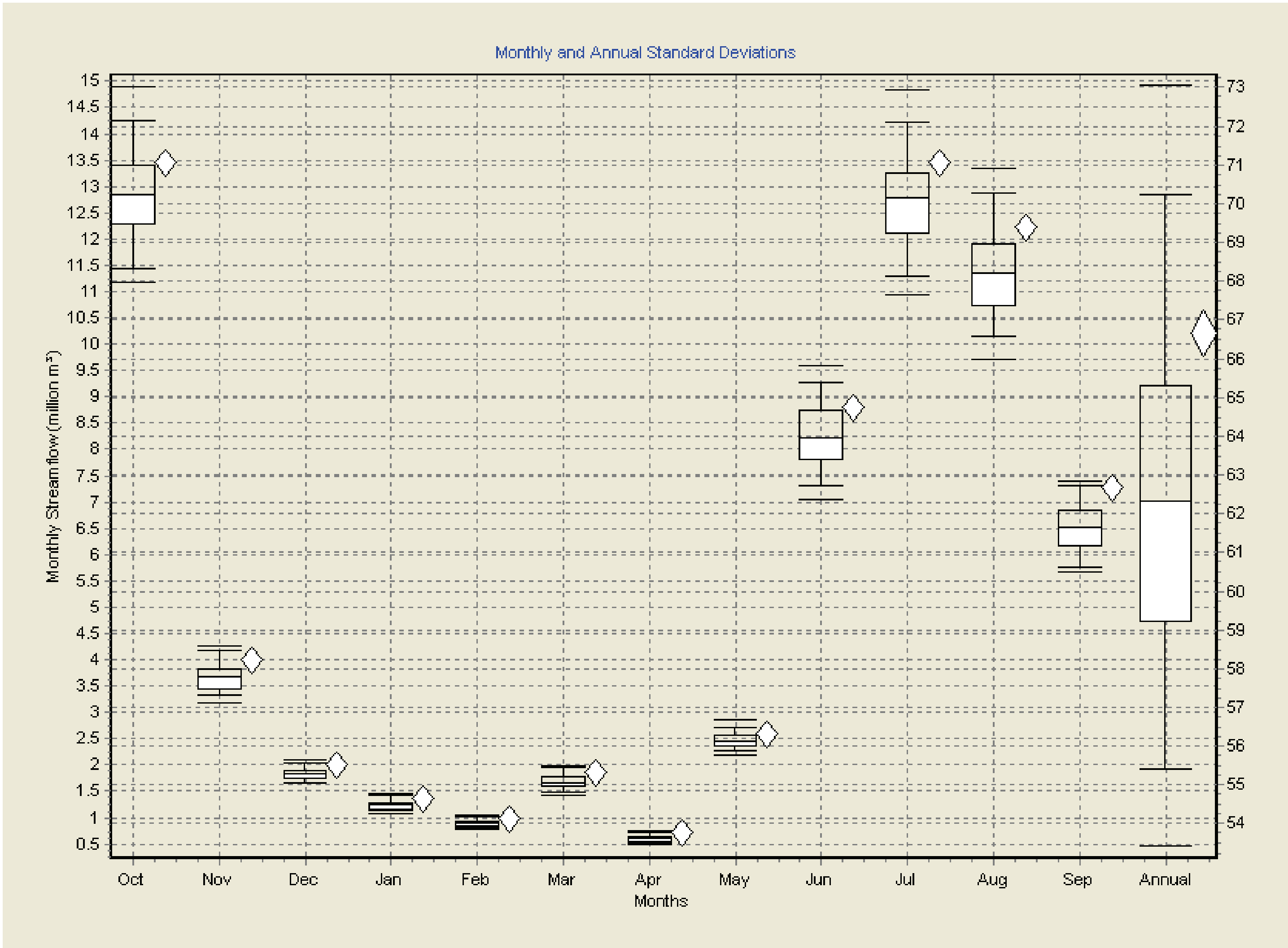

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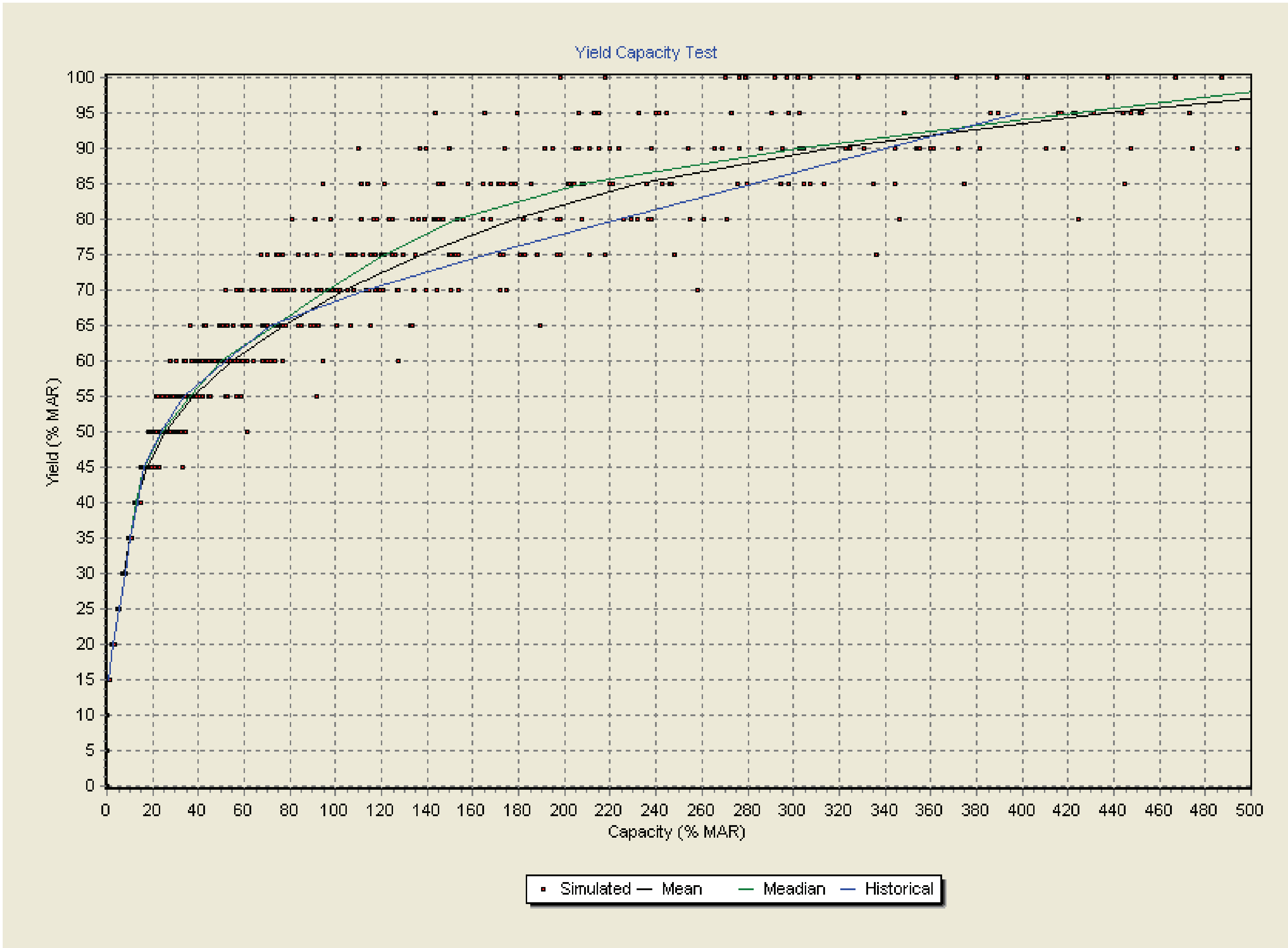

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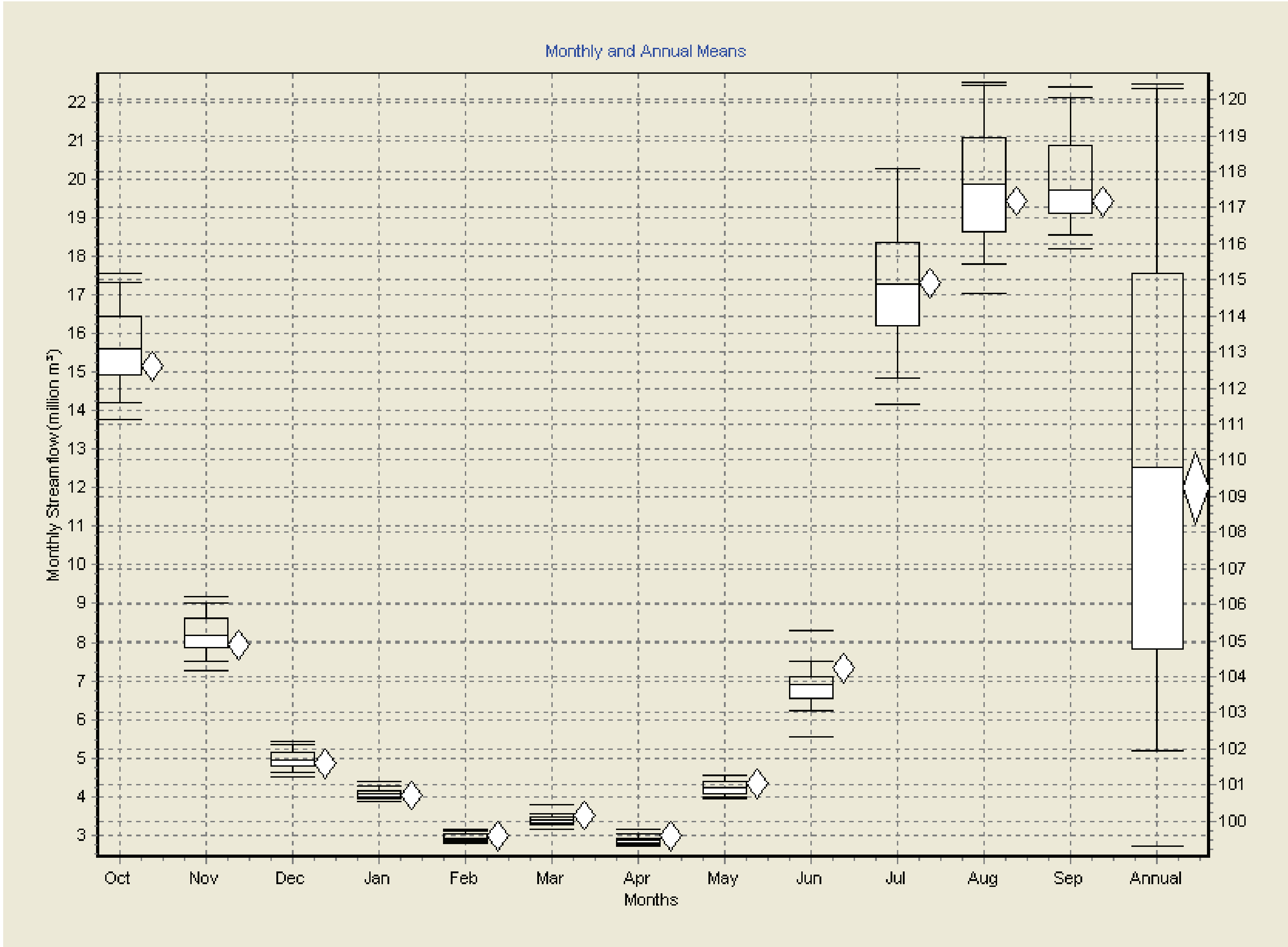

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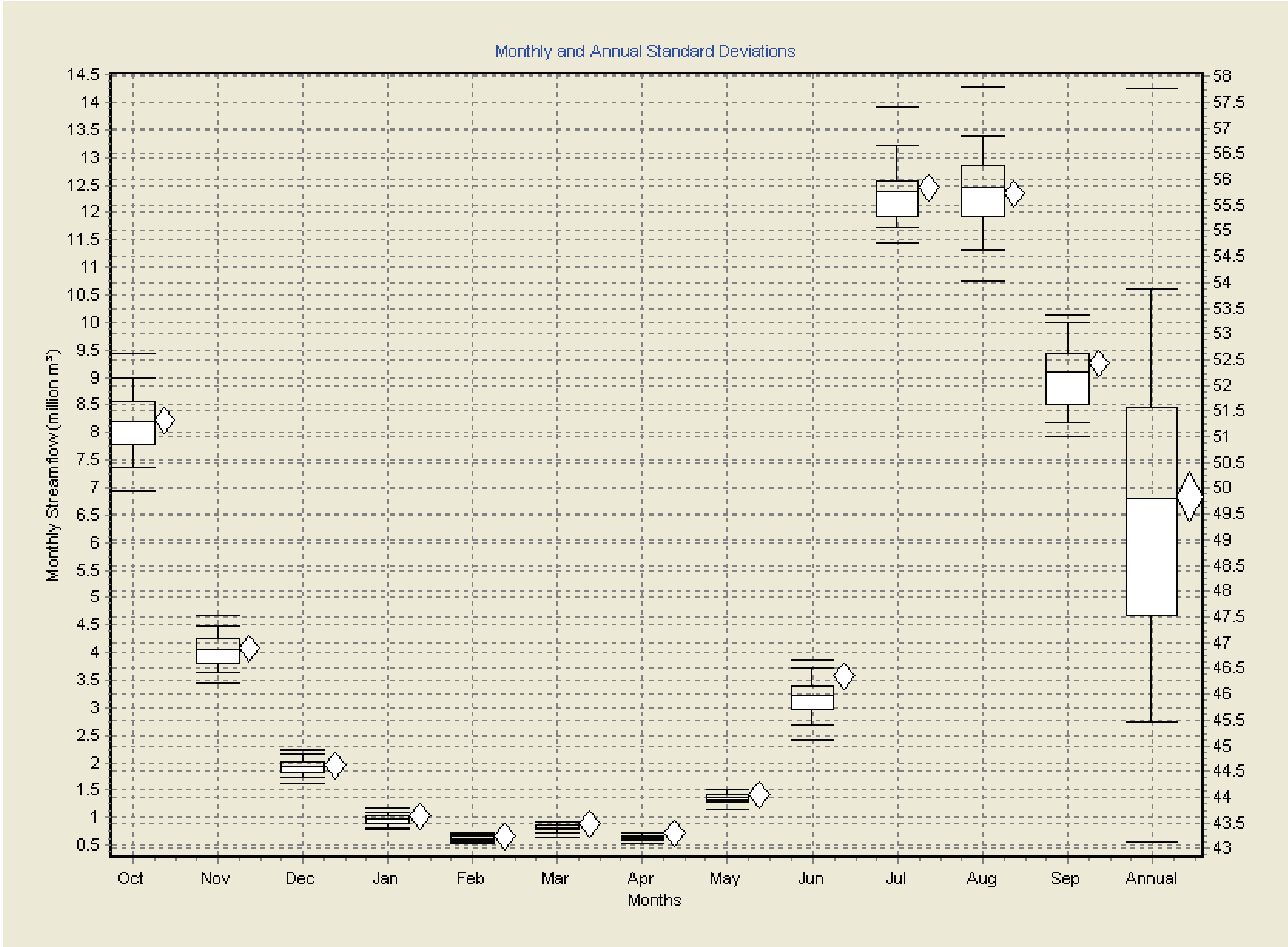

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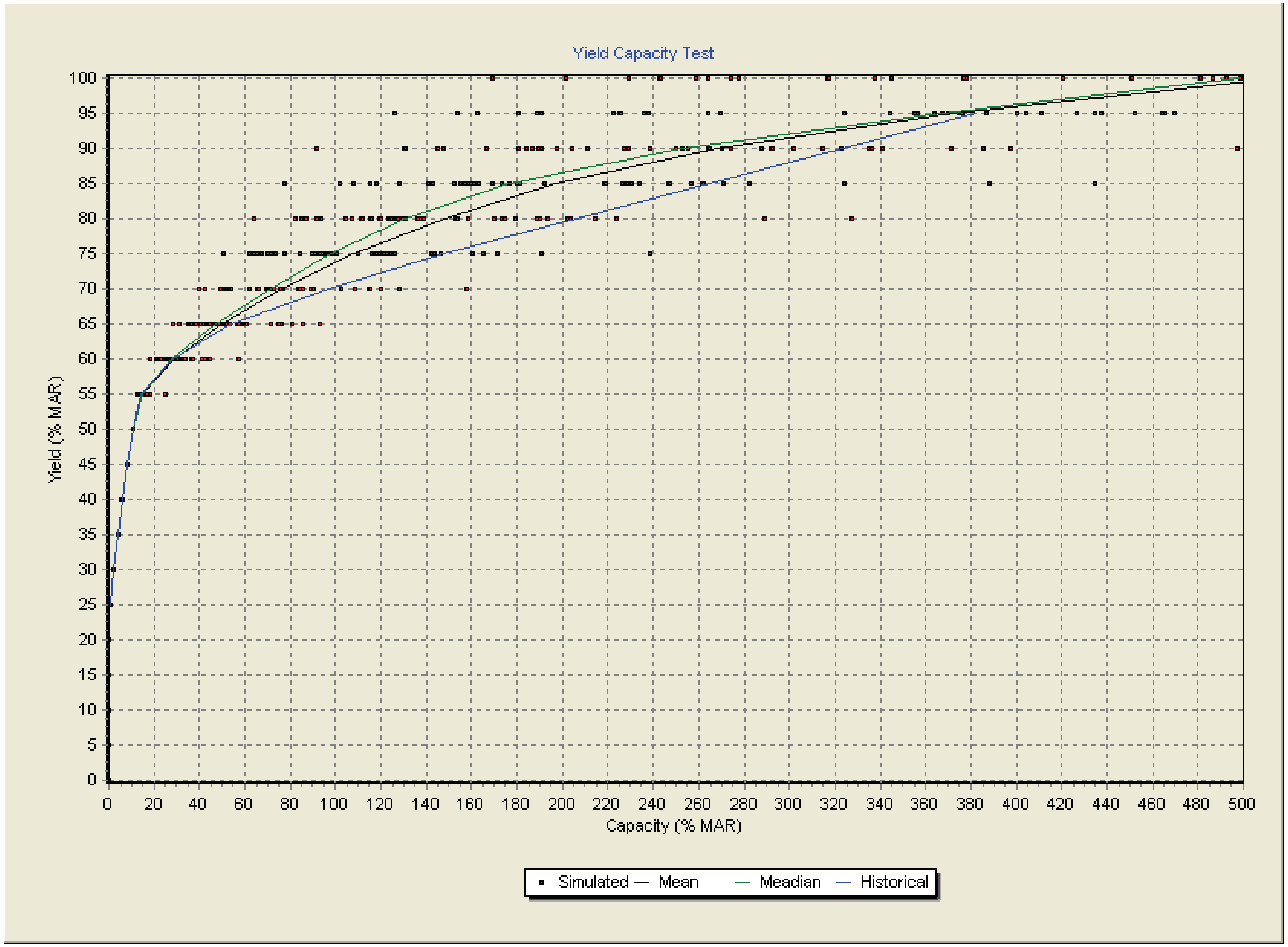
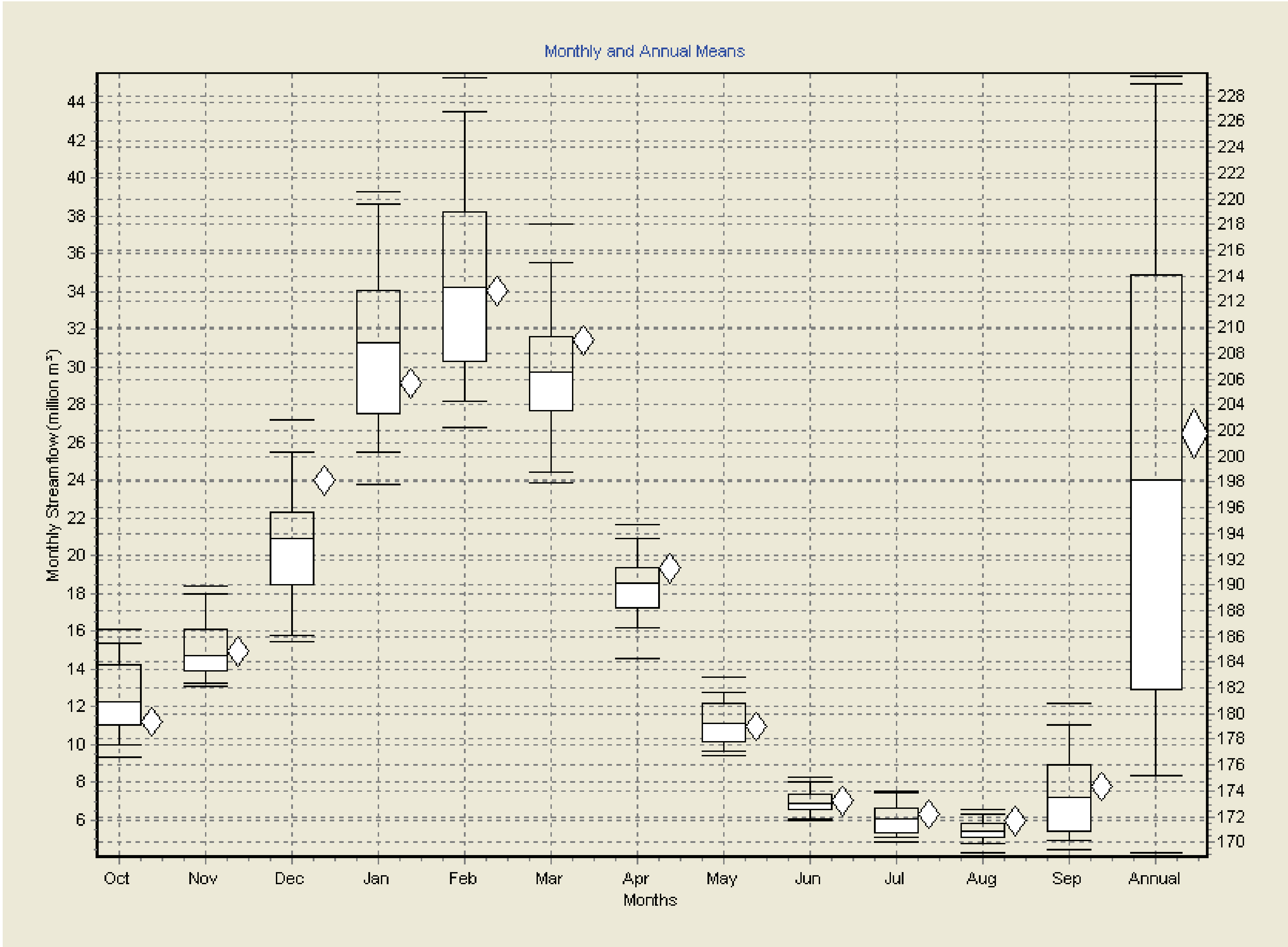
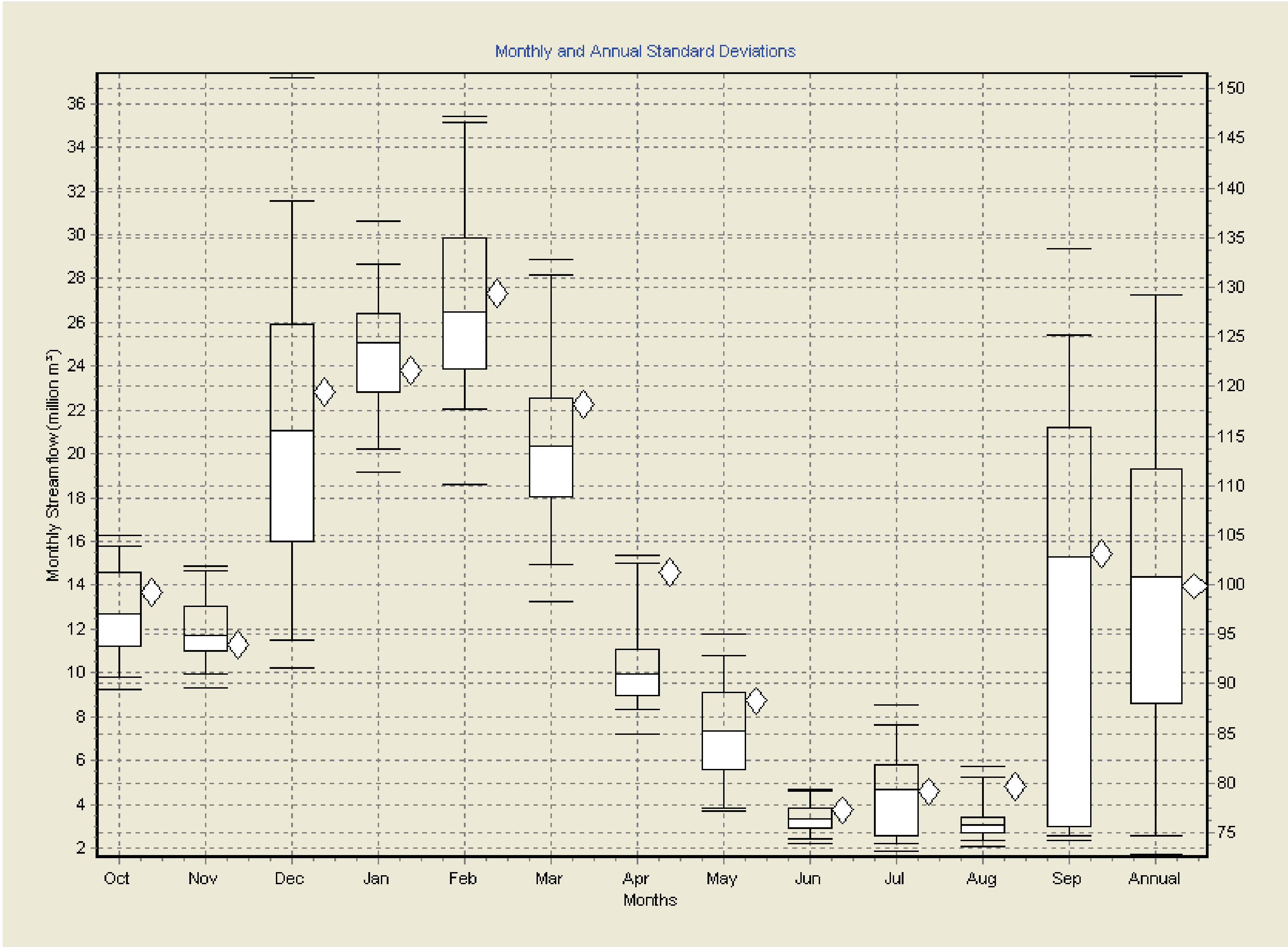


Appendix B.2: MIDMAR DAM

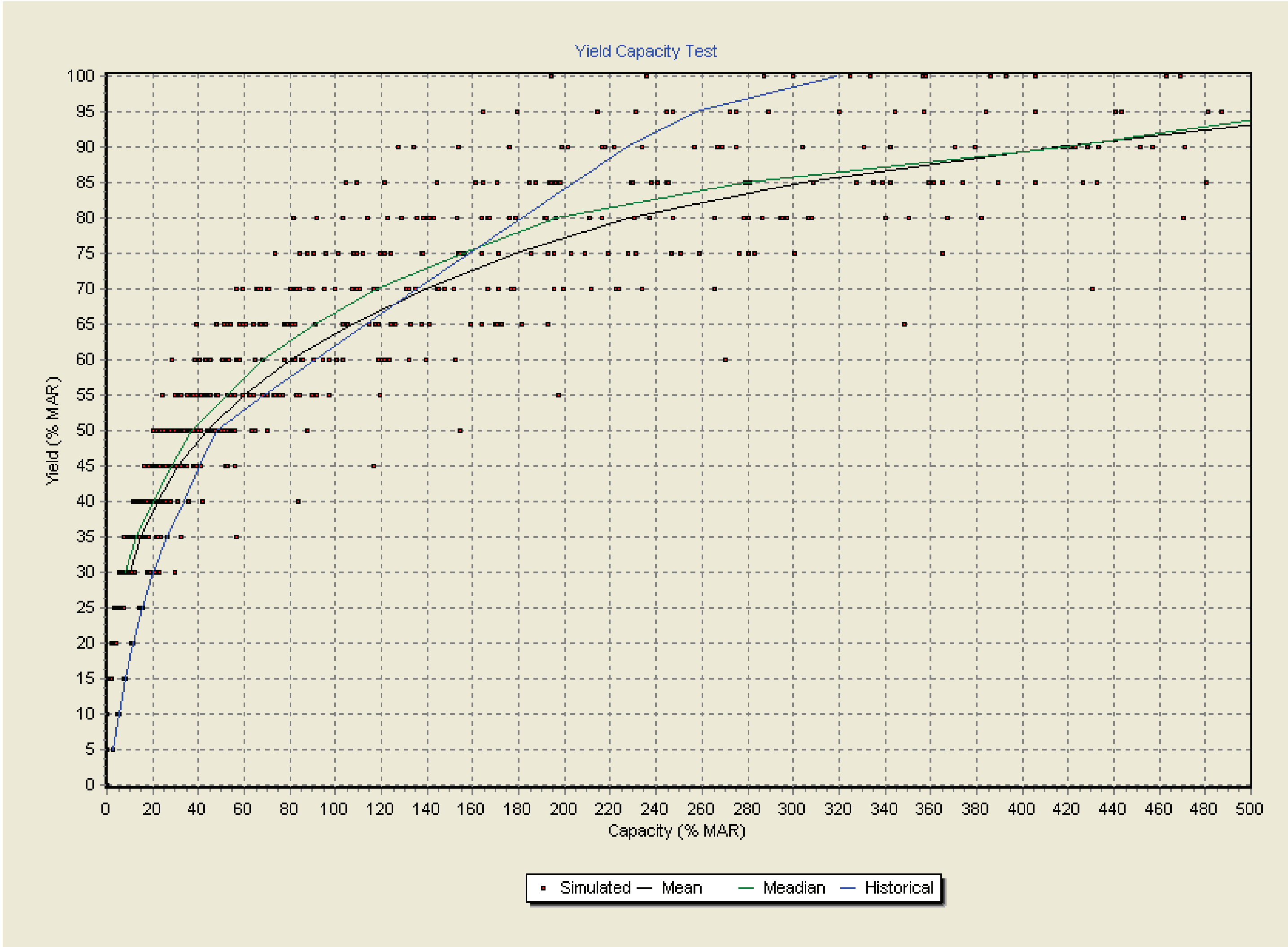
MIDMAR DAM: Detailed Study long-term runoff sequence



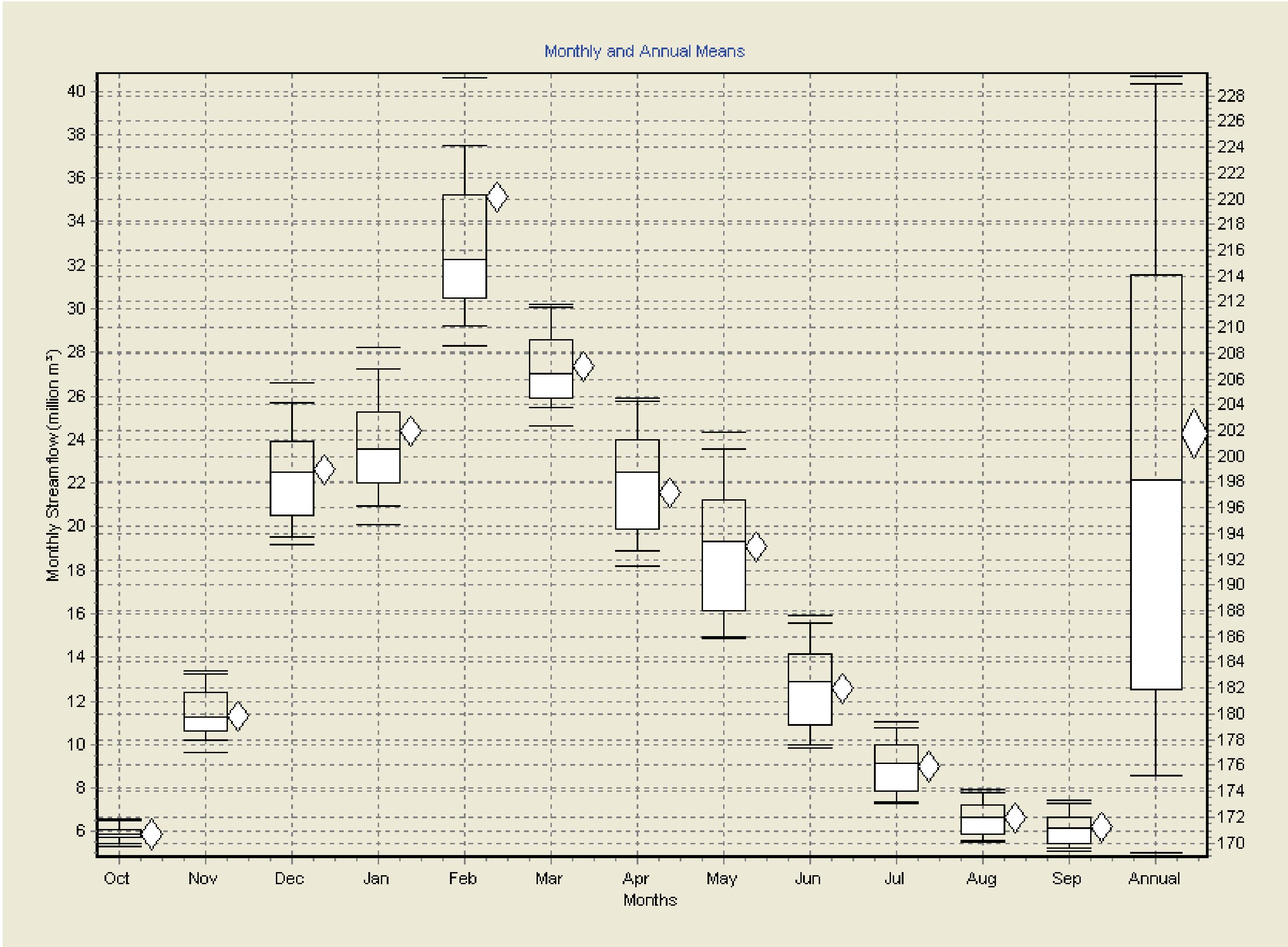
MIDMAR DAM: Detailed Study long-term runoff sequence



MIDMAR DAM: Detailed Study long-term runoff sequence



MIDMAR DAM: ECHAM 5: PRESENT



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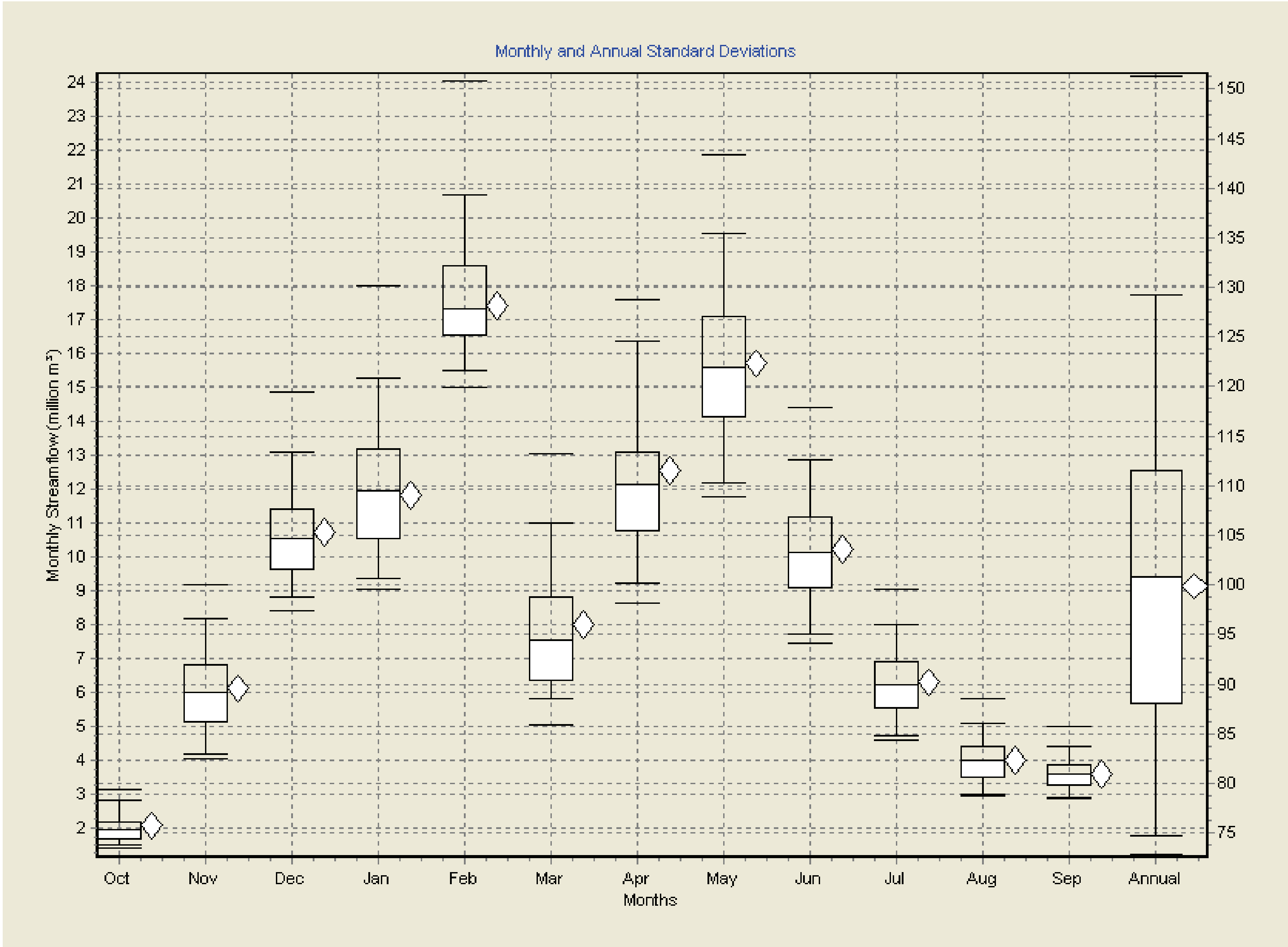

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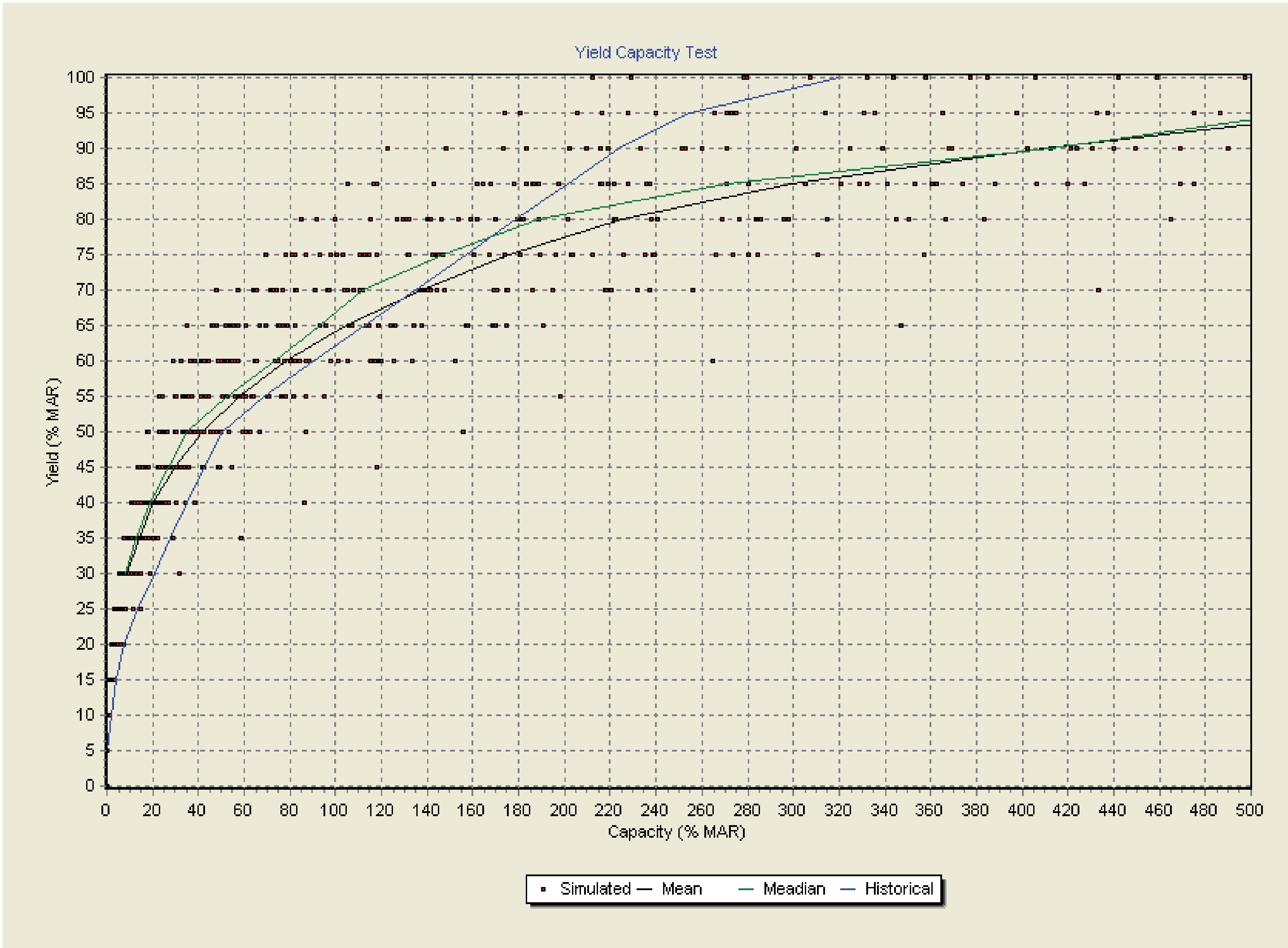

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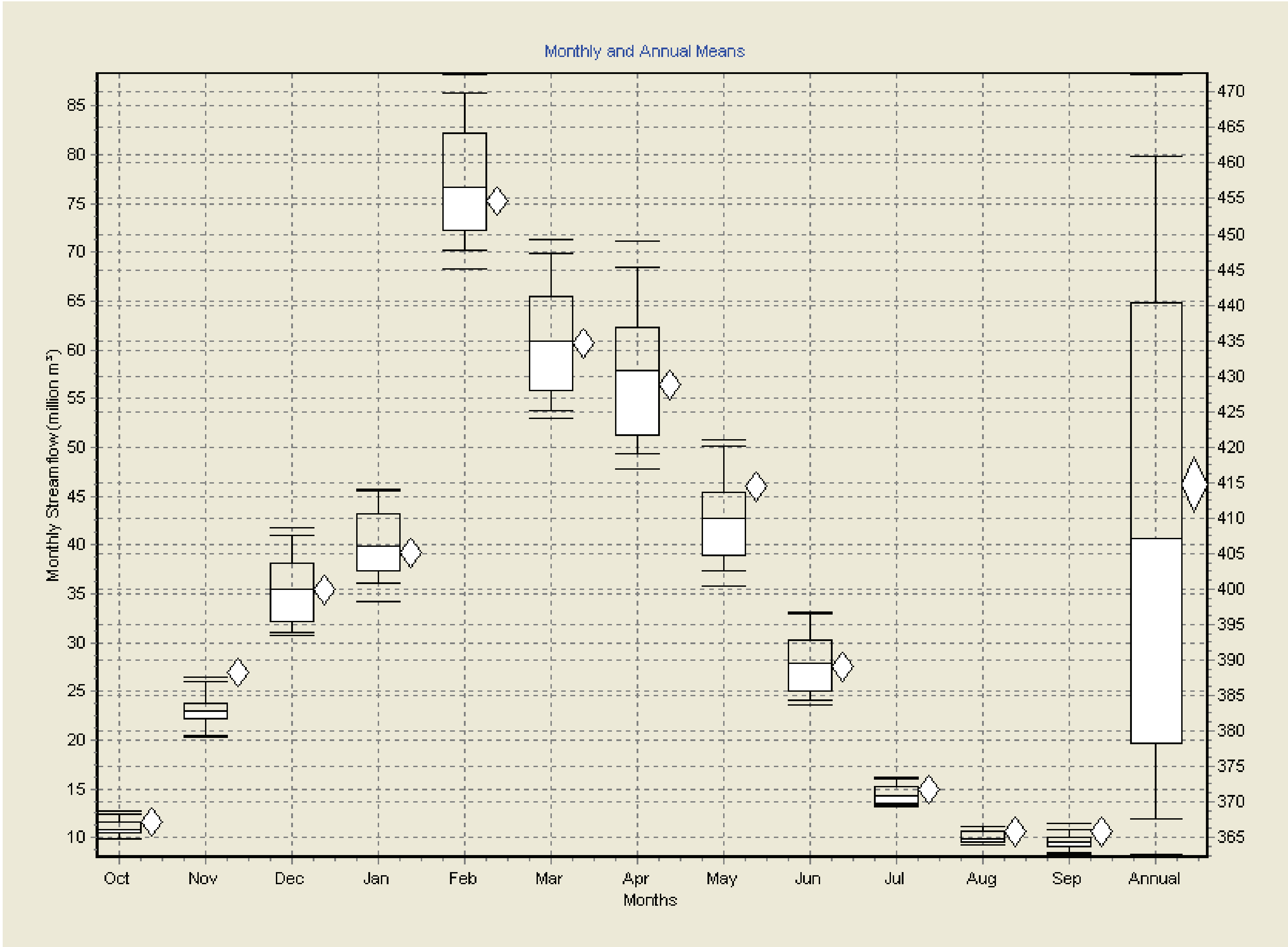

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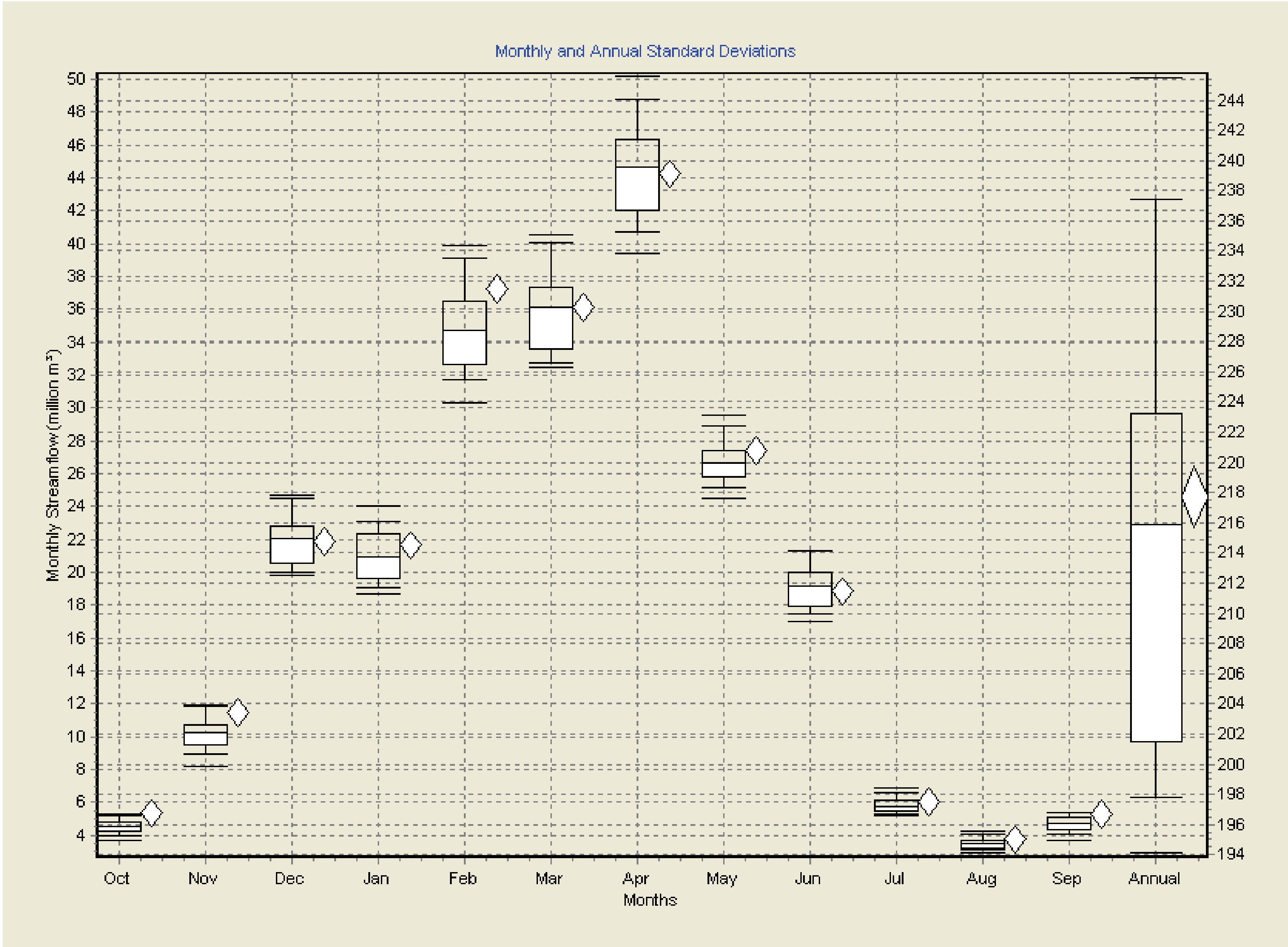

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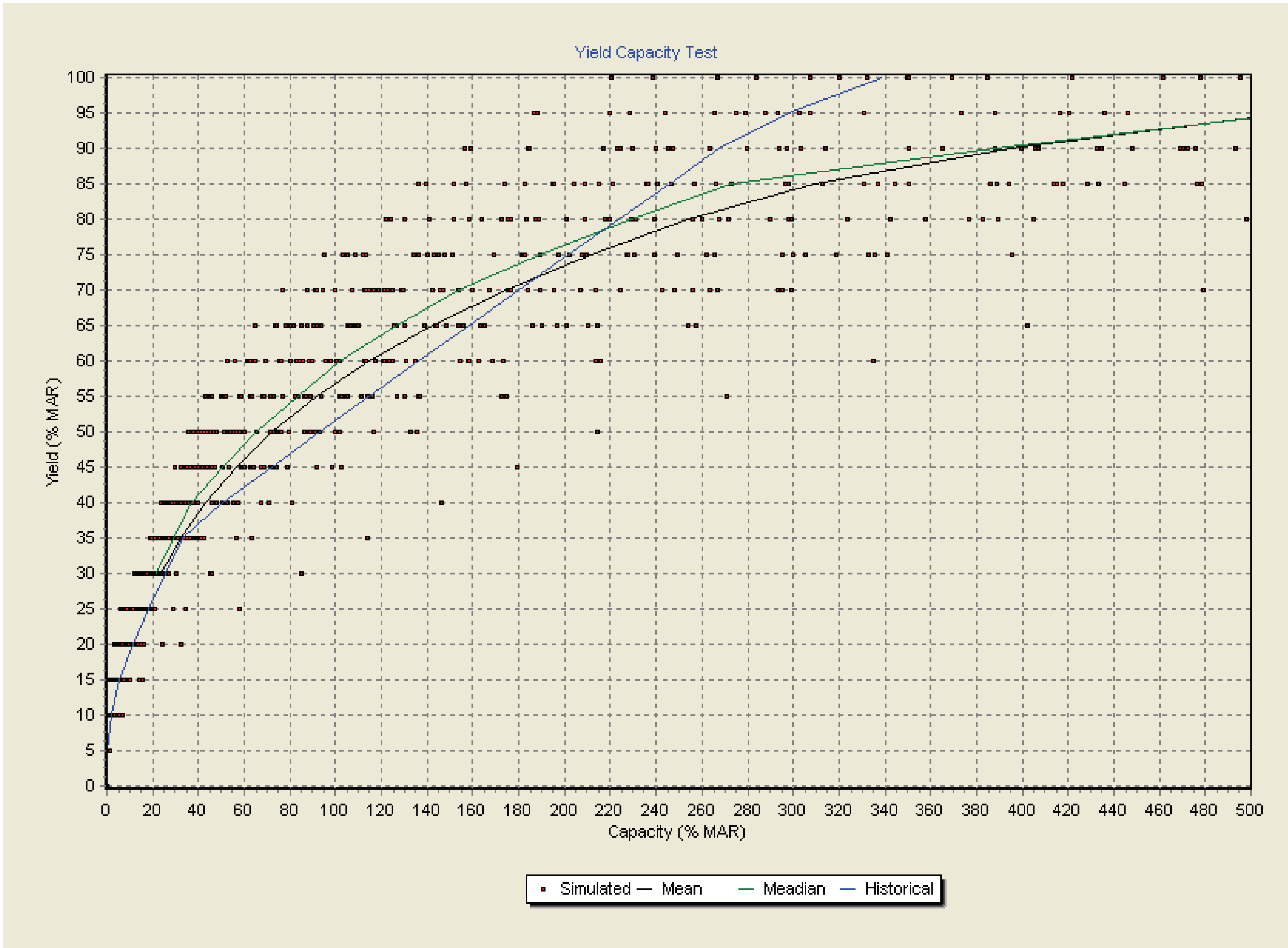

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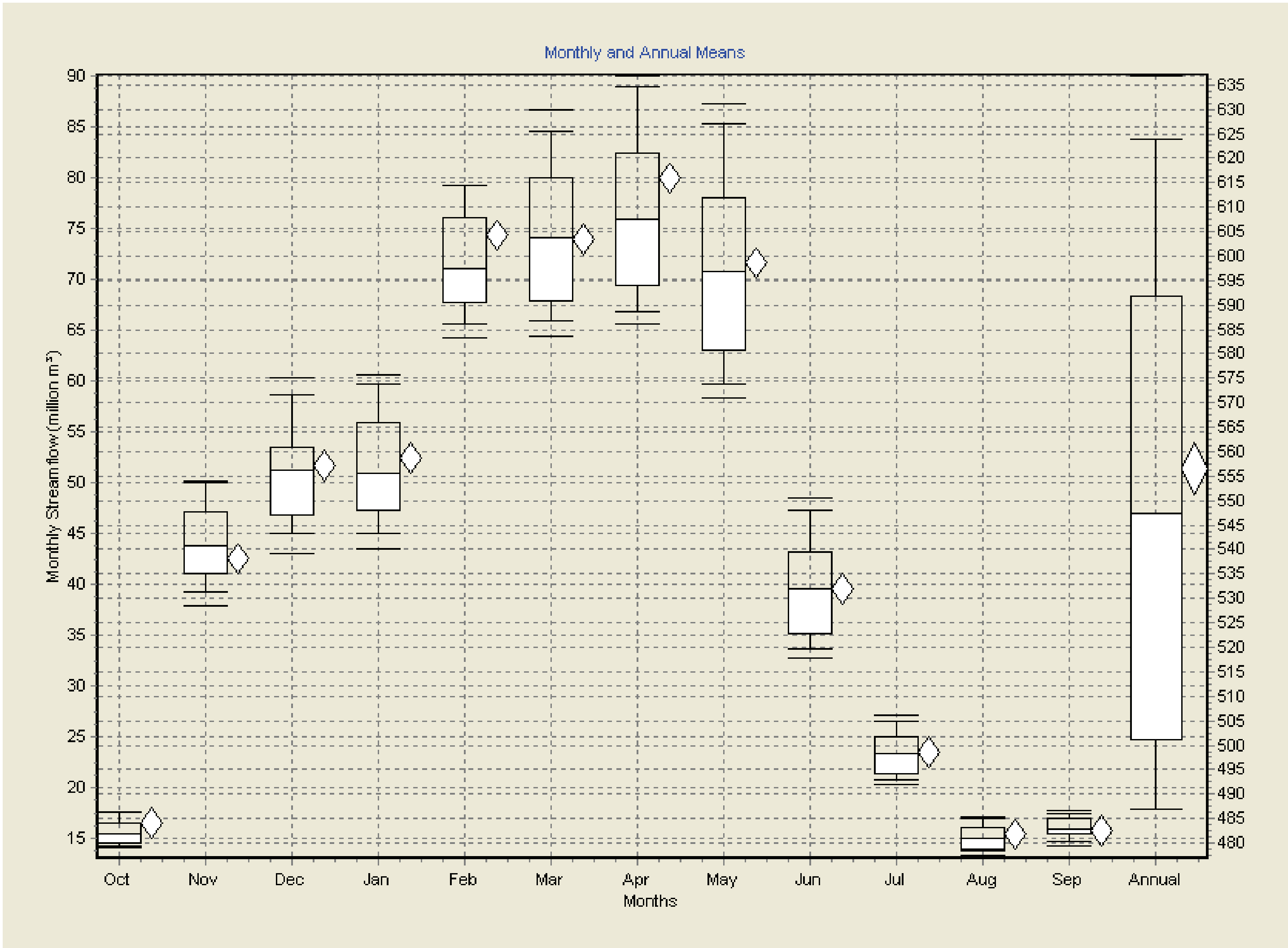

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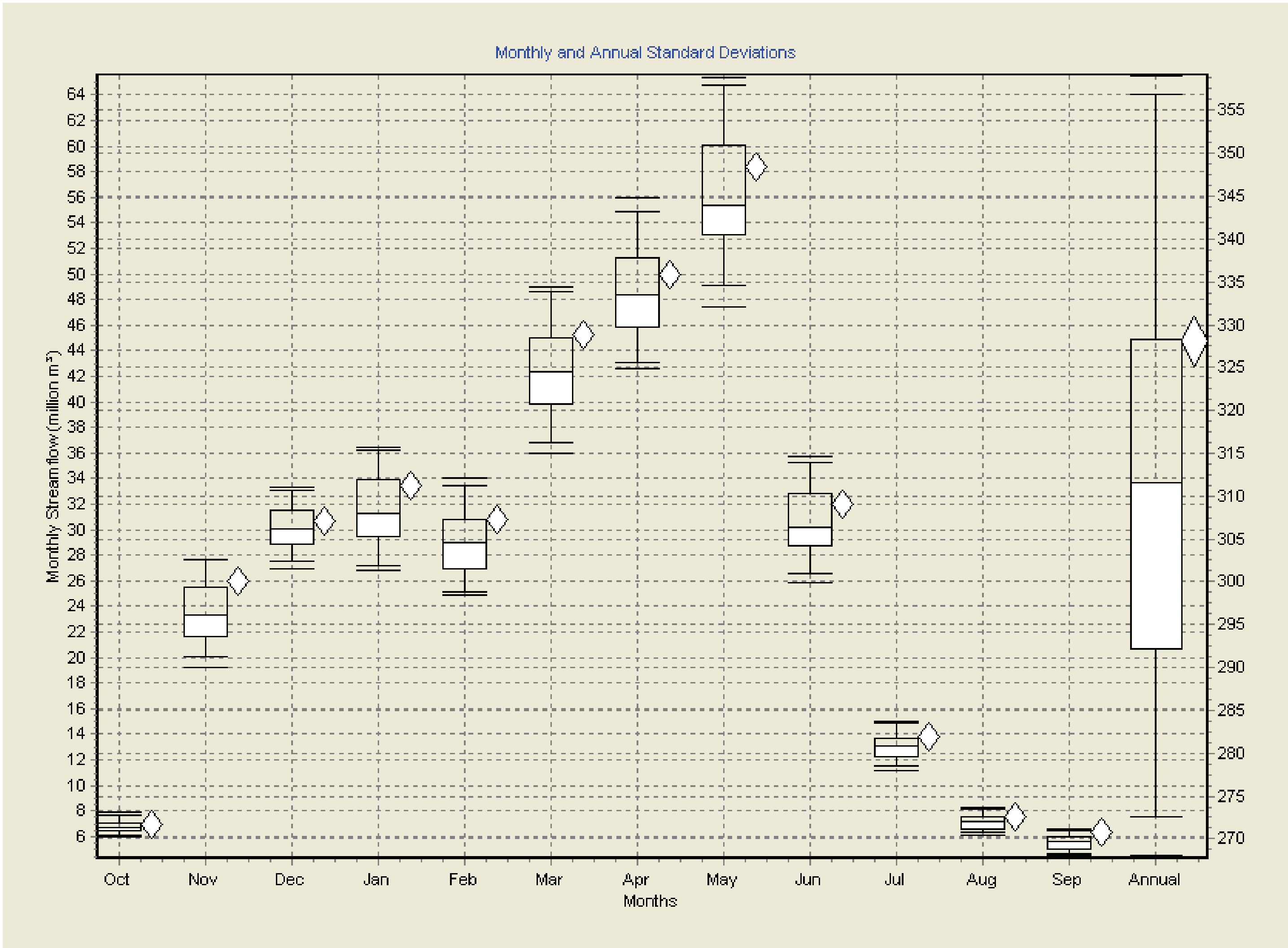

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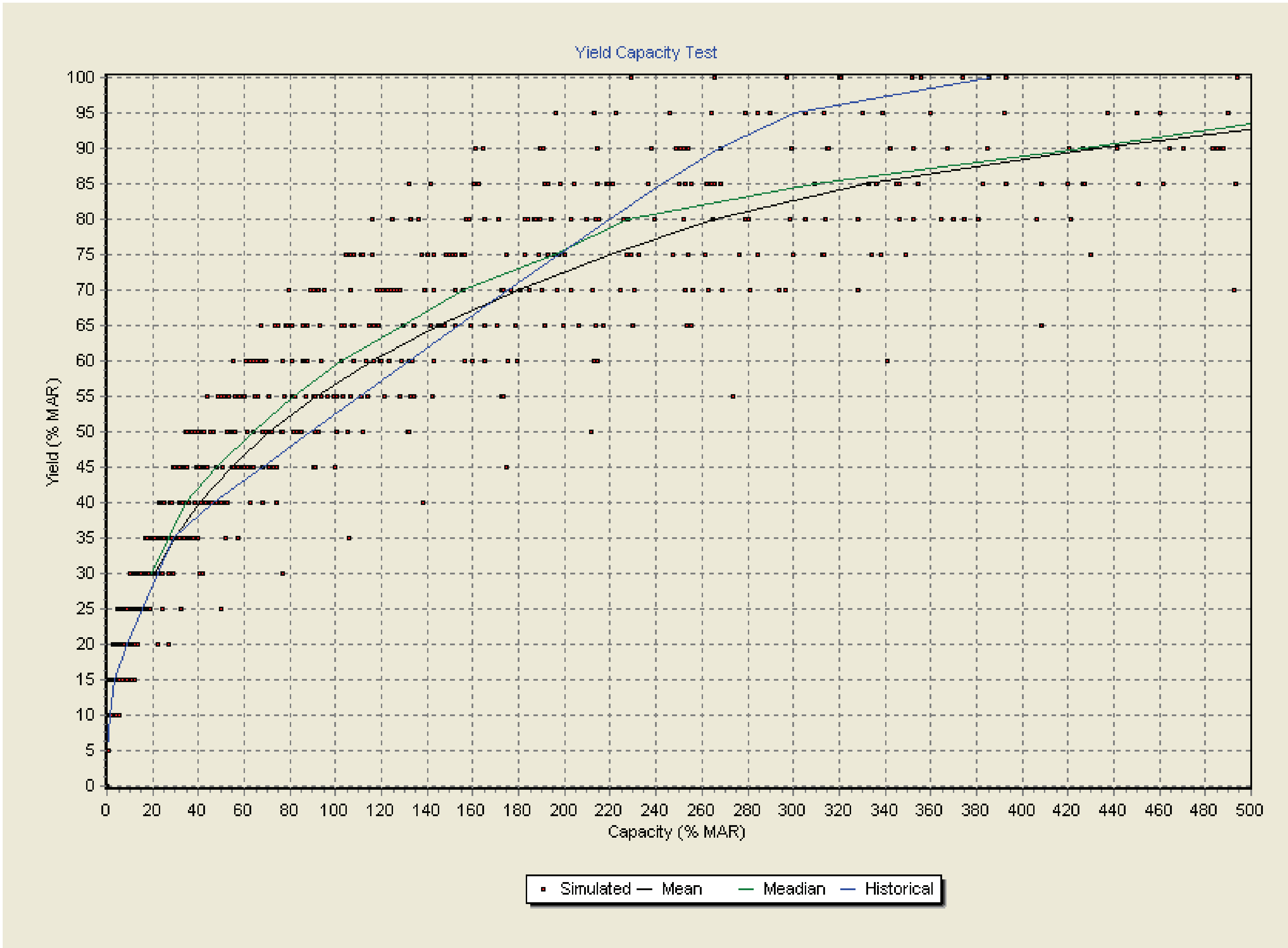

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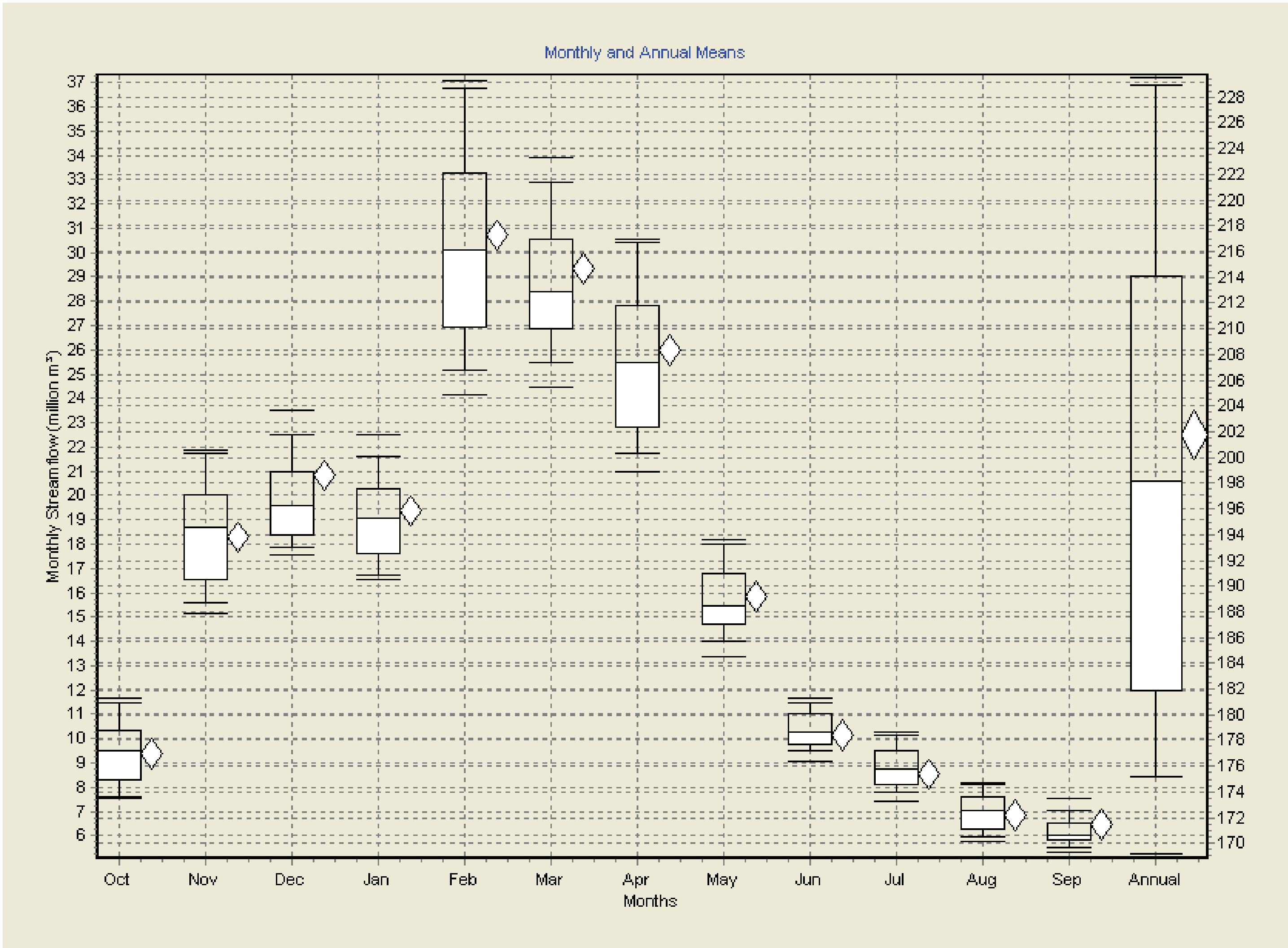

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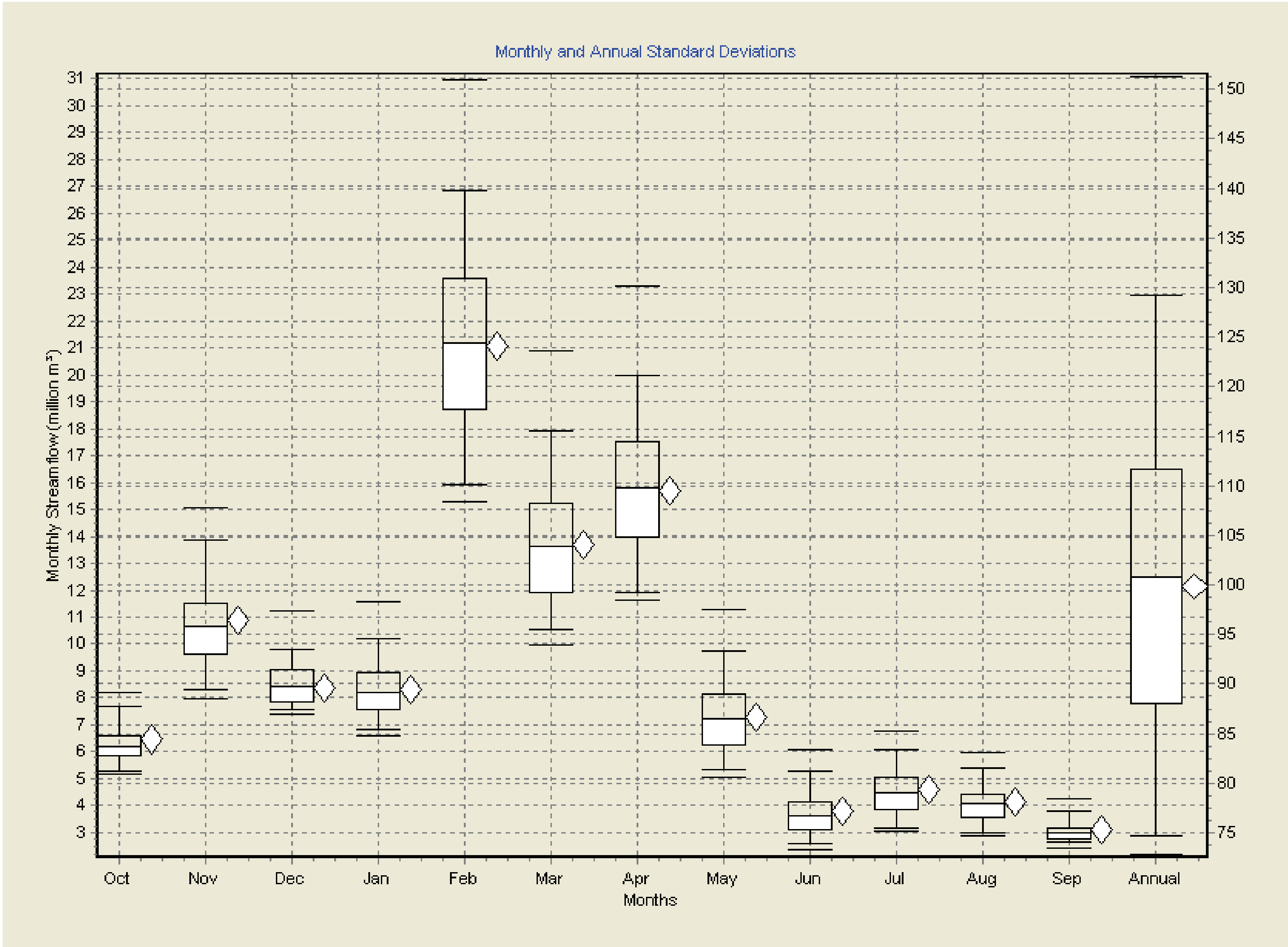

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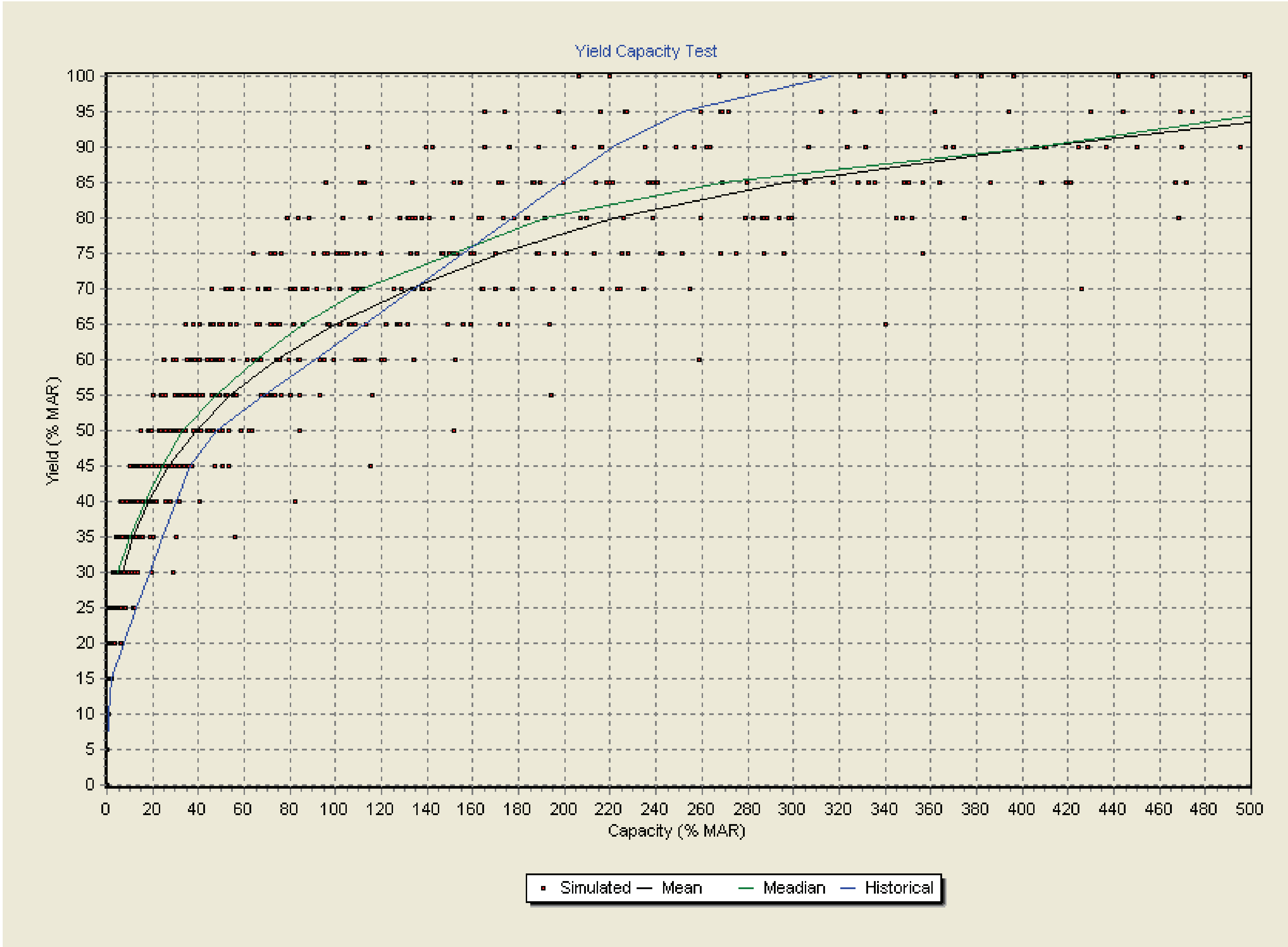

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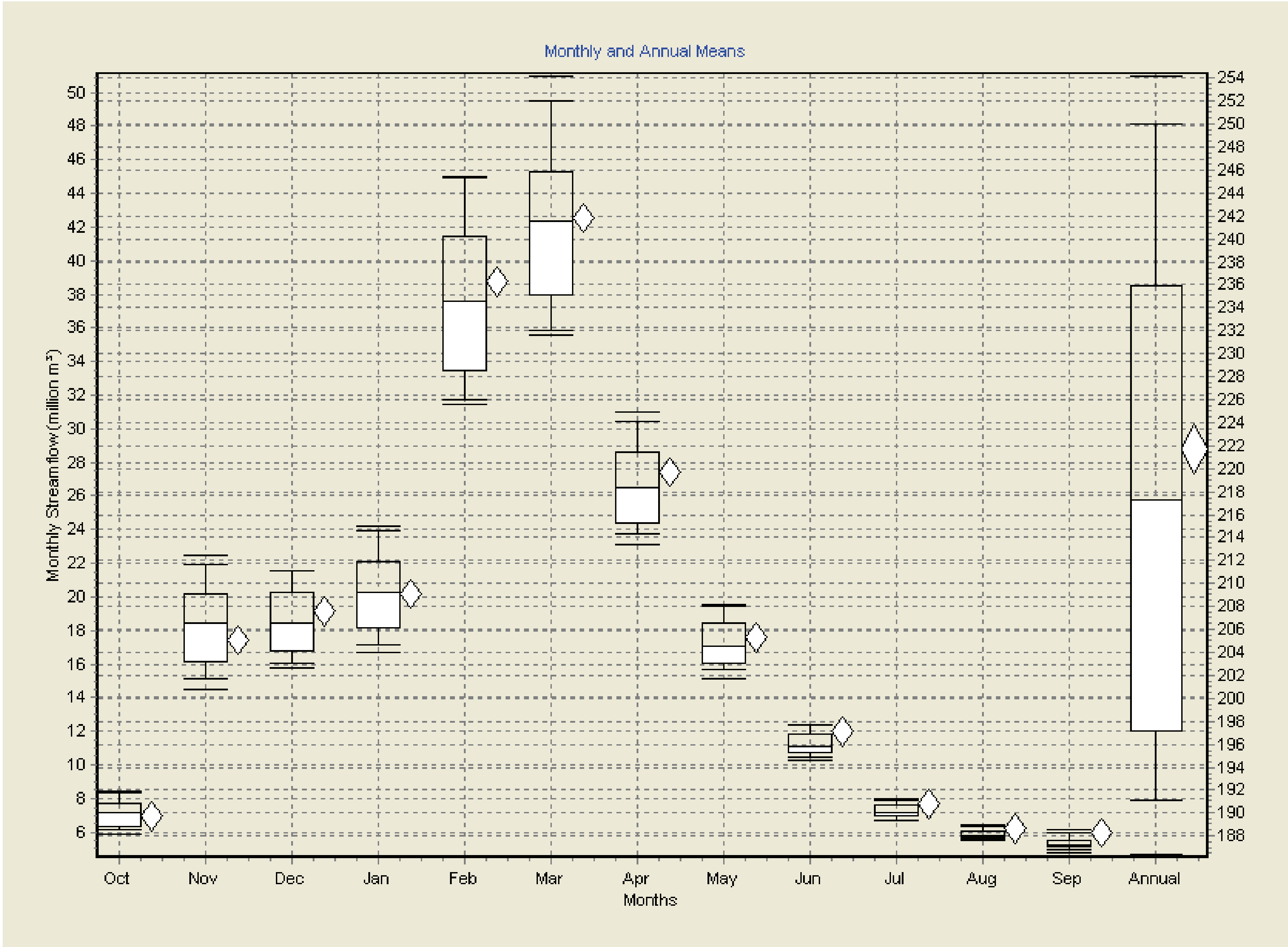

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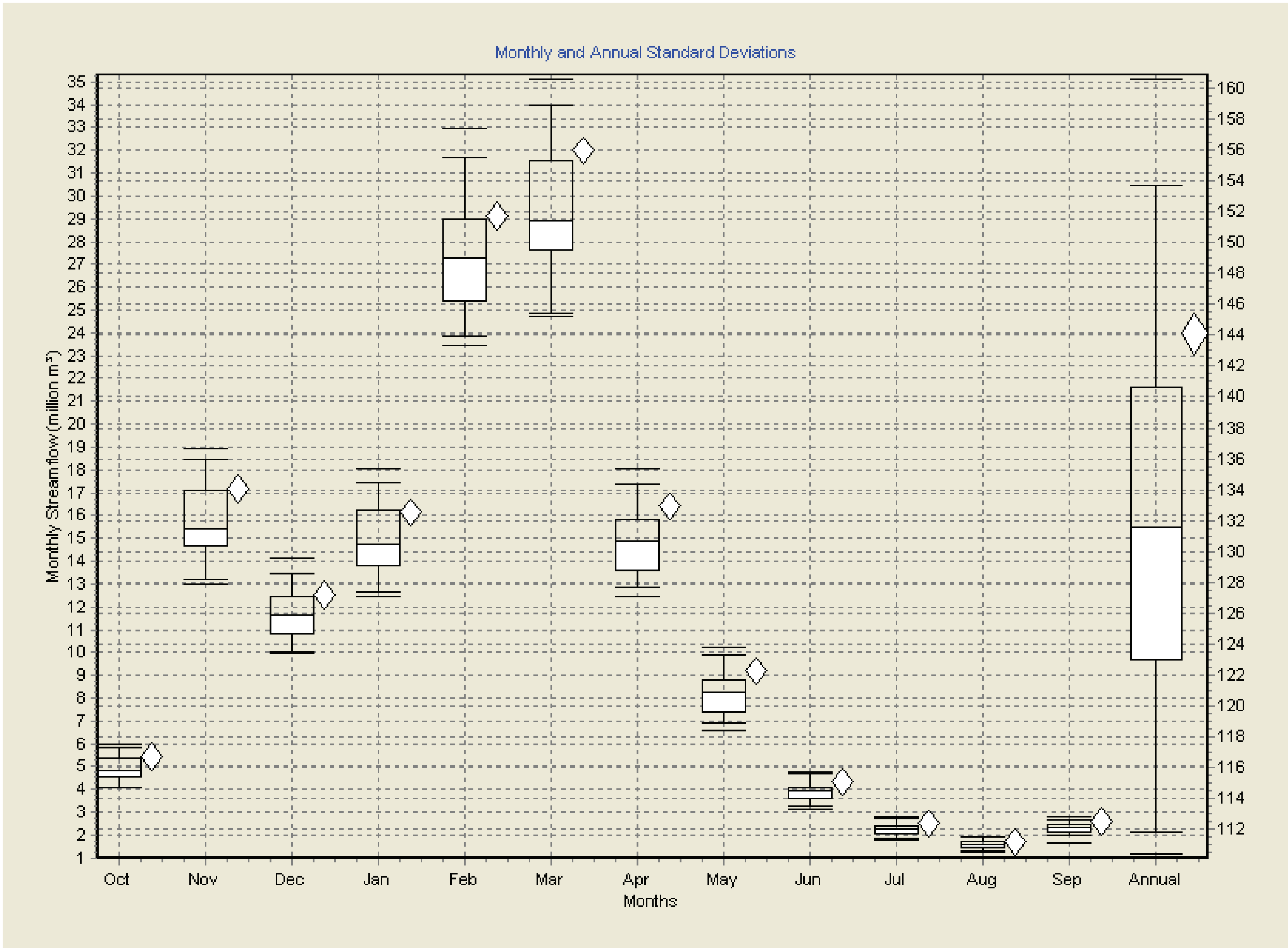

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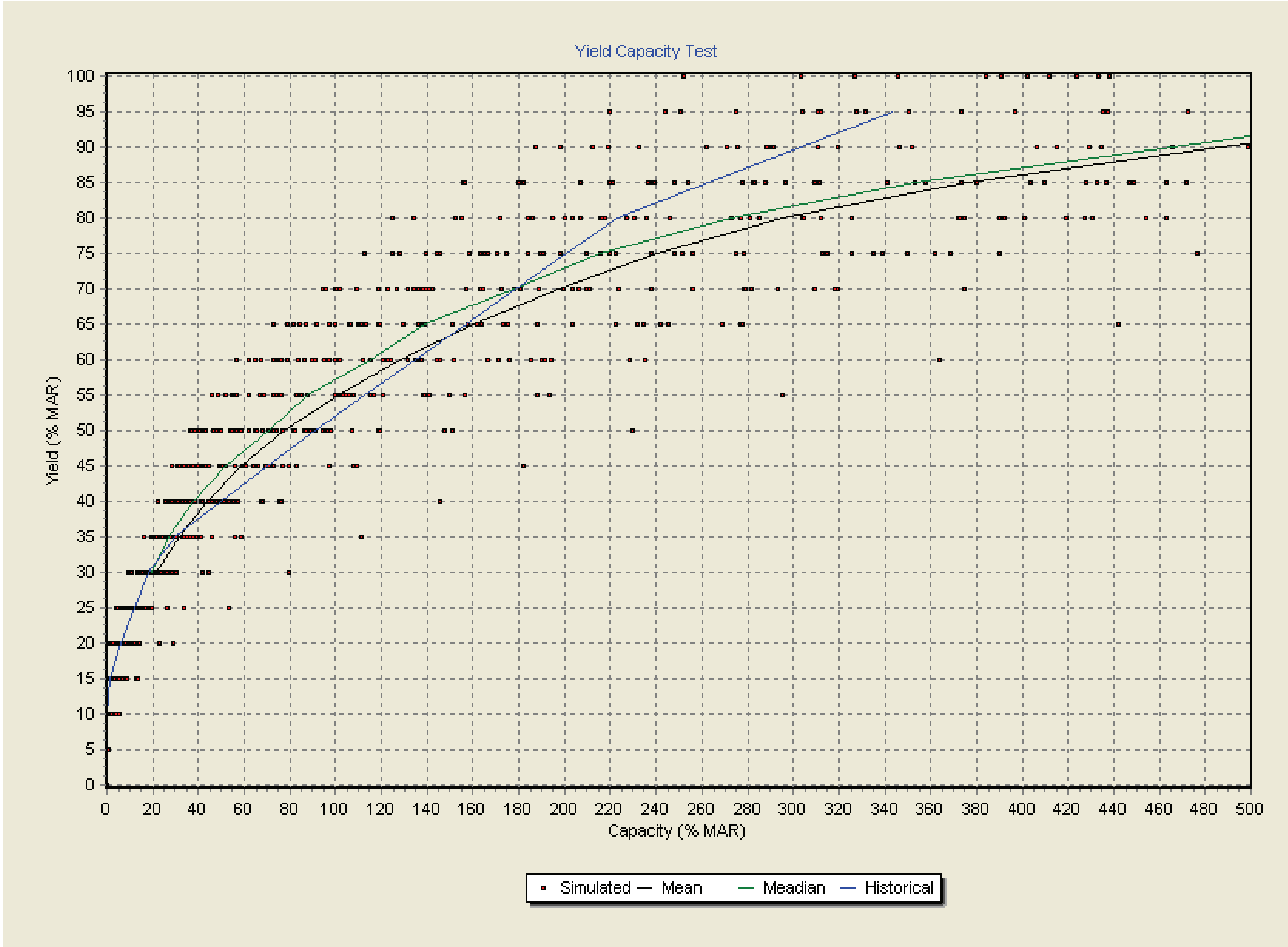

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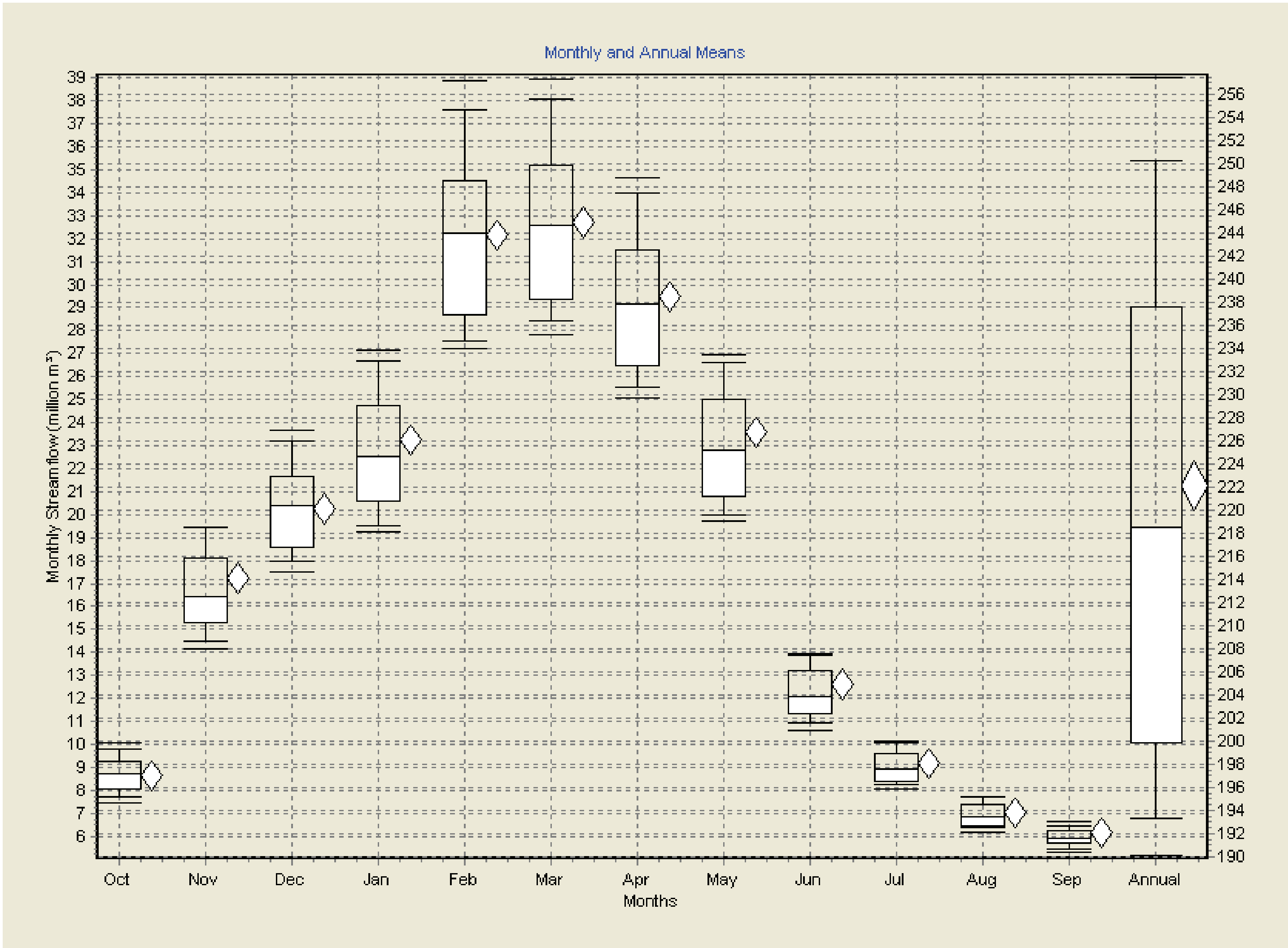

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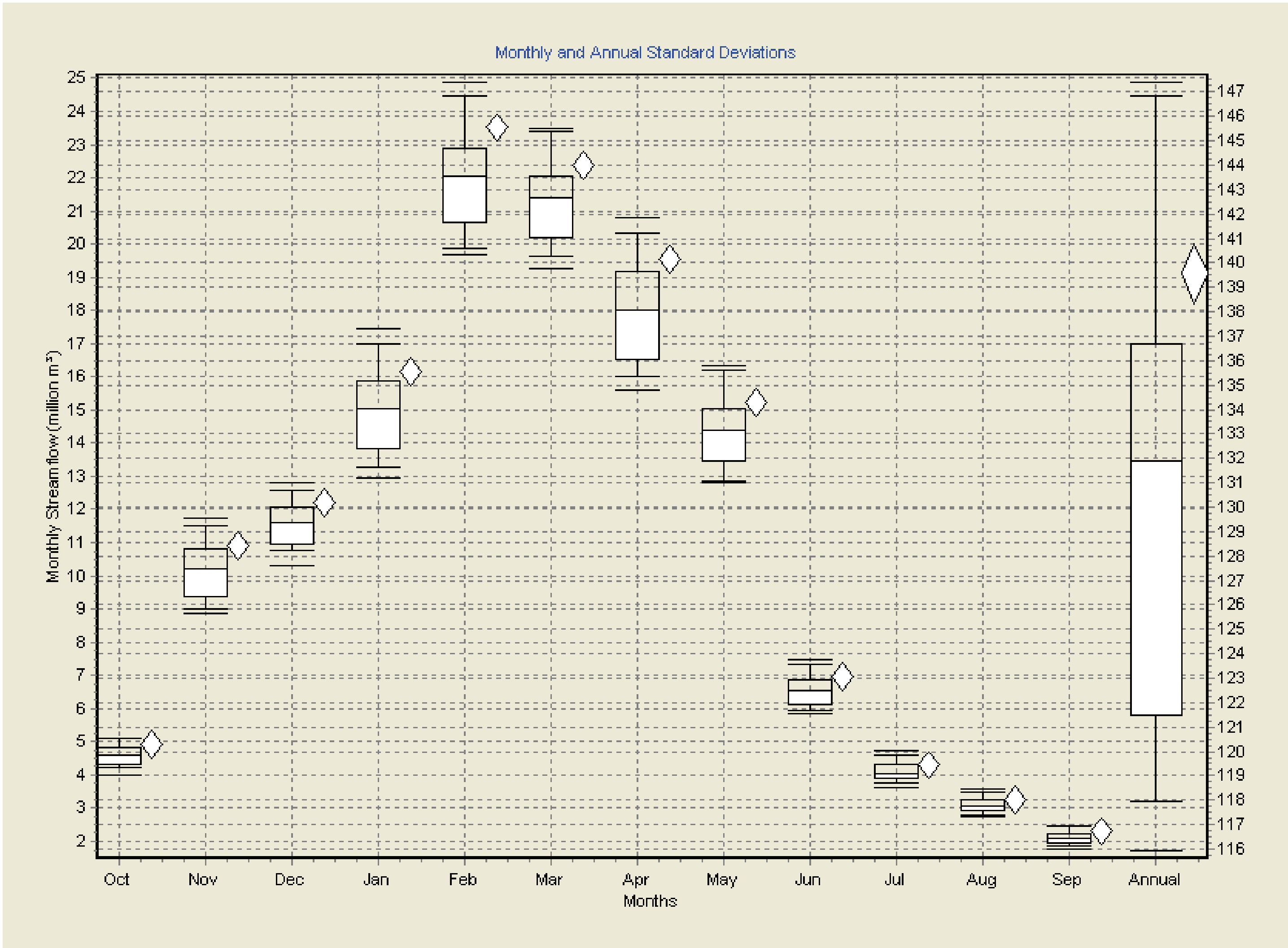

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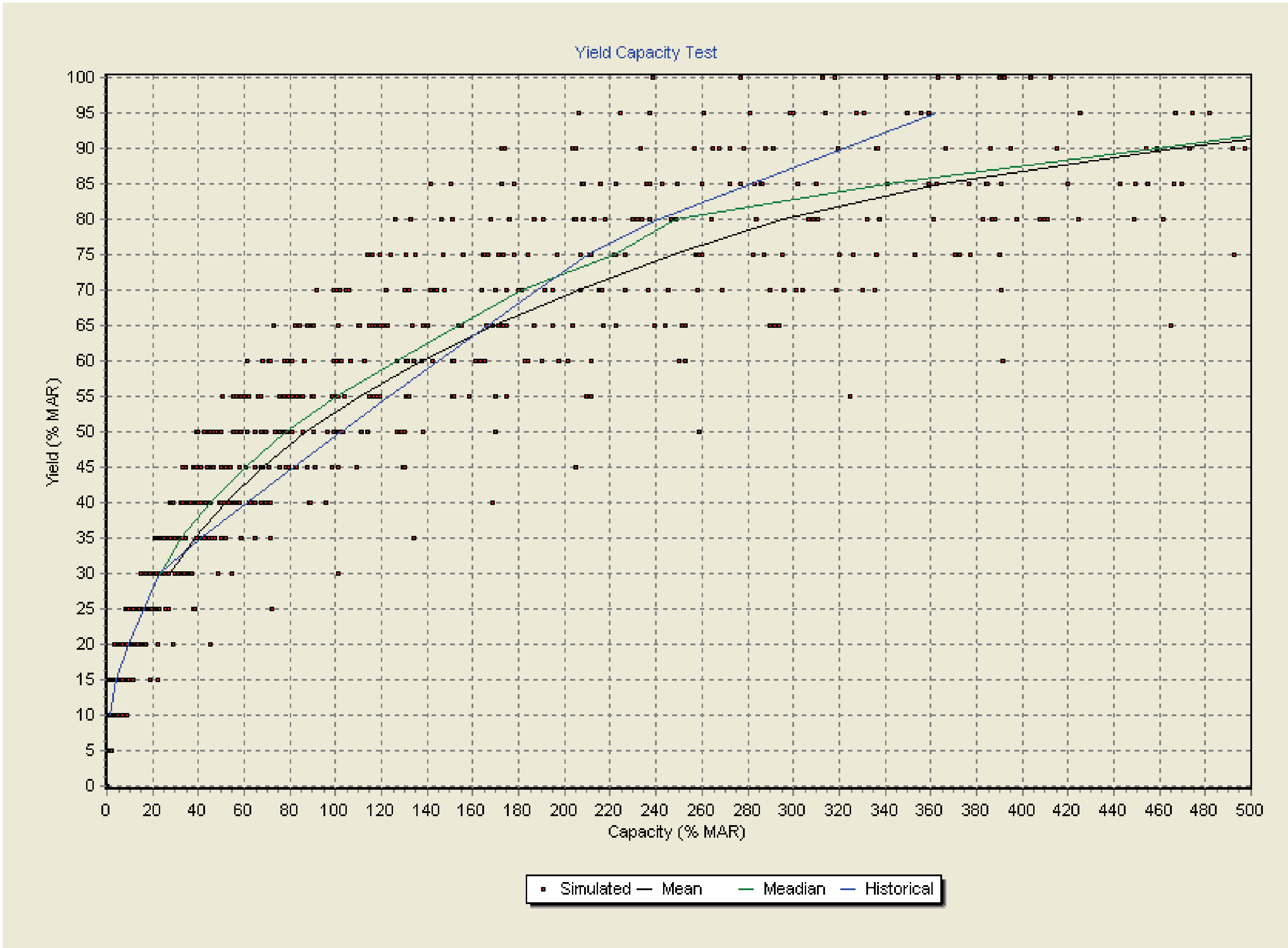

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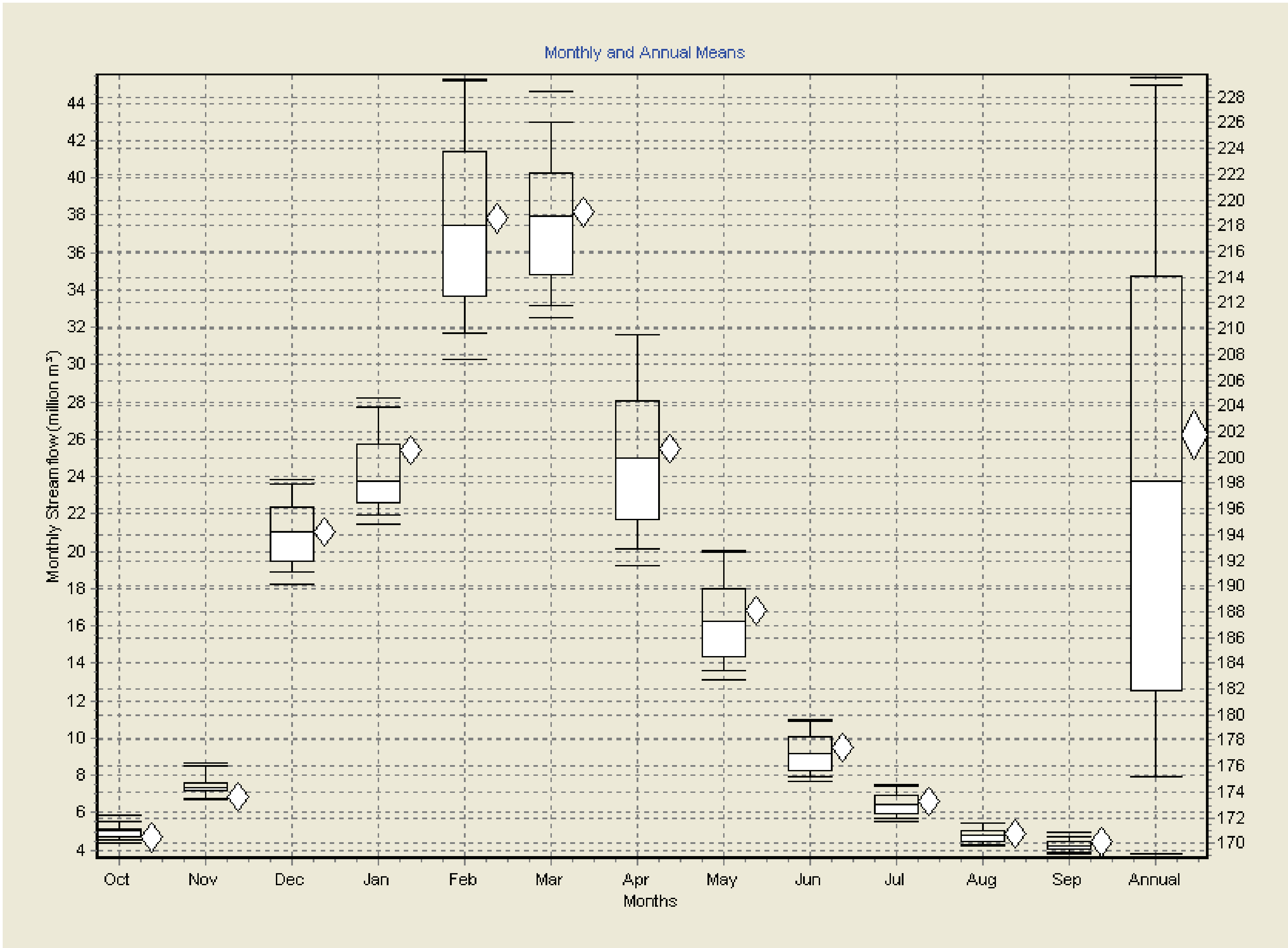

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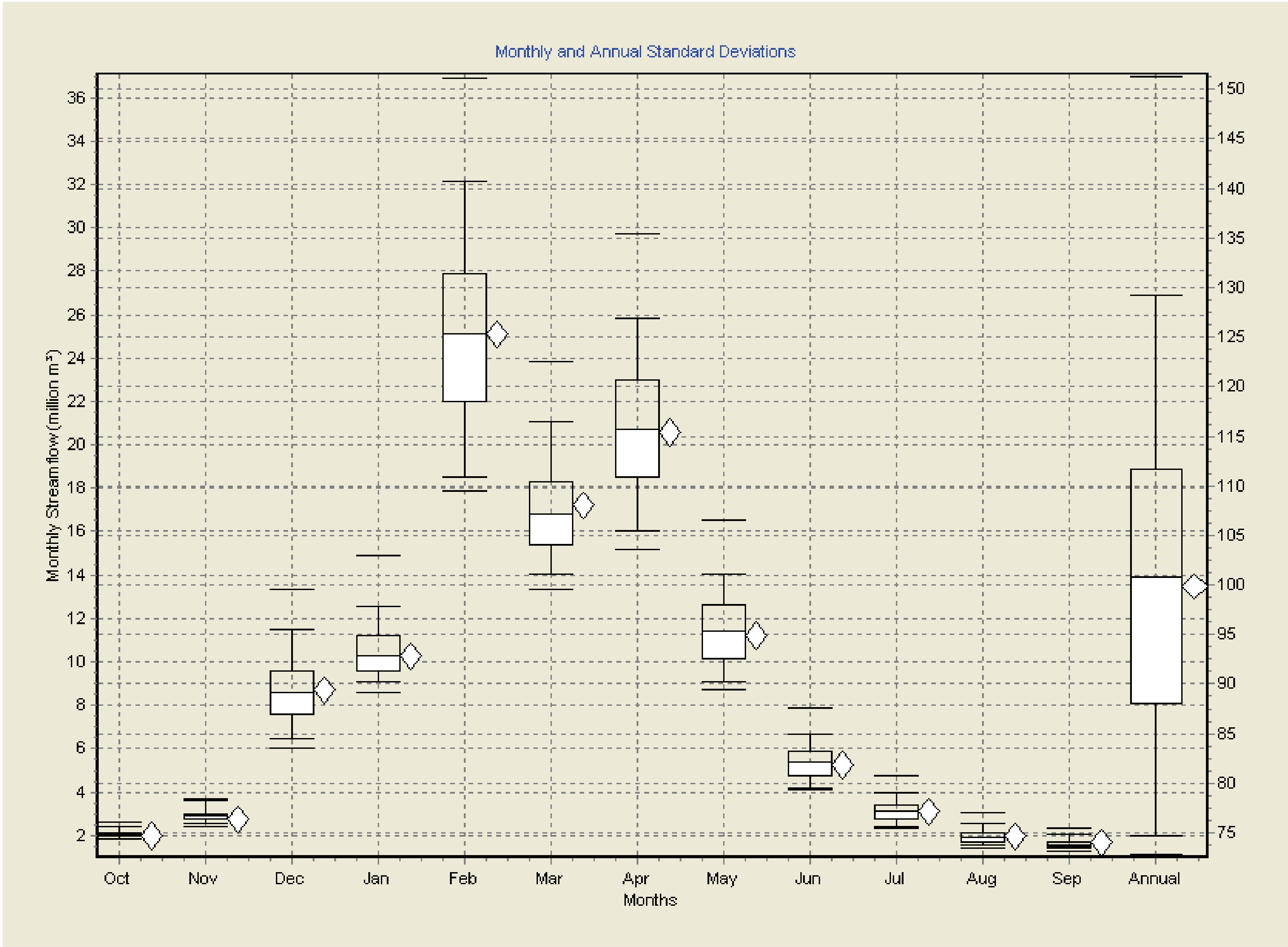

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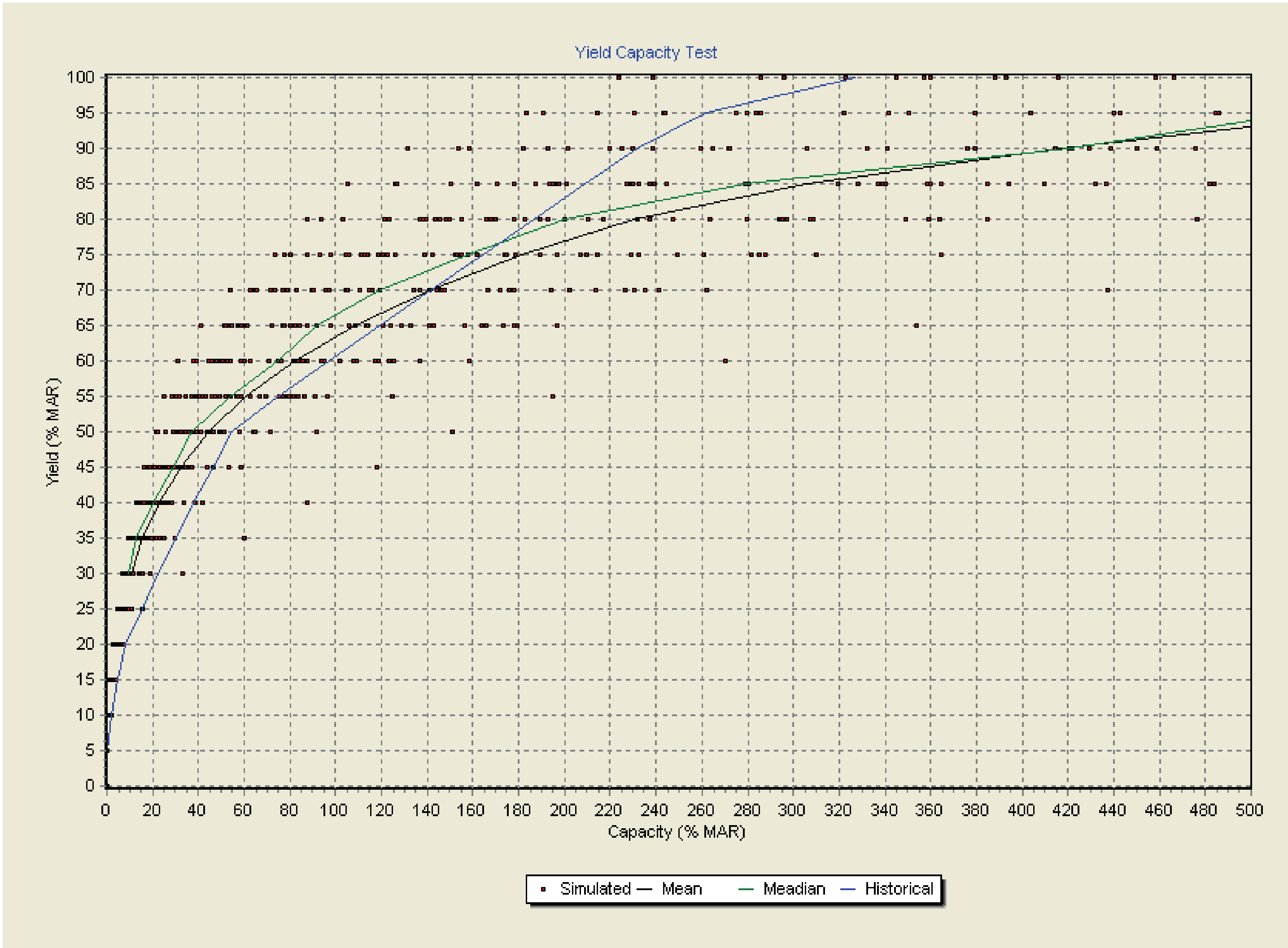

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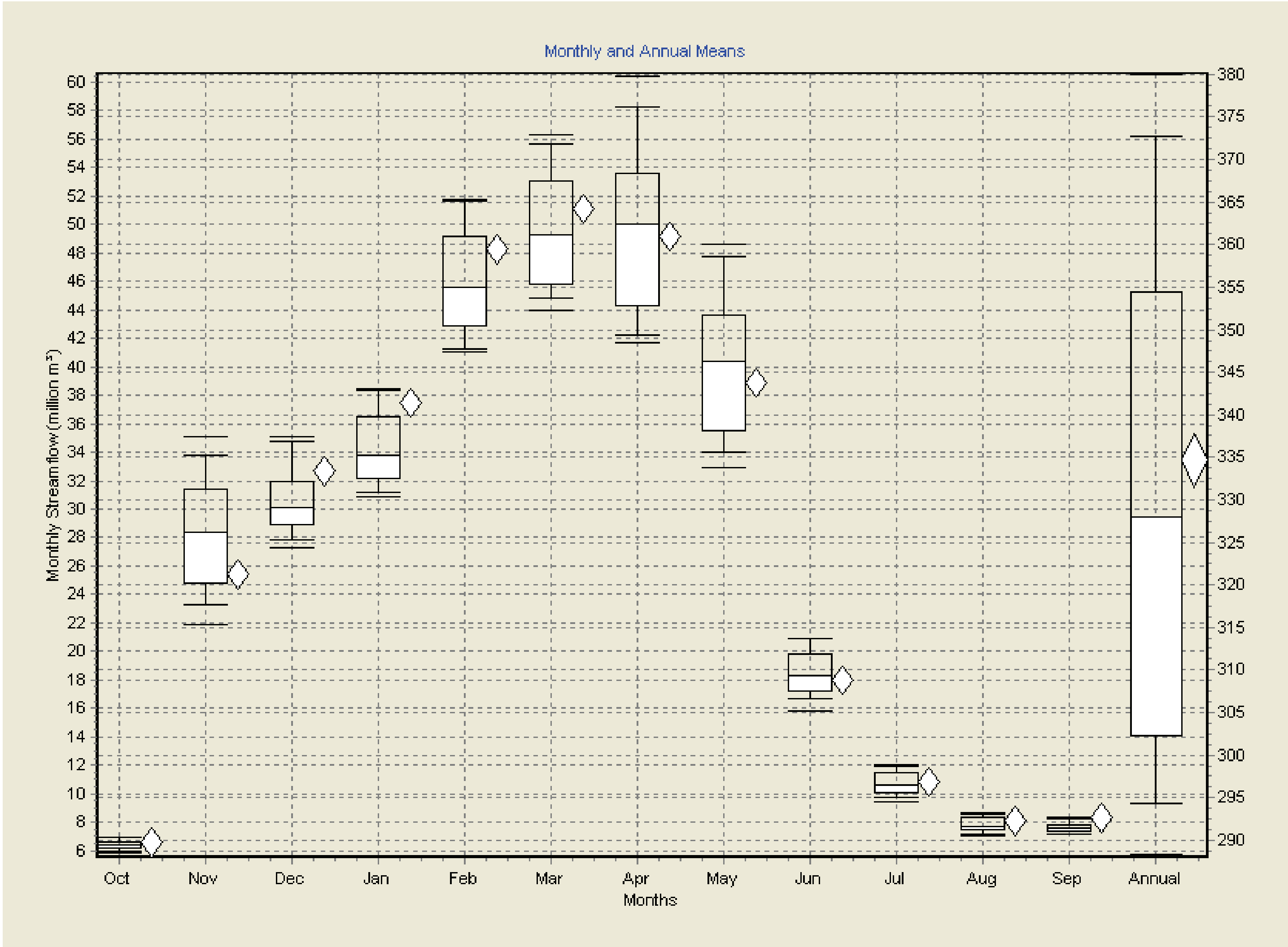

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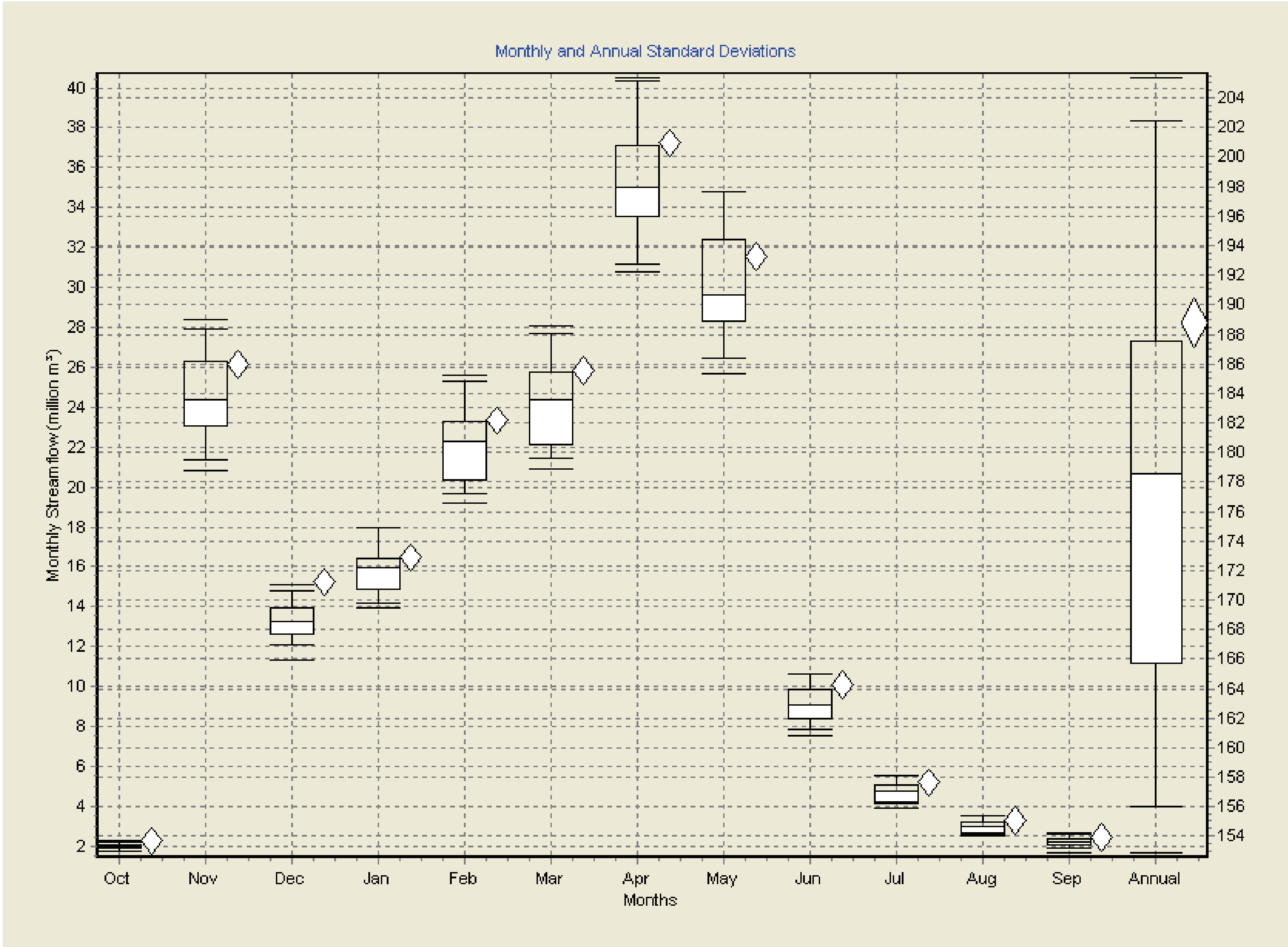

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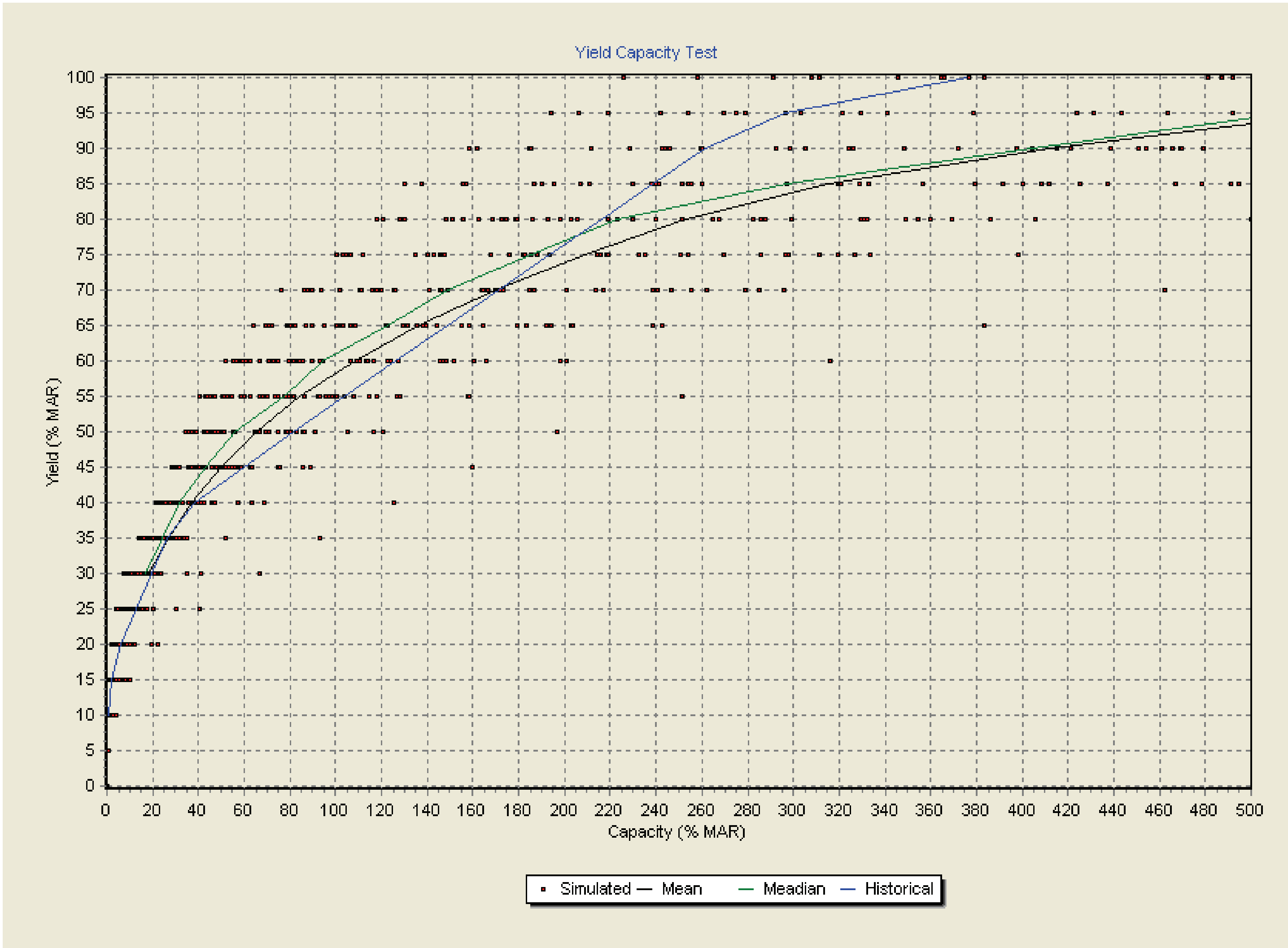

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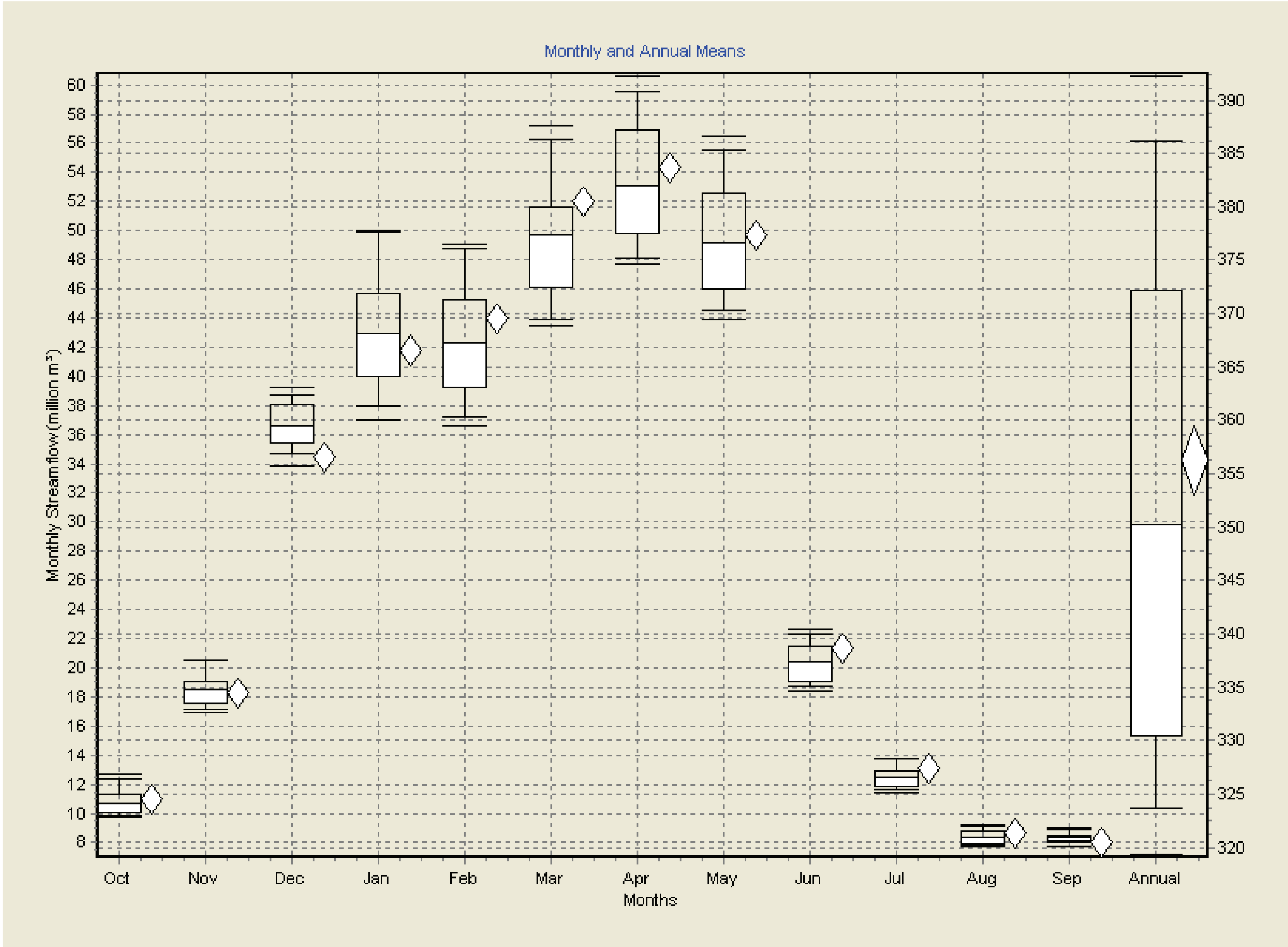

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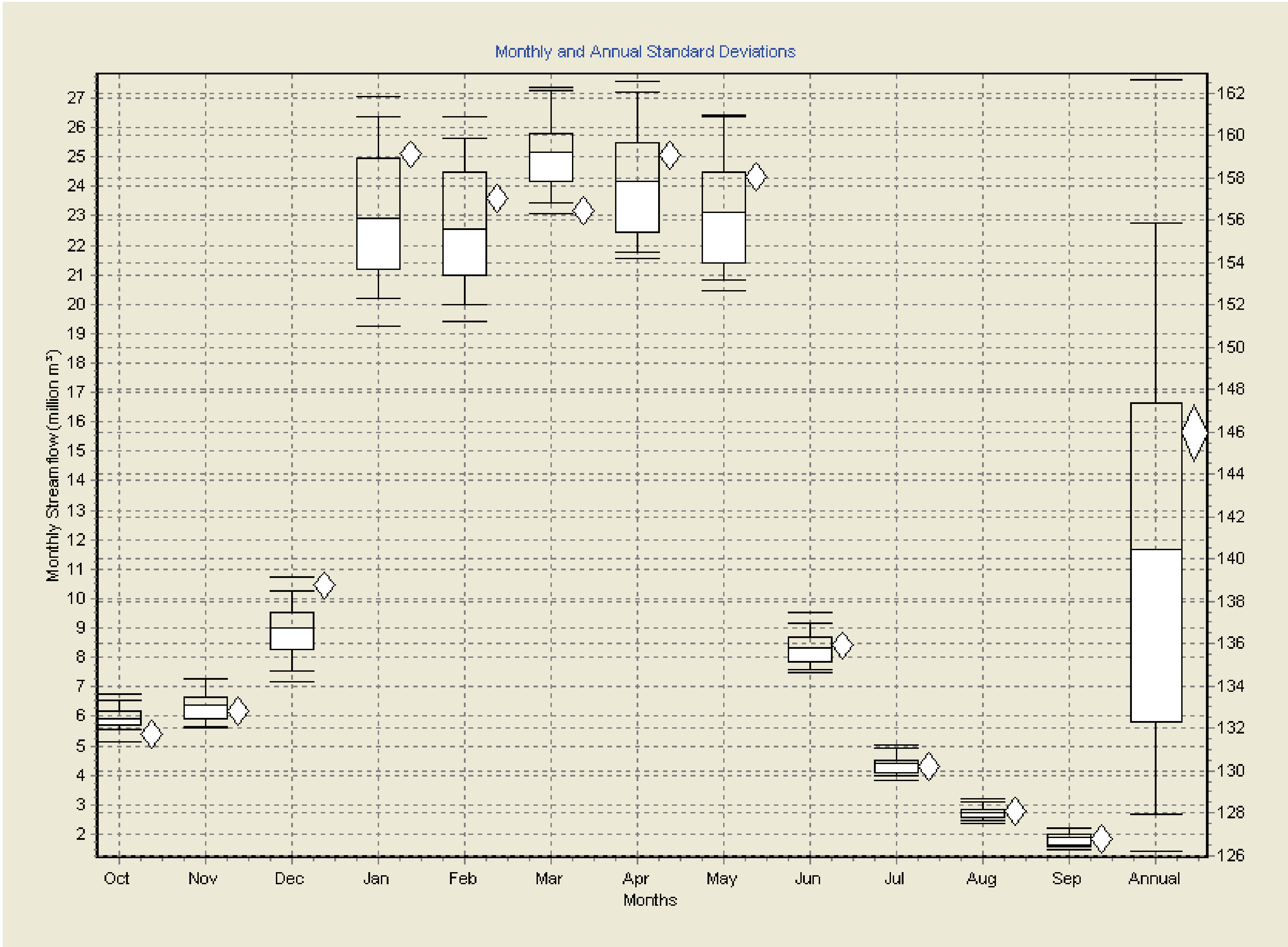

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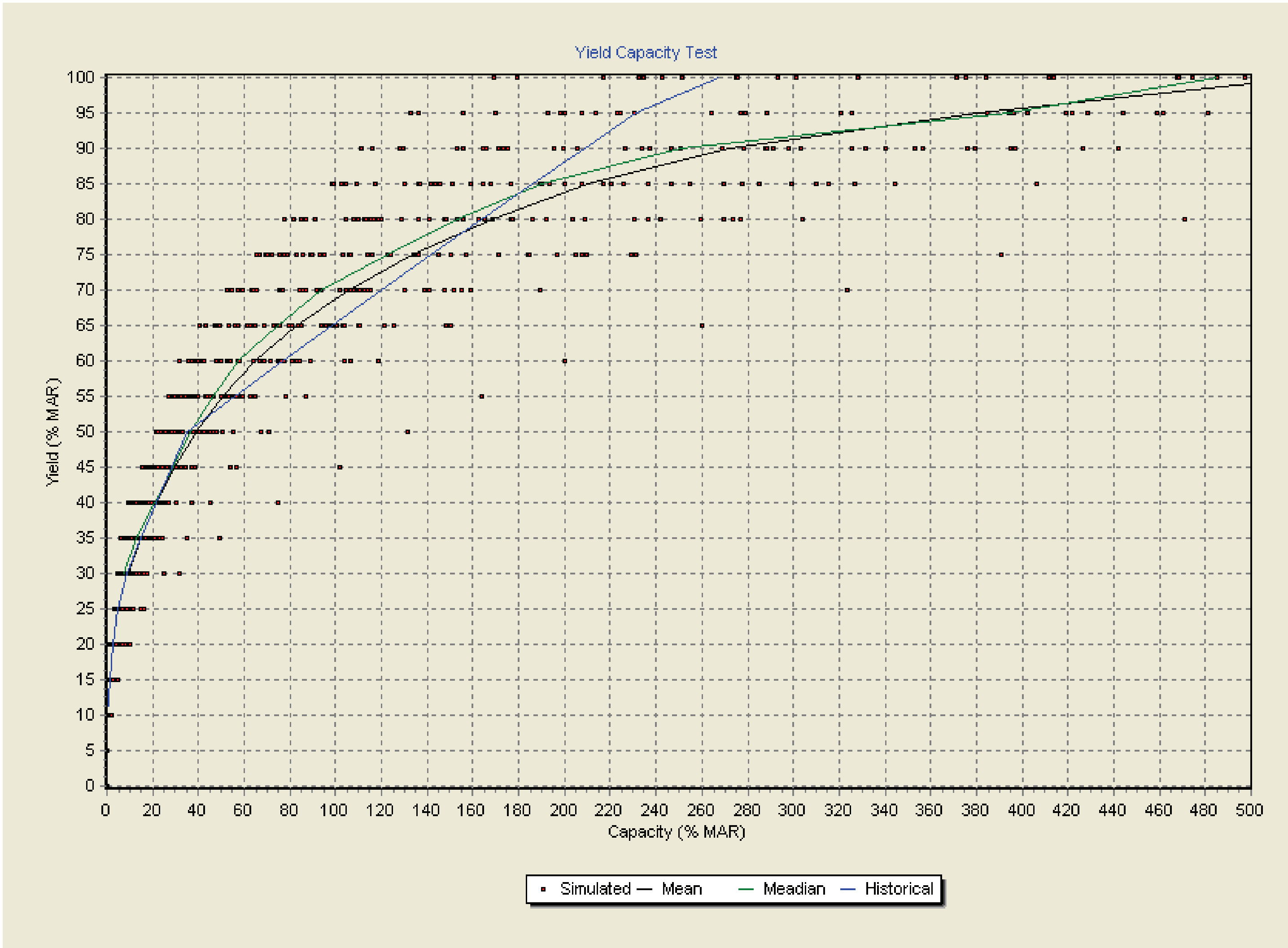

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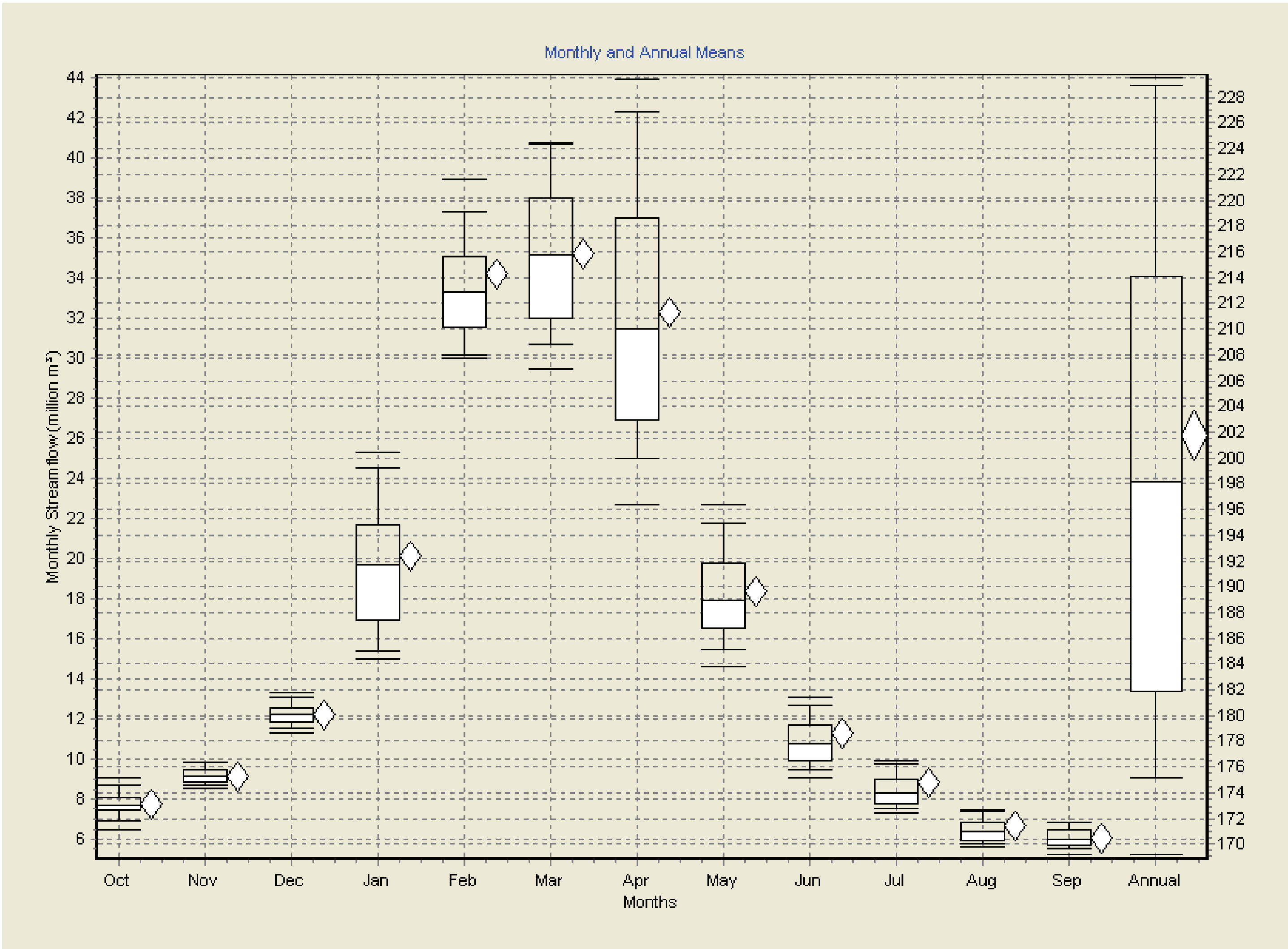

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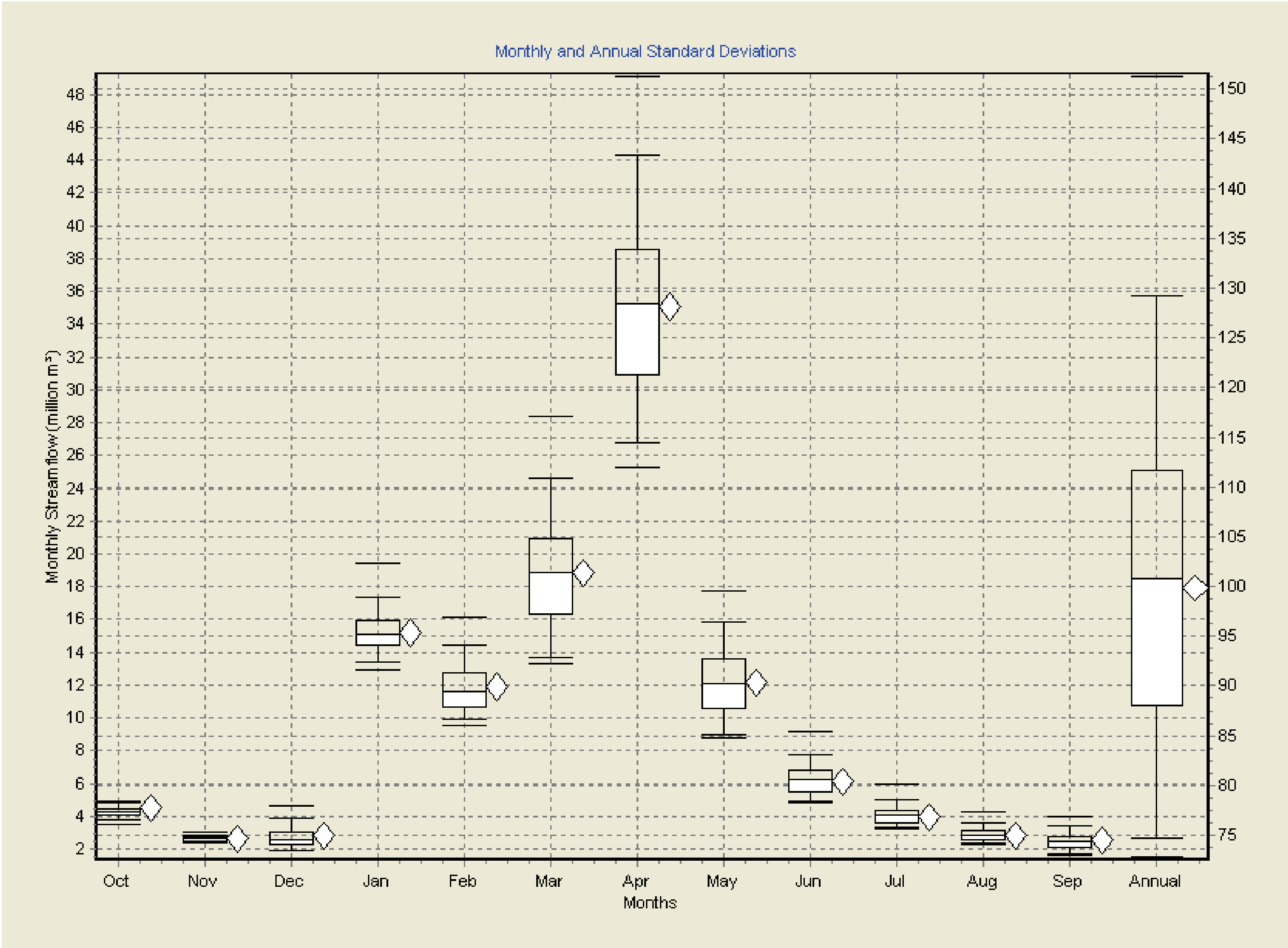

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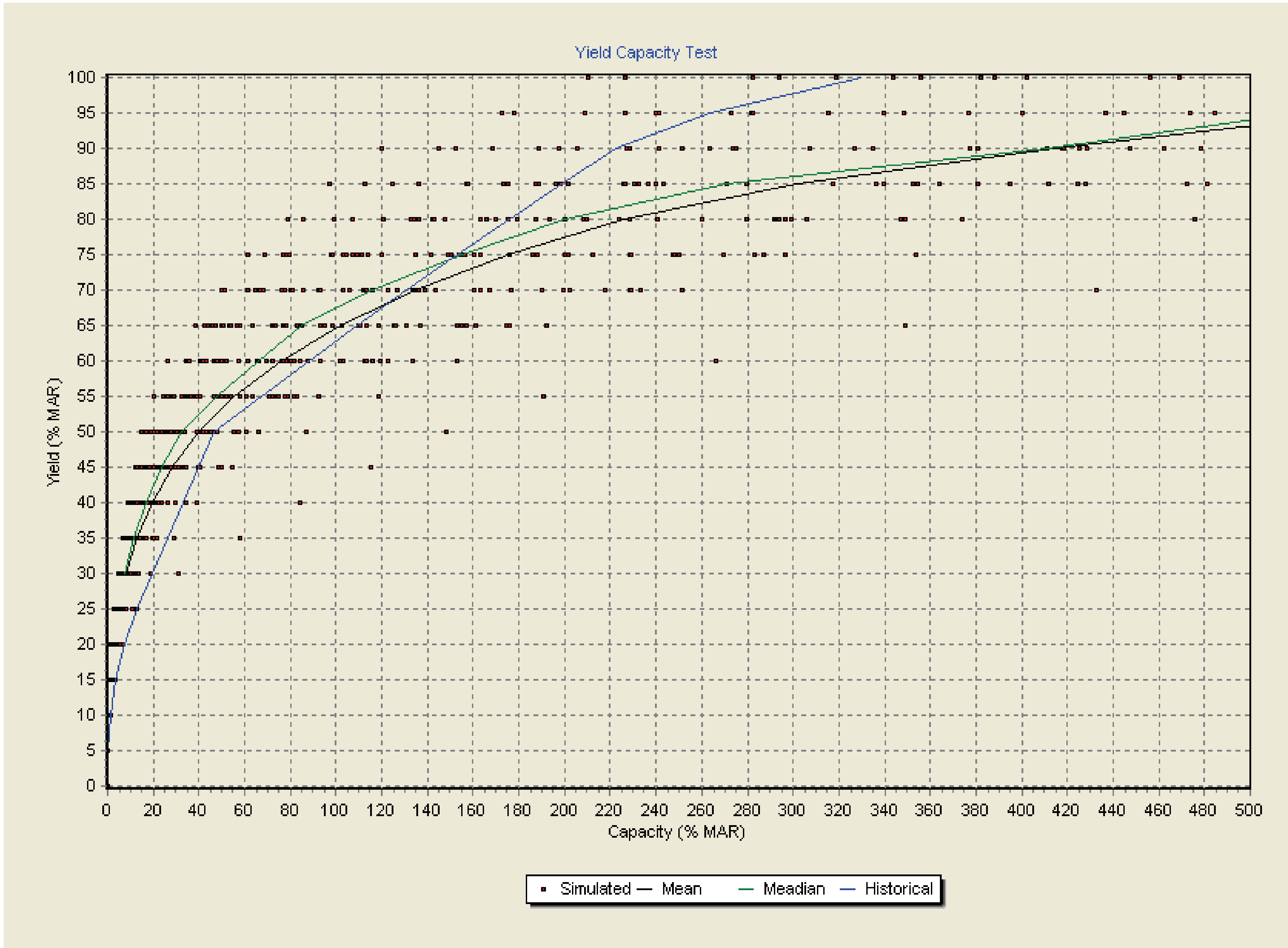

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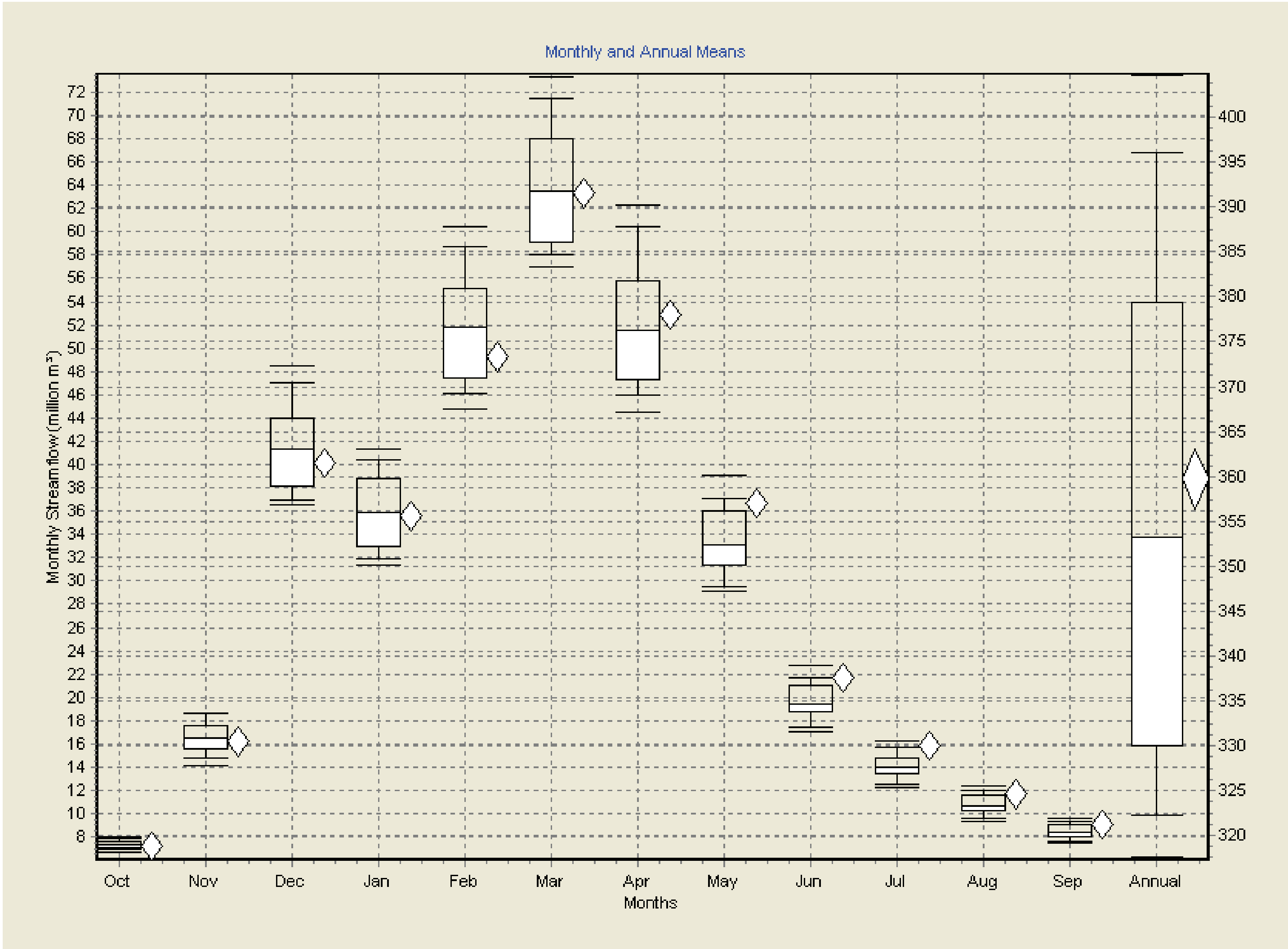

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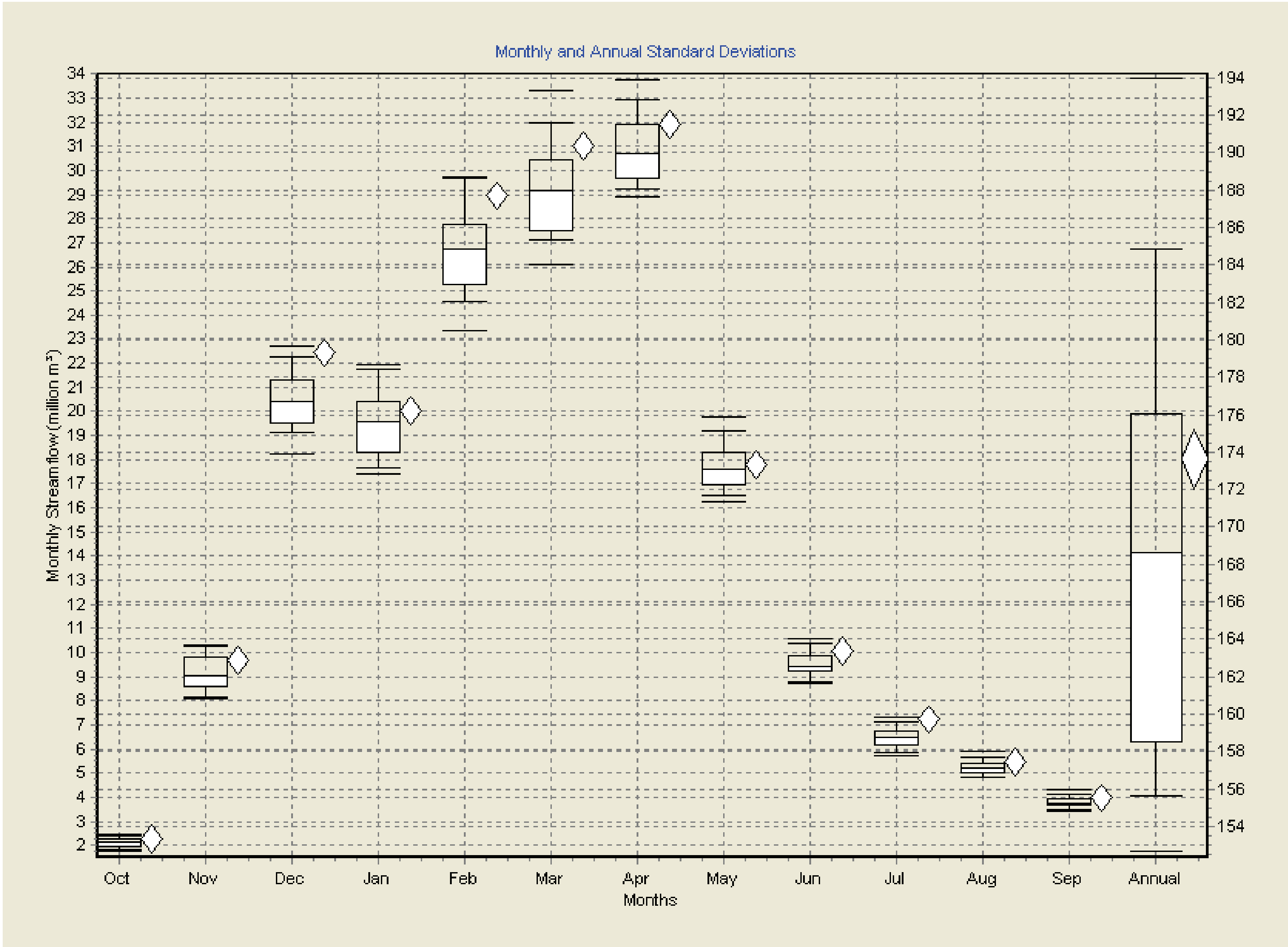

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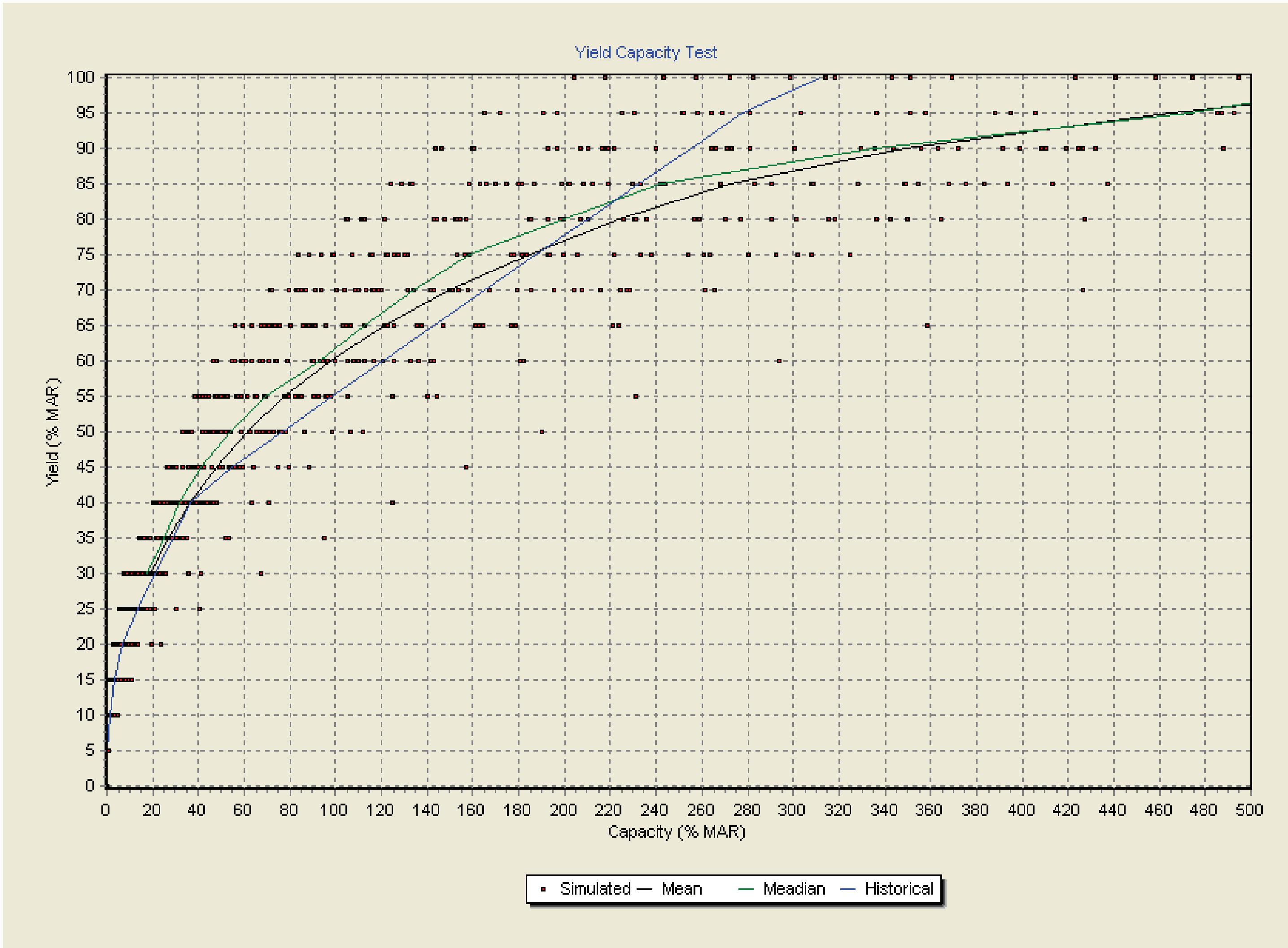

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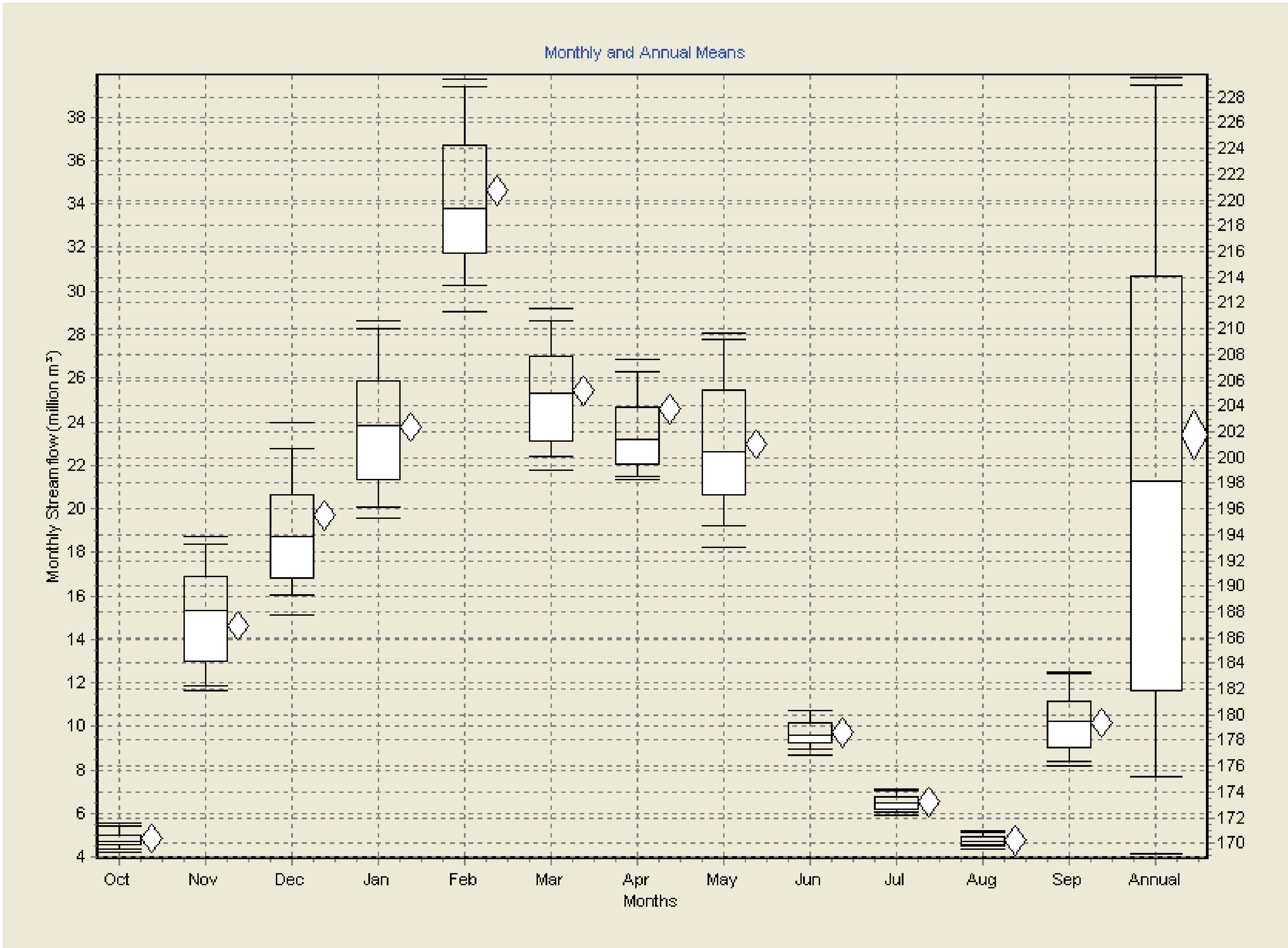

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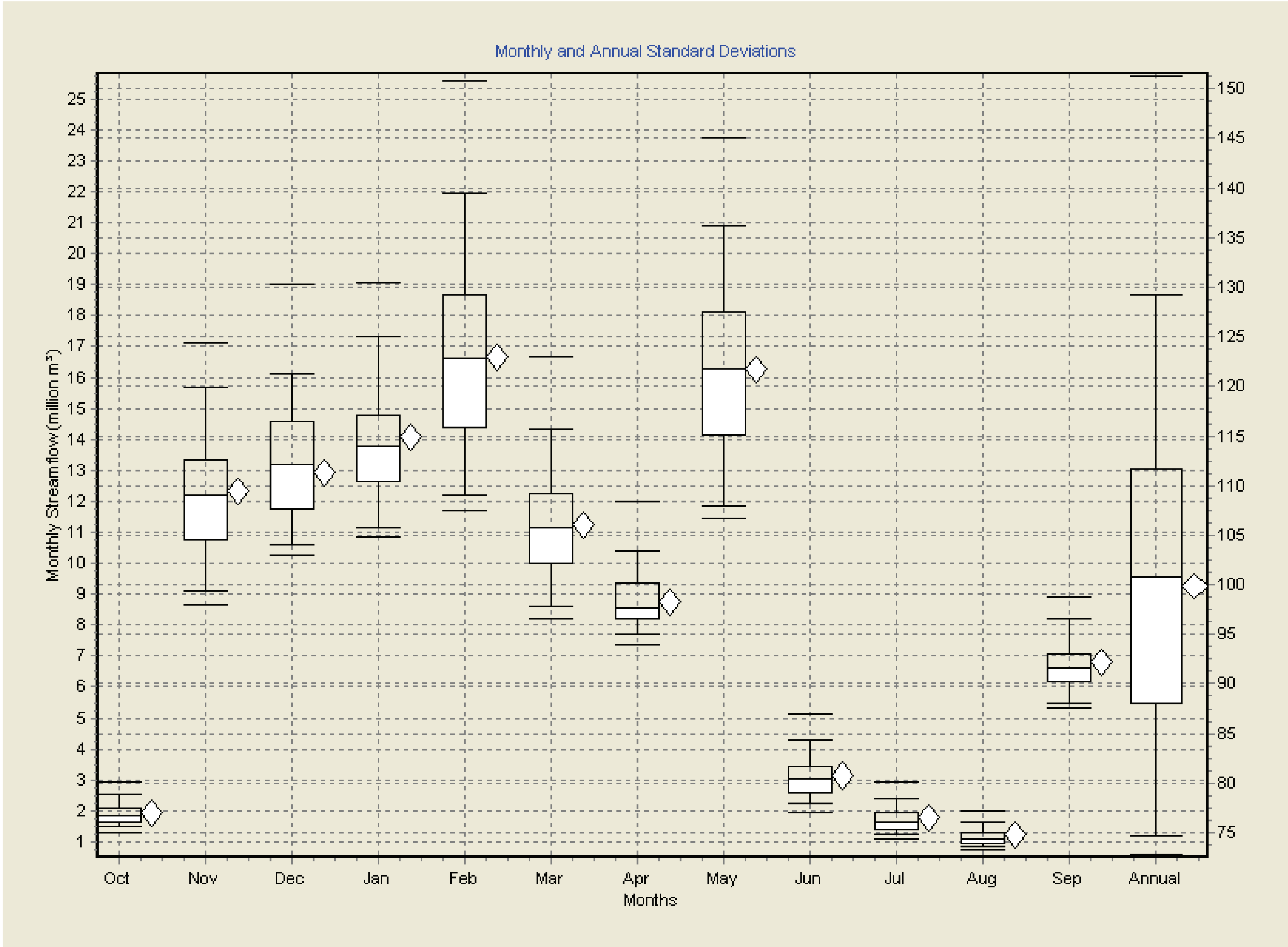

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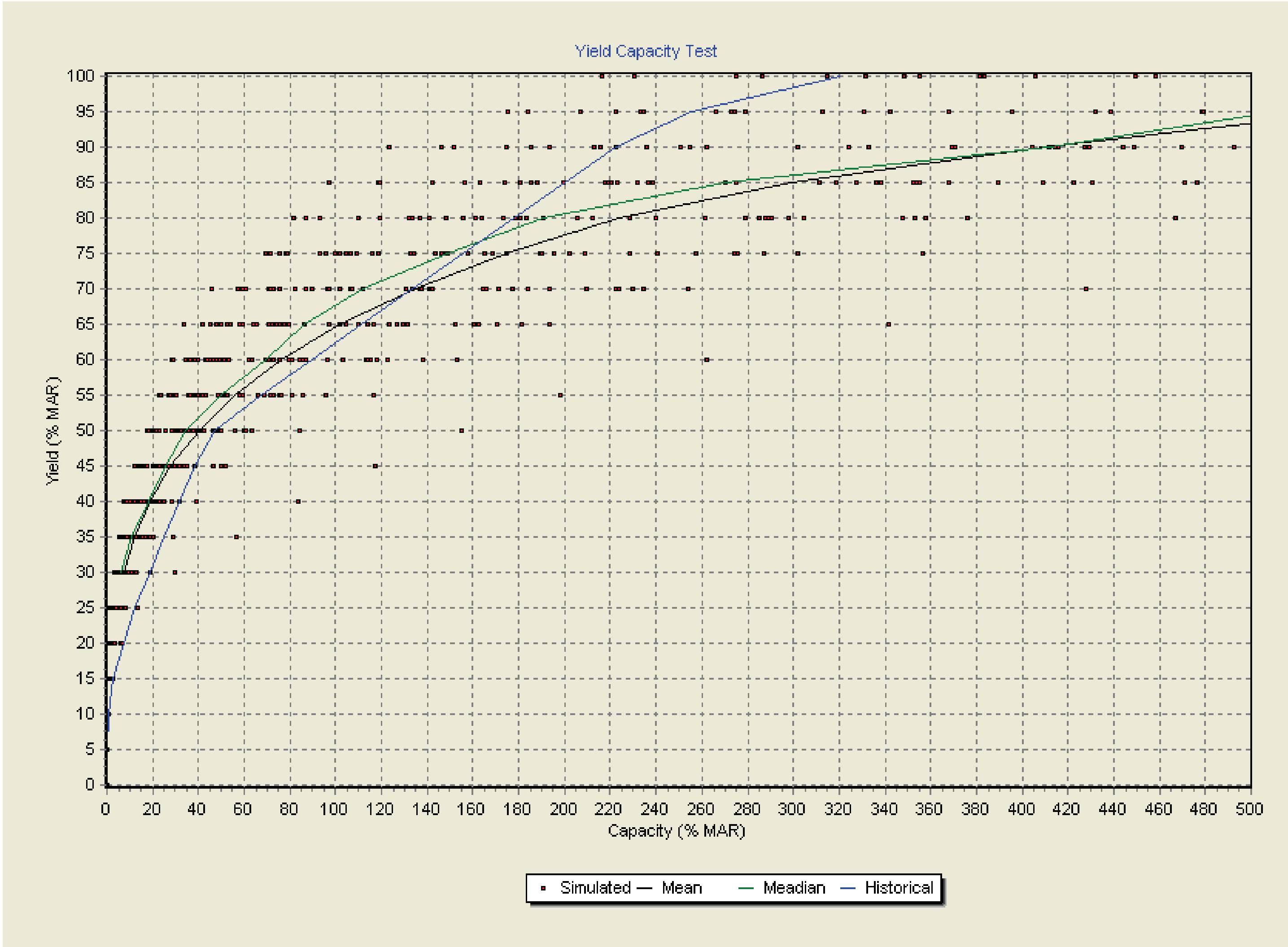

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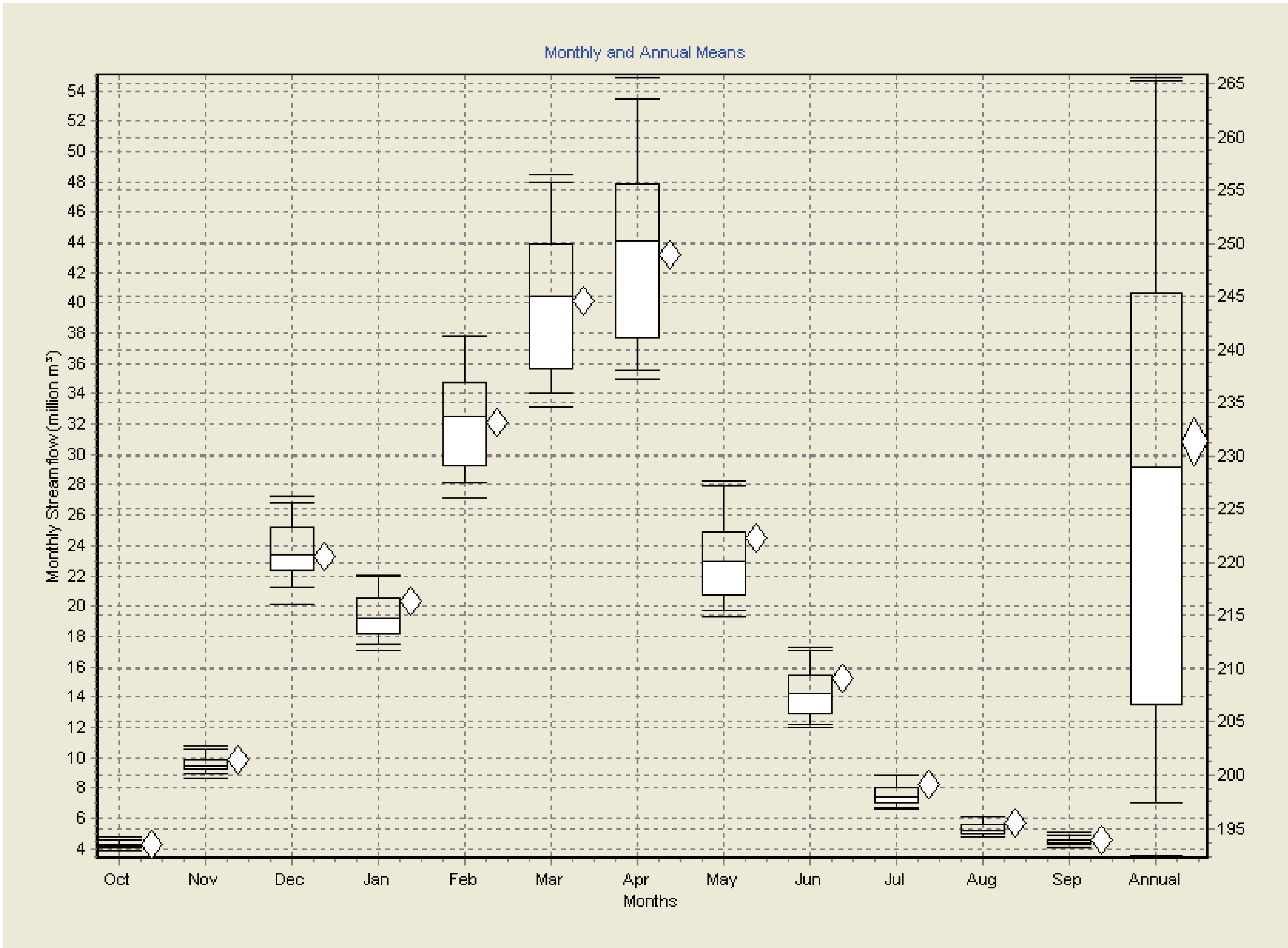

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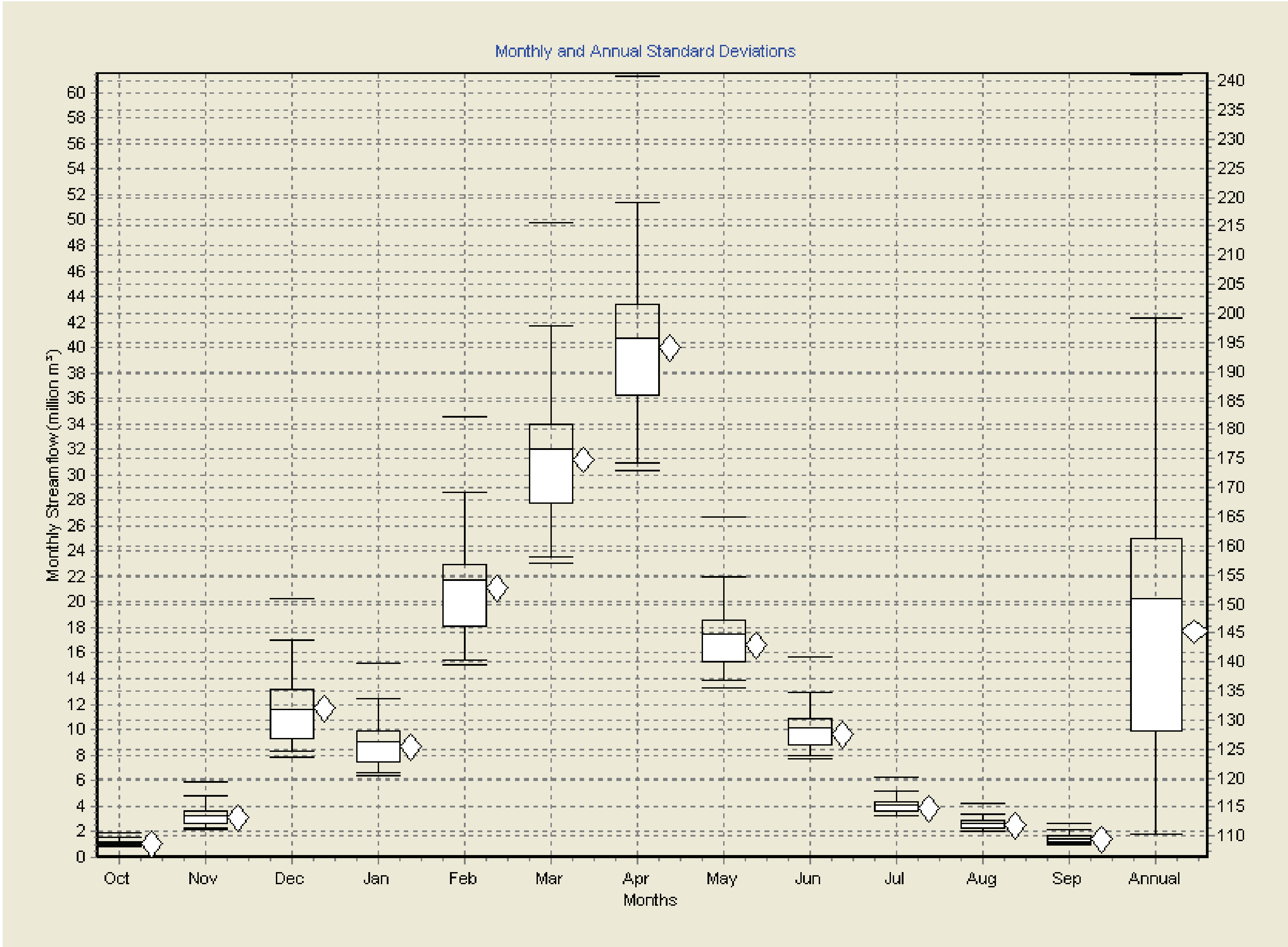

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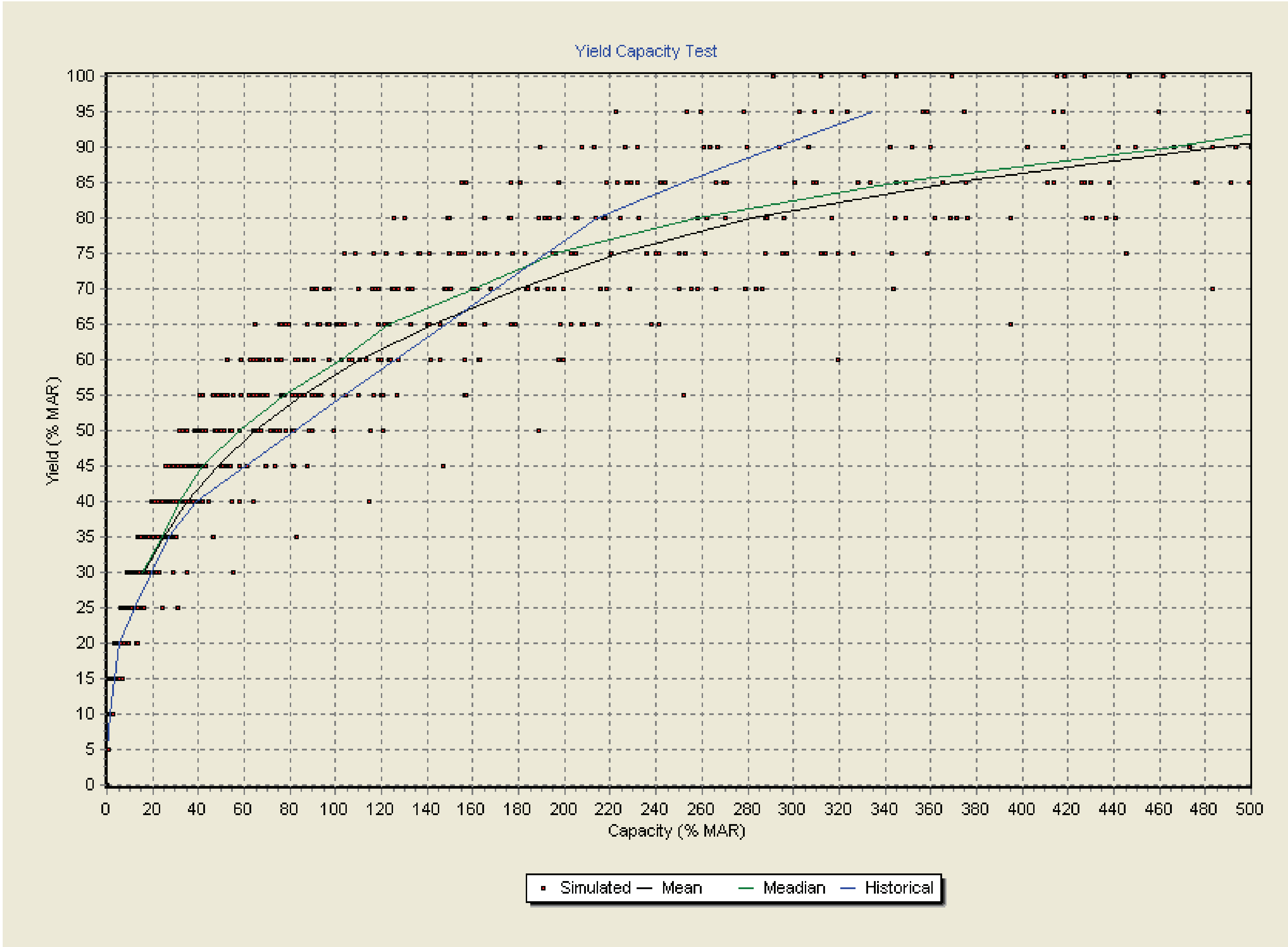

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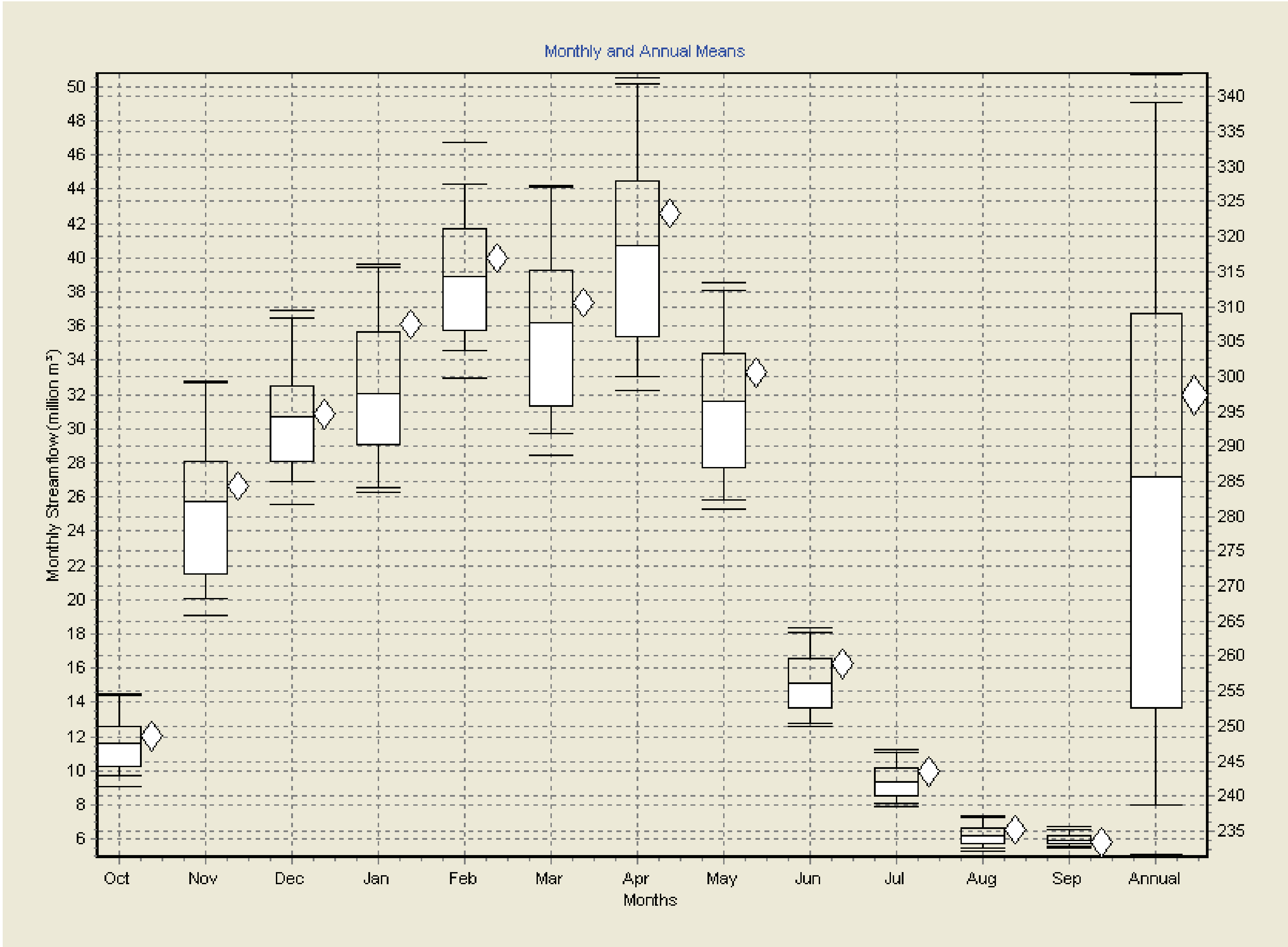

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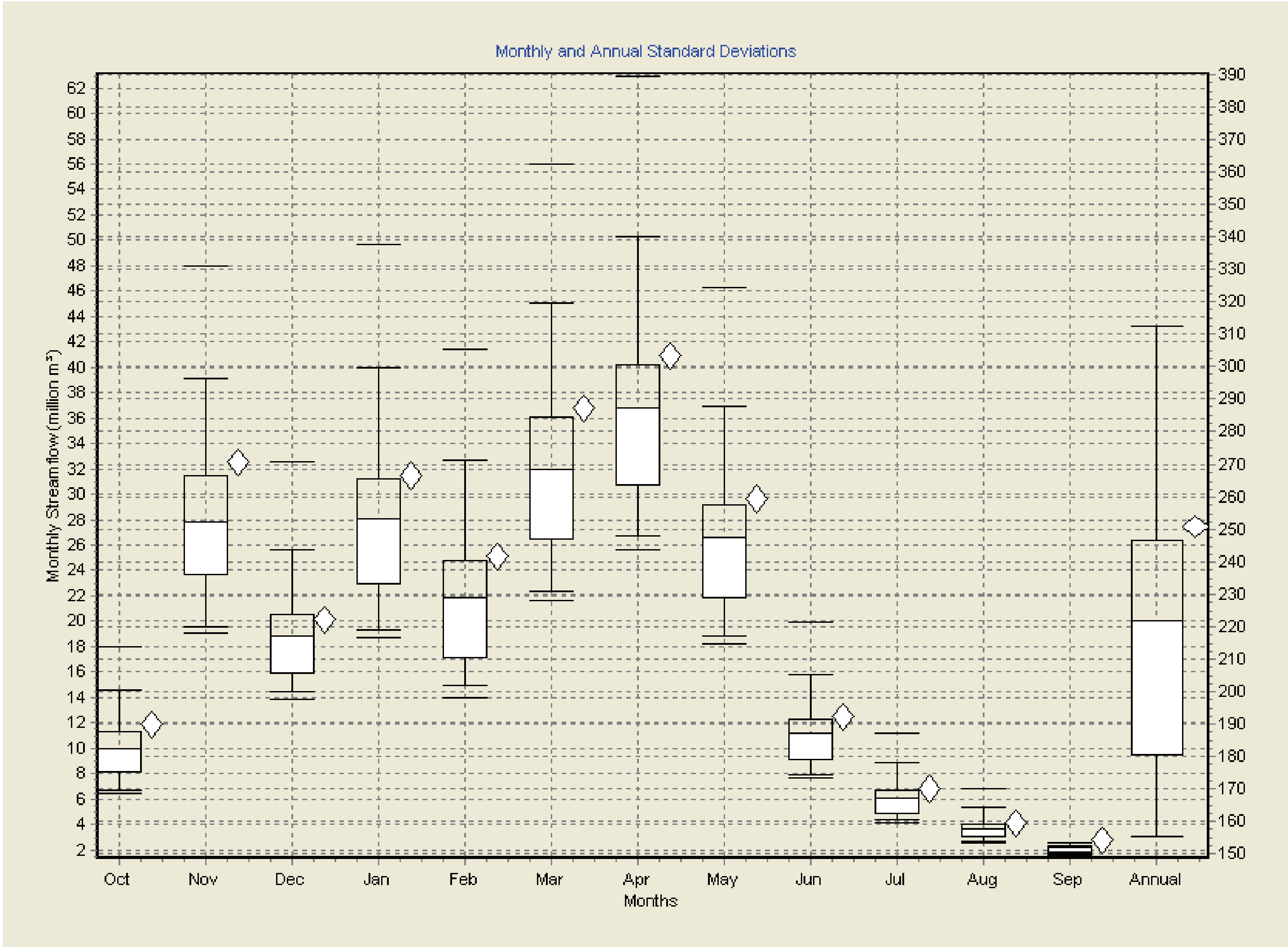

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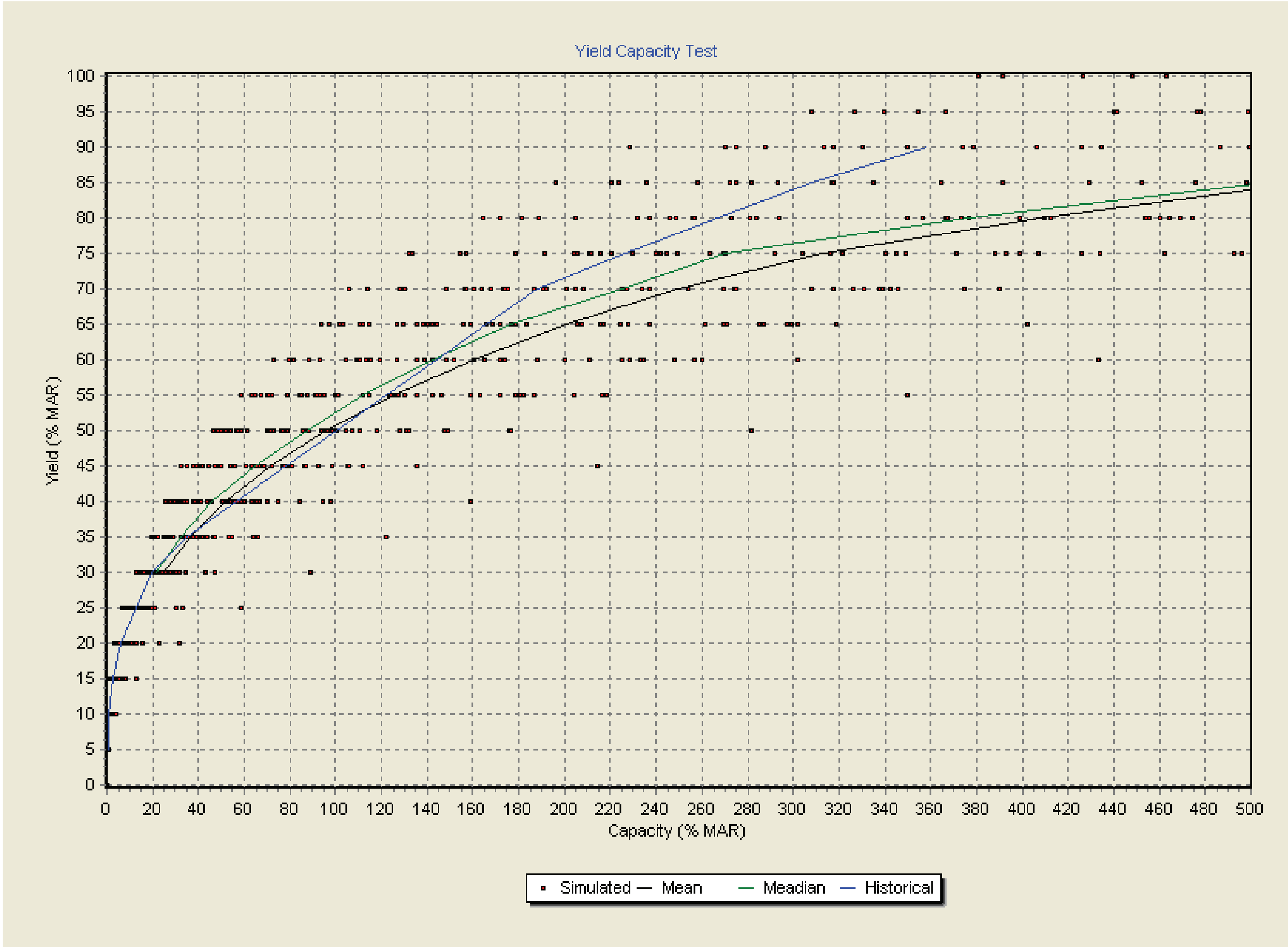
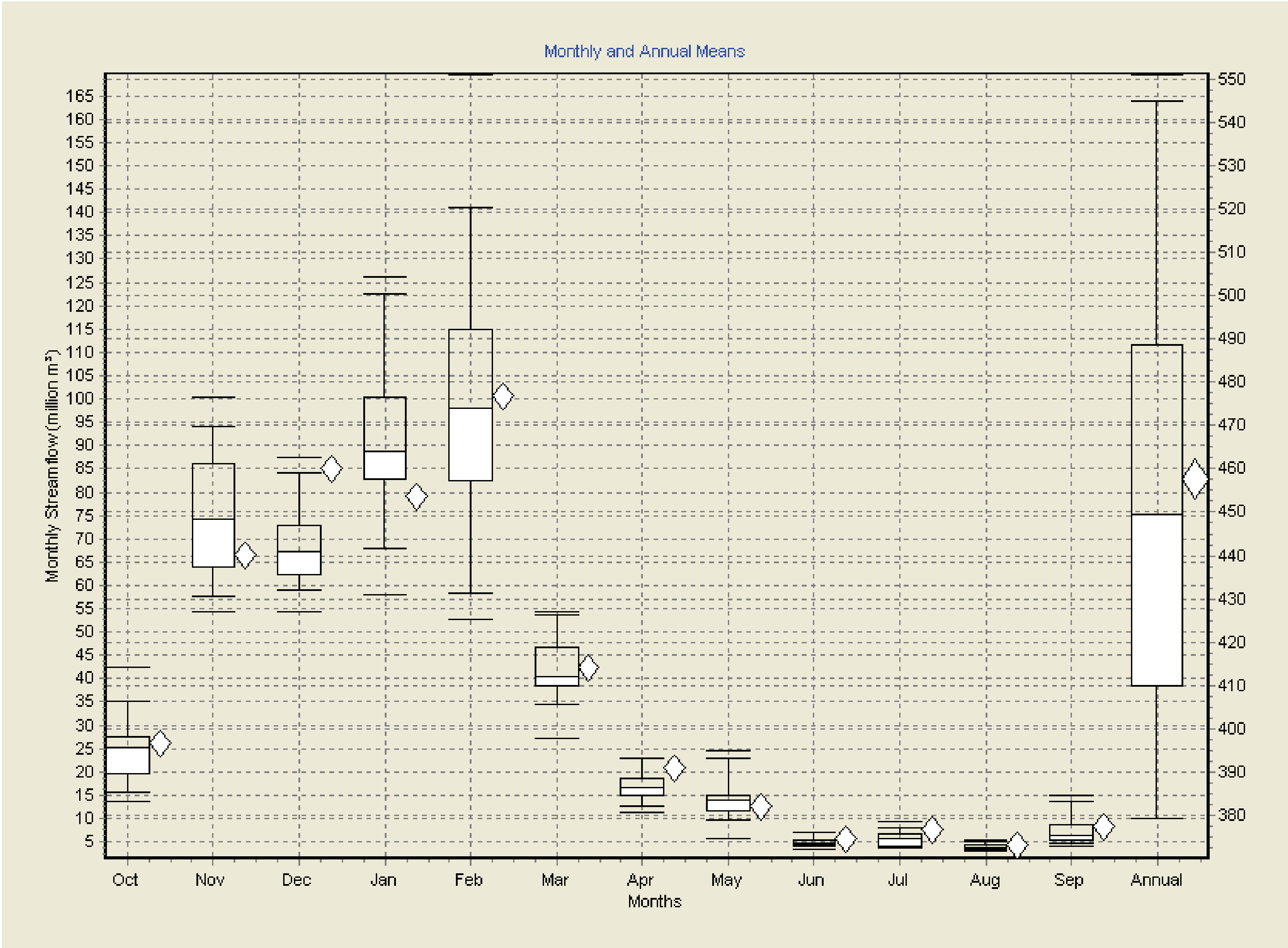
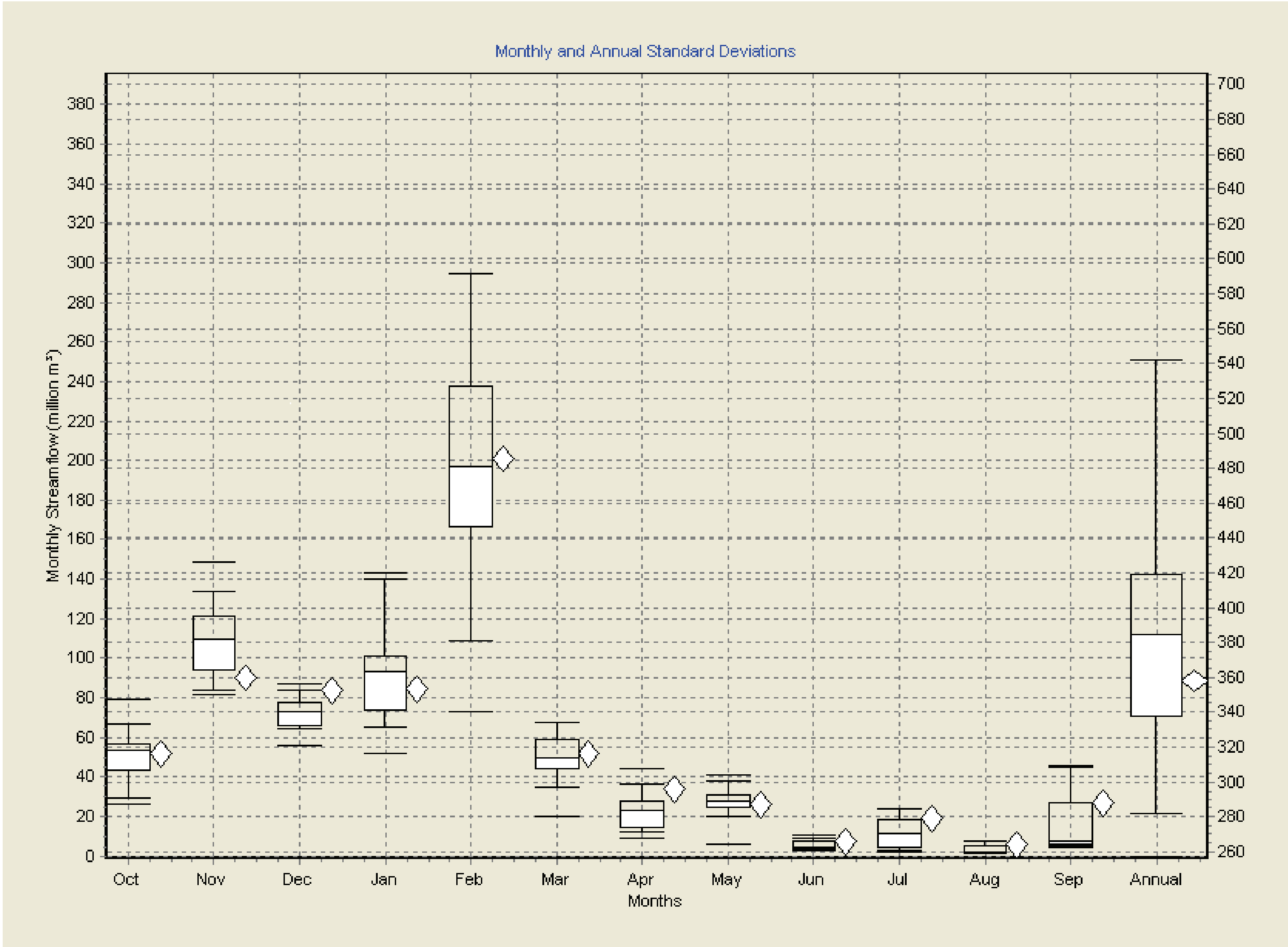


Appendix B.3: GROOTDRAAI DAM

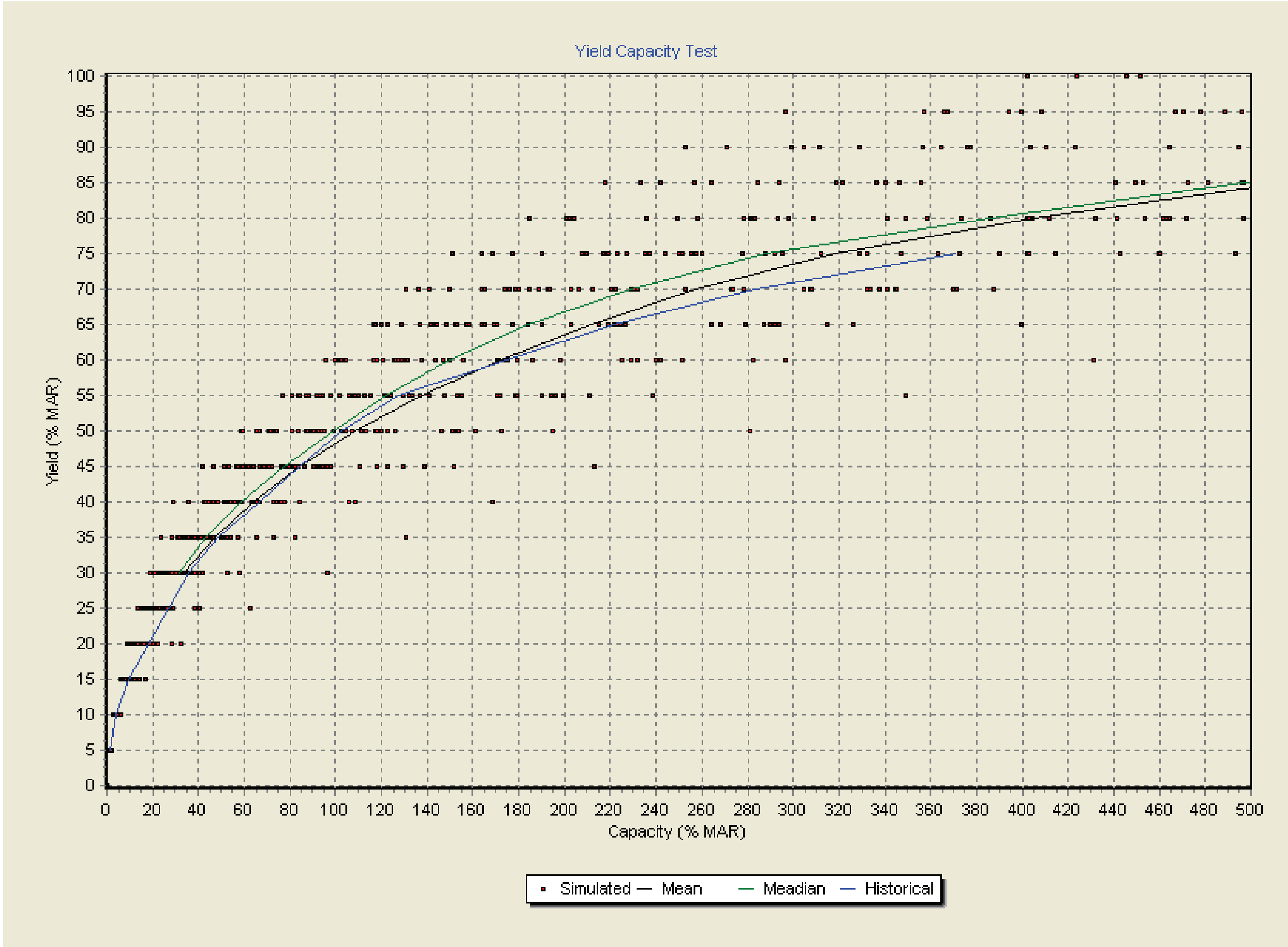
GROOTDRAAI DAM: Detailed Study long-term runoff sequence



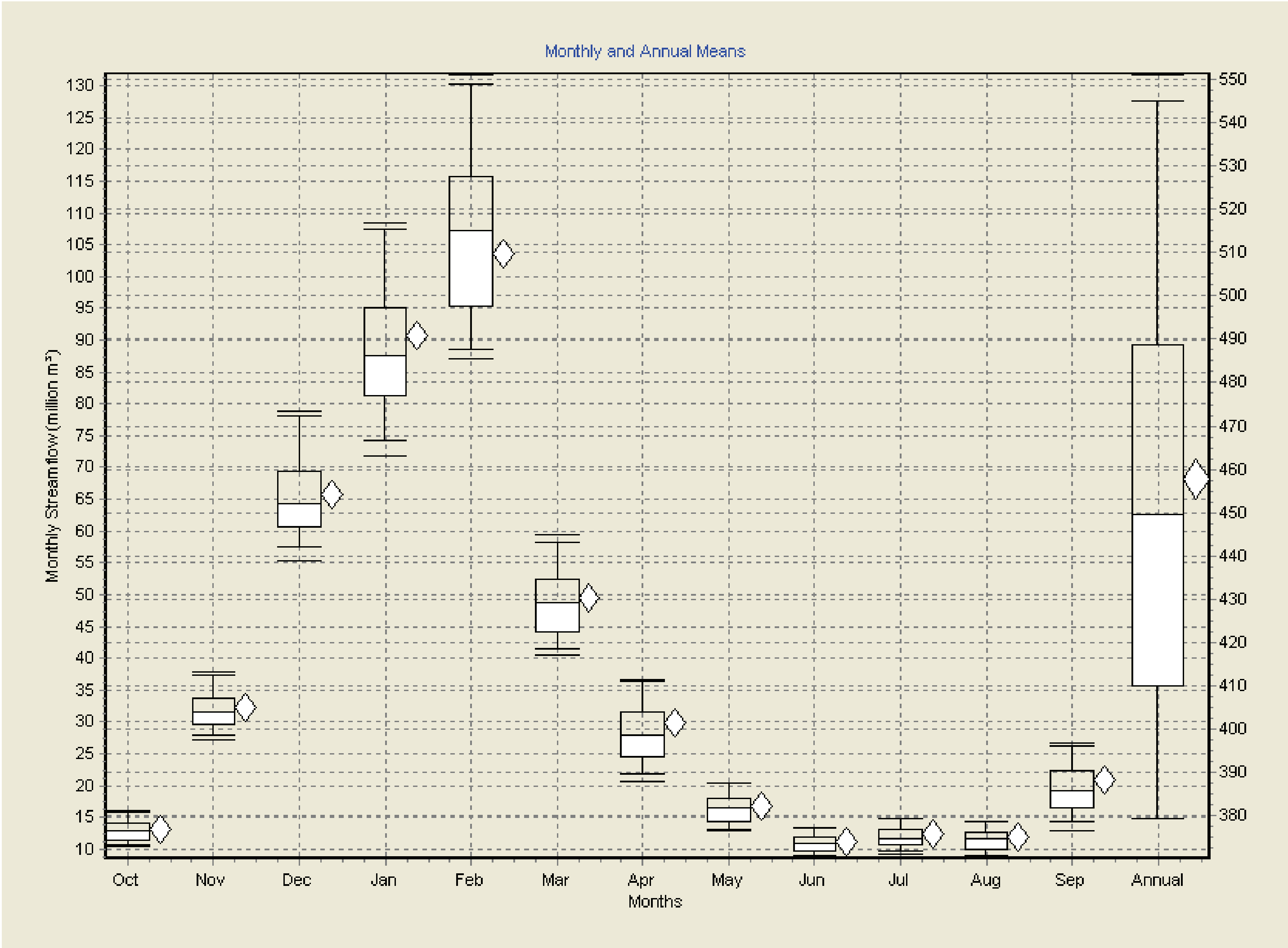
GROOTDRAAI DAM: Detailed Study long-term runoff sequence



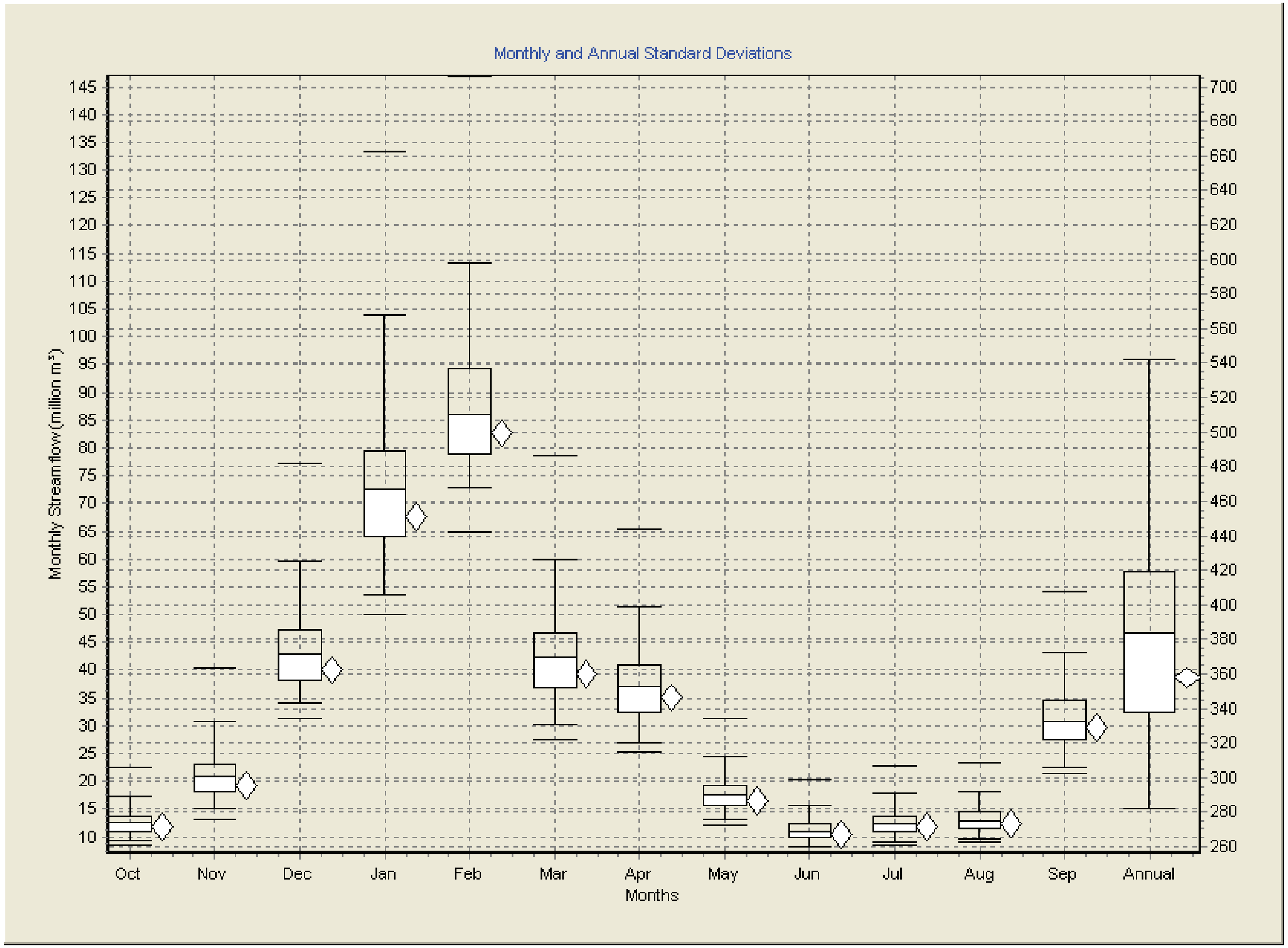
GROOTDRAAI DAM: Detailed Study long-term runoff sequence



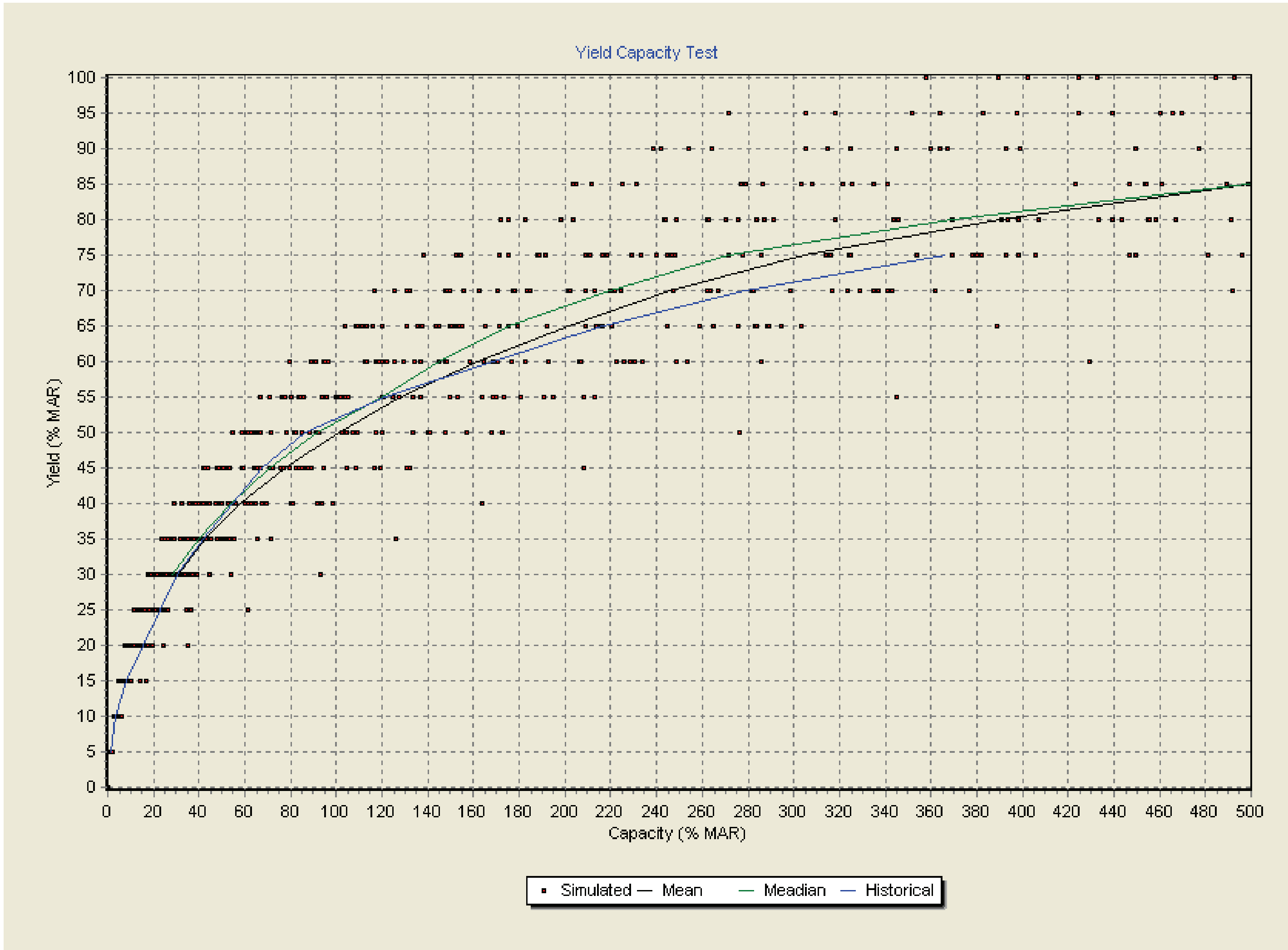
GROOTDRAAI DAM: ECHAM 5: Present



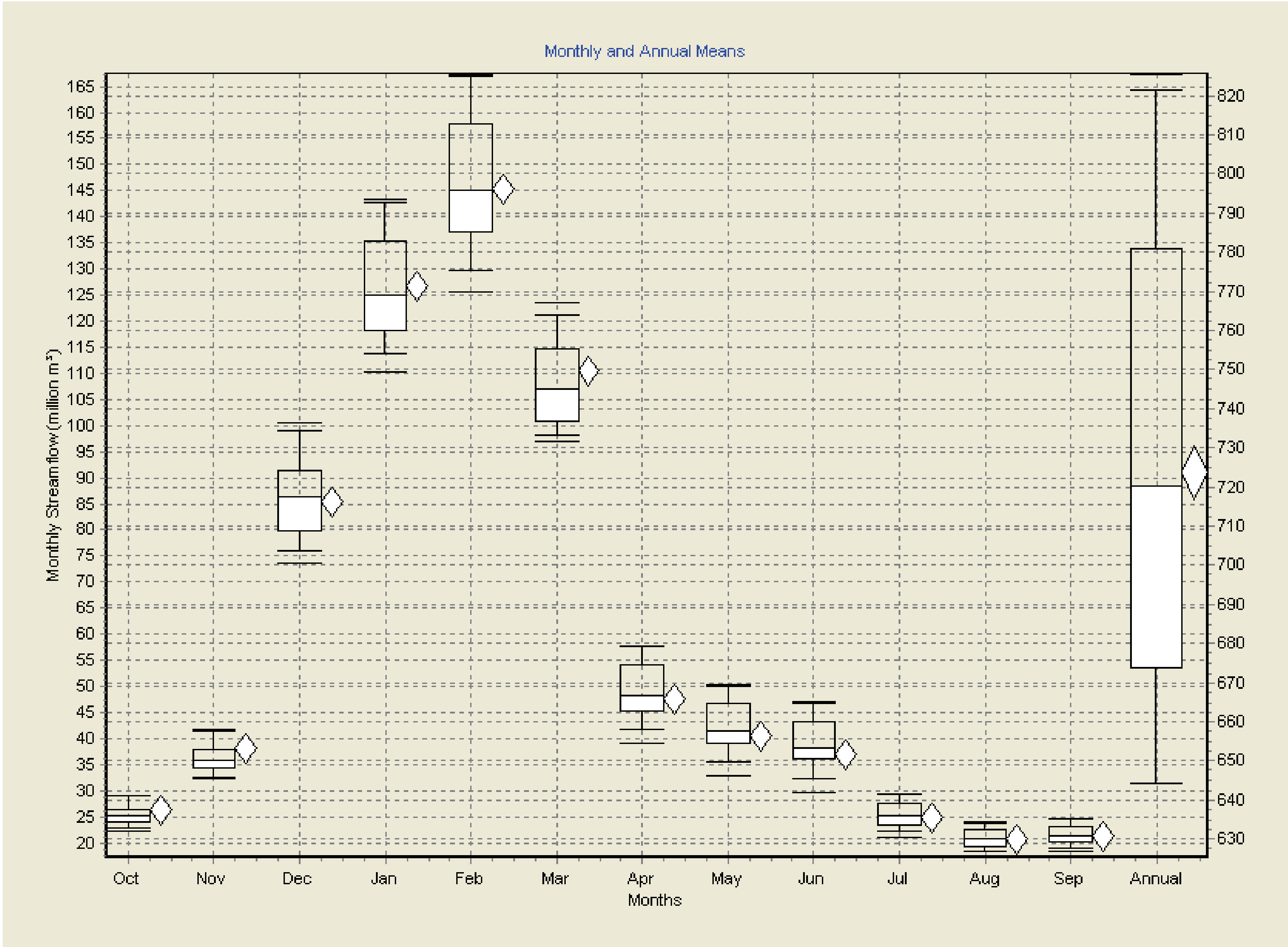
GROOTDRAAI DAM: ECHAM 5: Present



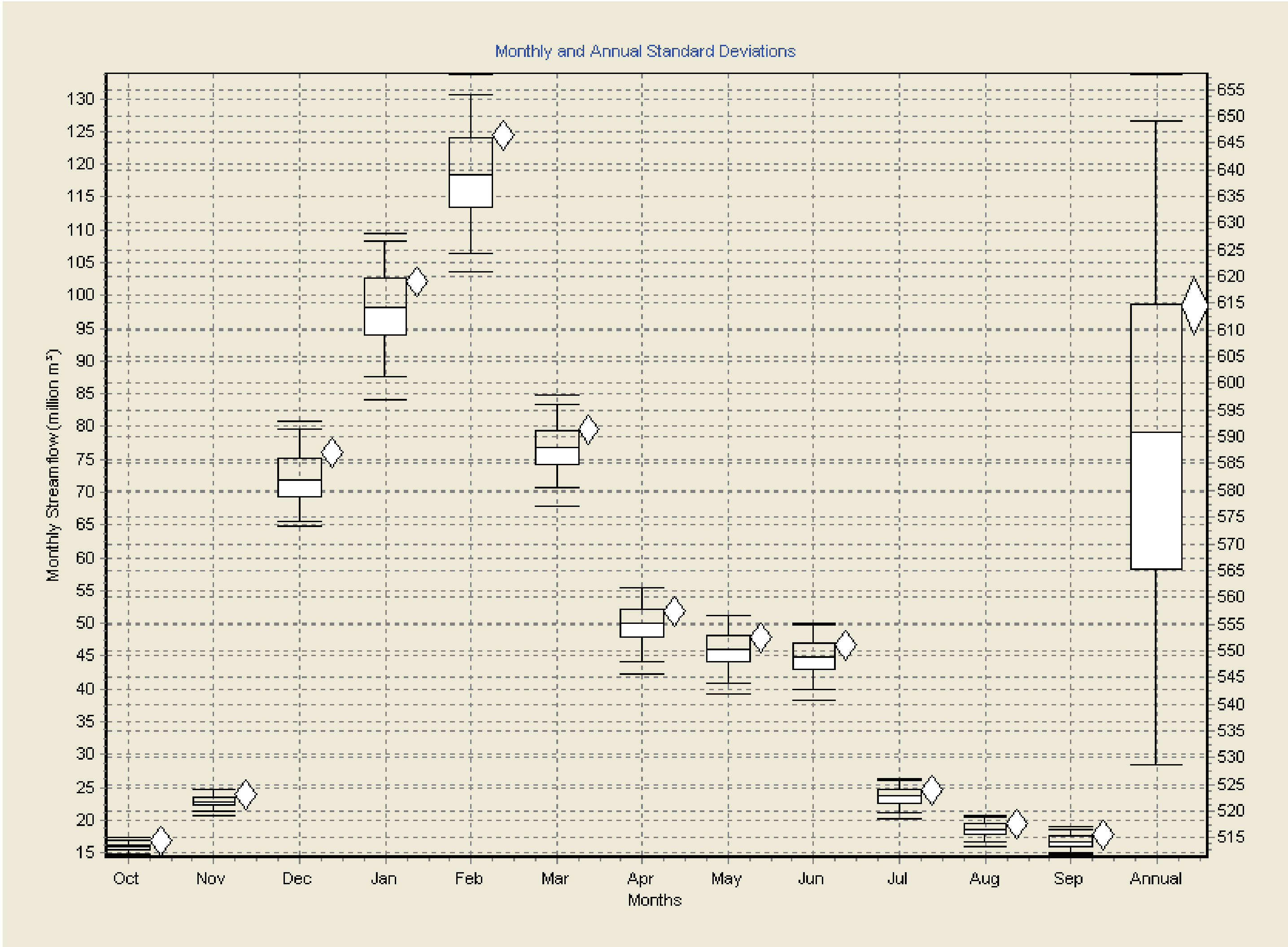
GROOTDRAAI DAM: ECHAM 5: Present



GROOTDRAAI DAM: ECHAM 5: Intermediate Future



GROOTDRAAI DAM: ECHAM 5: Intermediate Future



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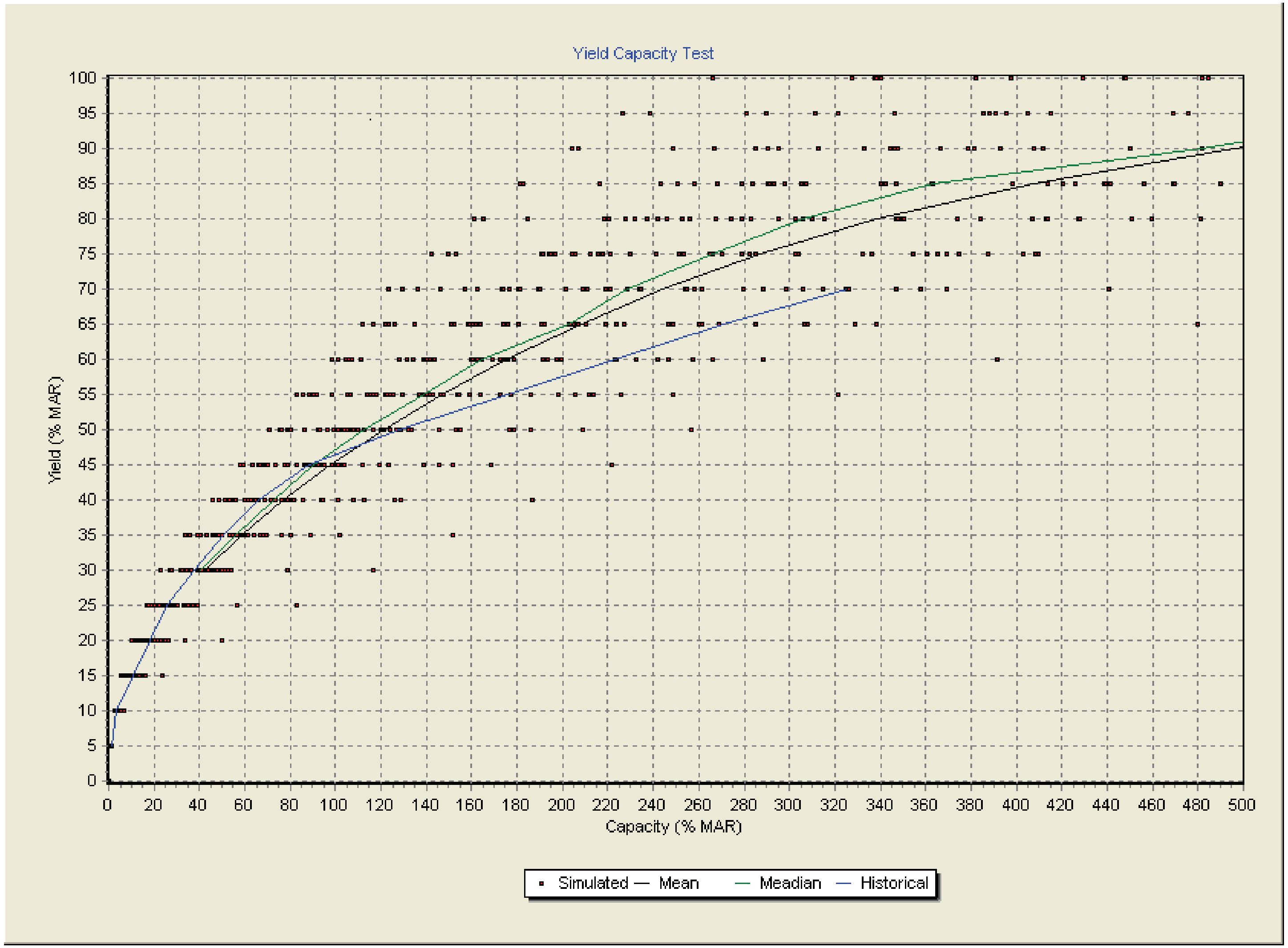
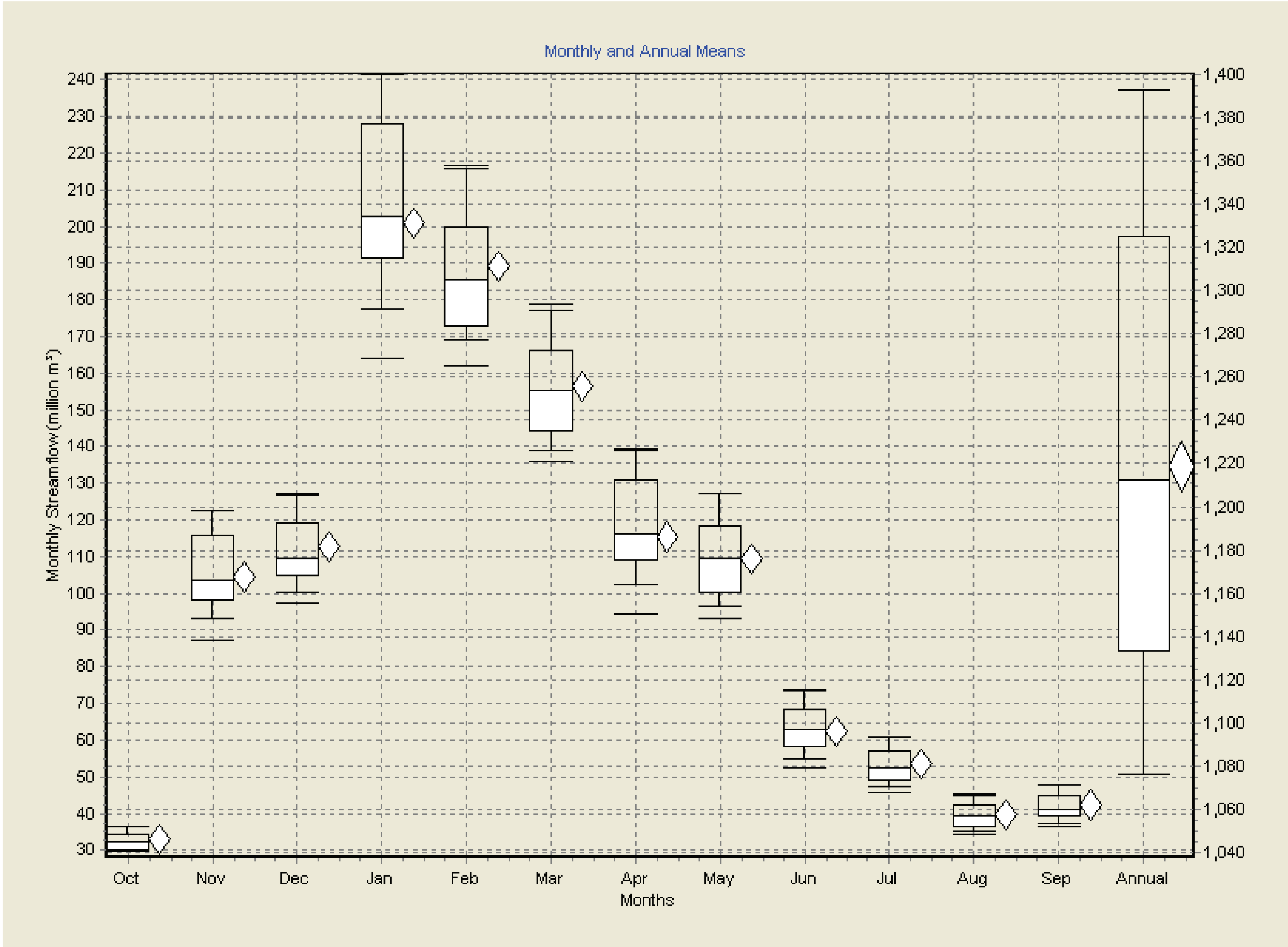
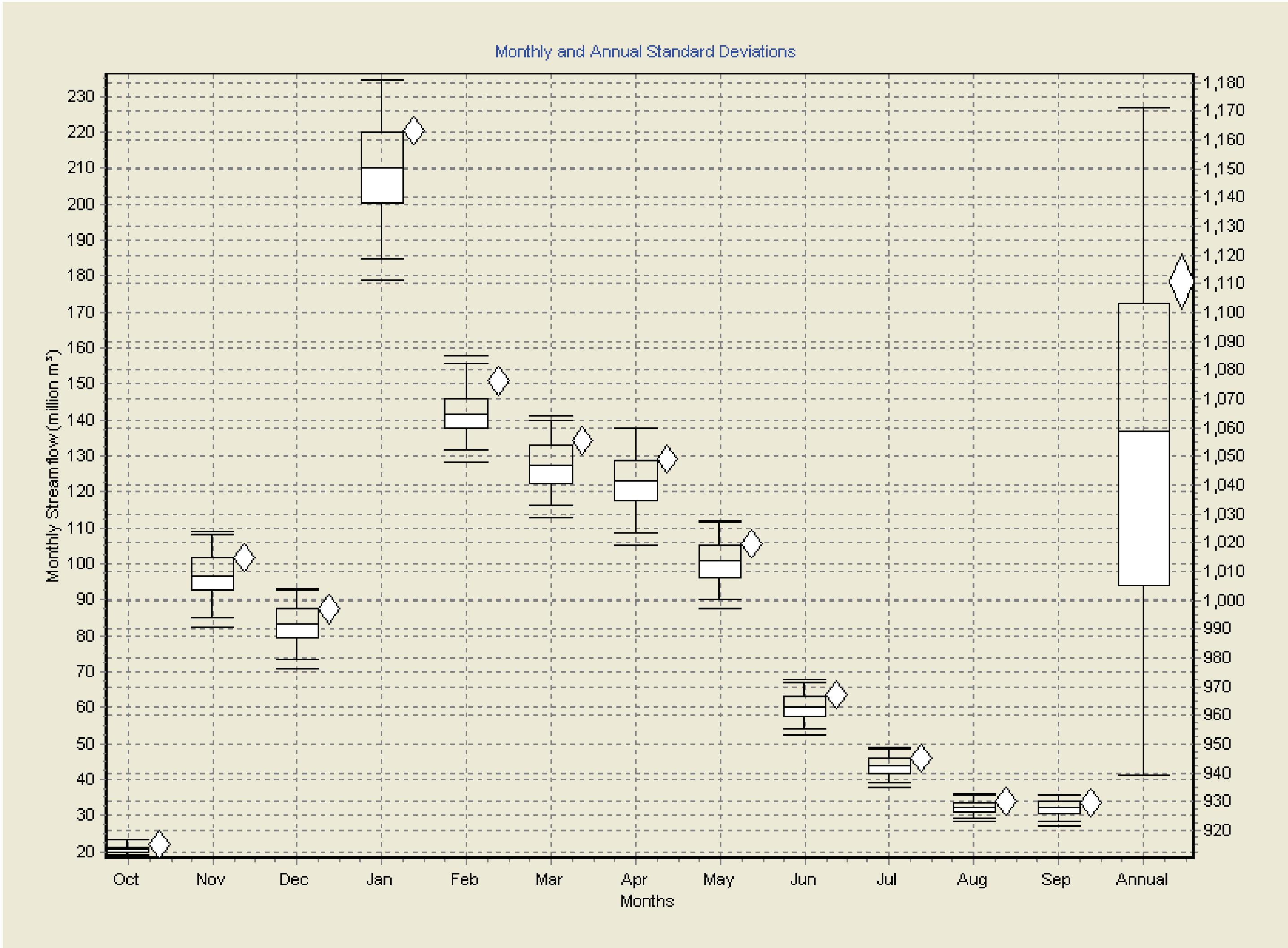


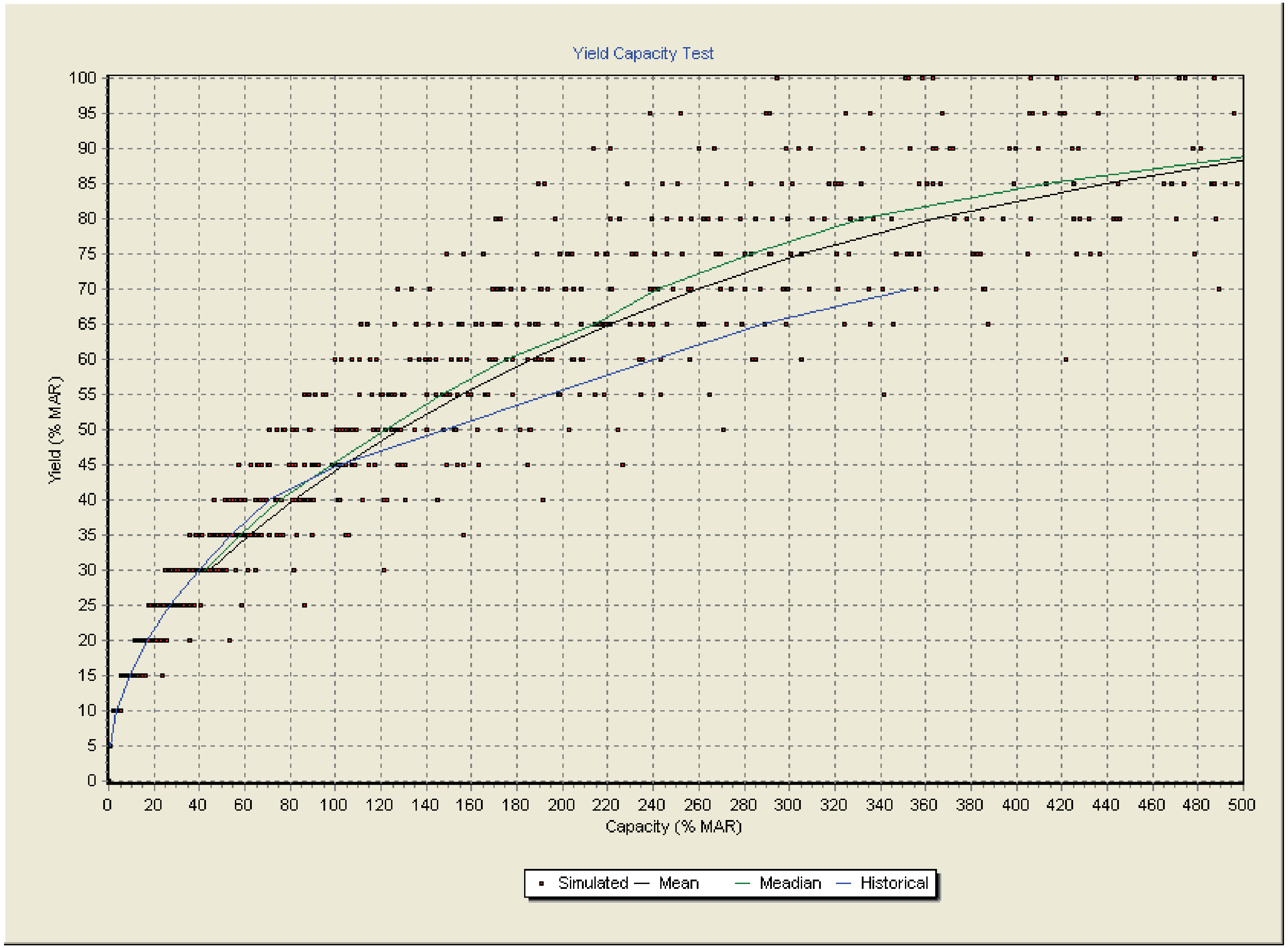
GROOTDRAAI DAM: ECHAM 5: Distant Future



GROOTDRAAI DAM: ECHAM 5: Distant Future



GROOTDRAAI DAM: ECHAM 5: Distant Future



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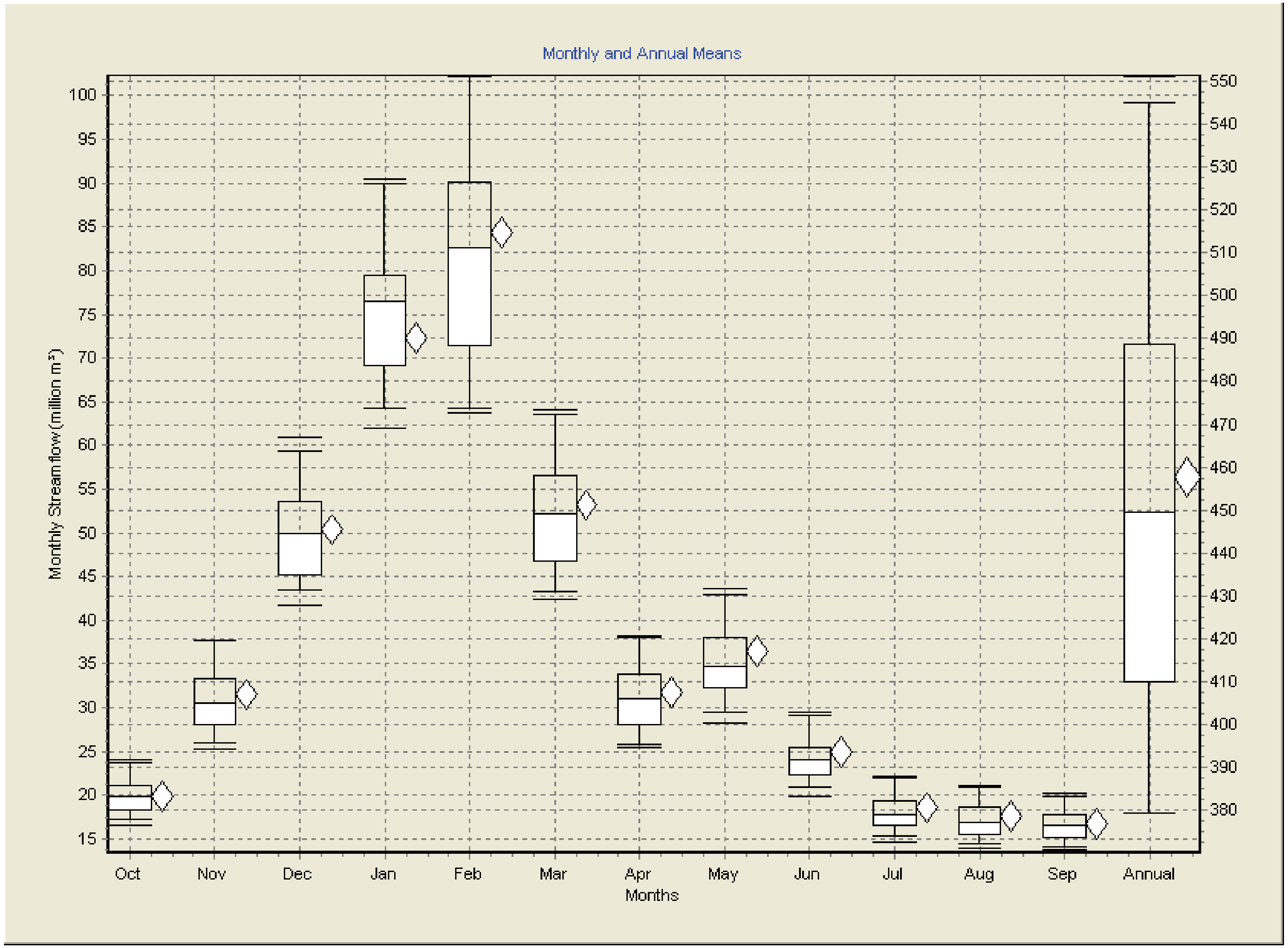
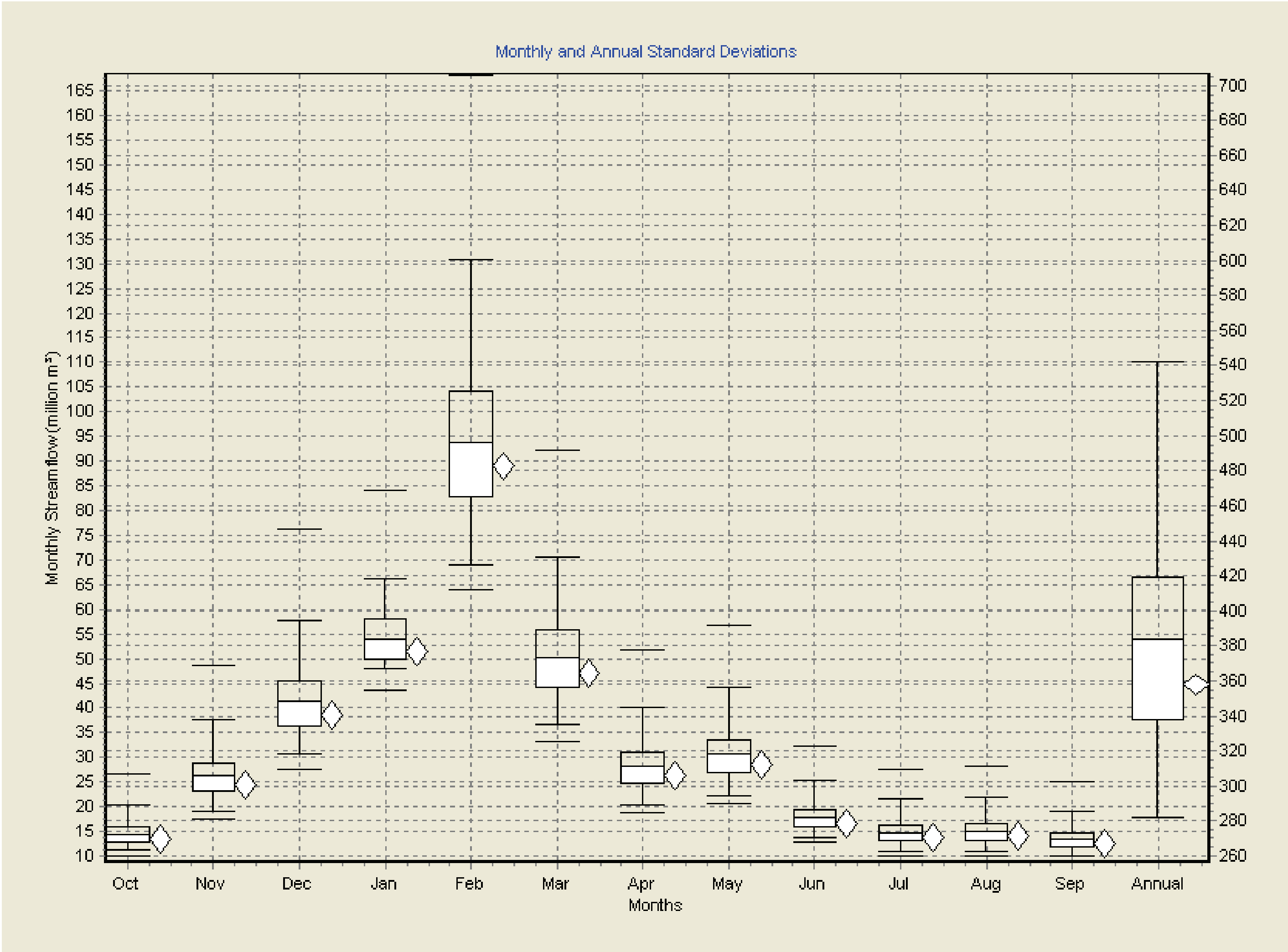


GROOTDRAAI DAM: GISS-ER: Present



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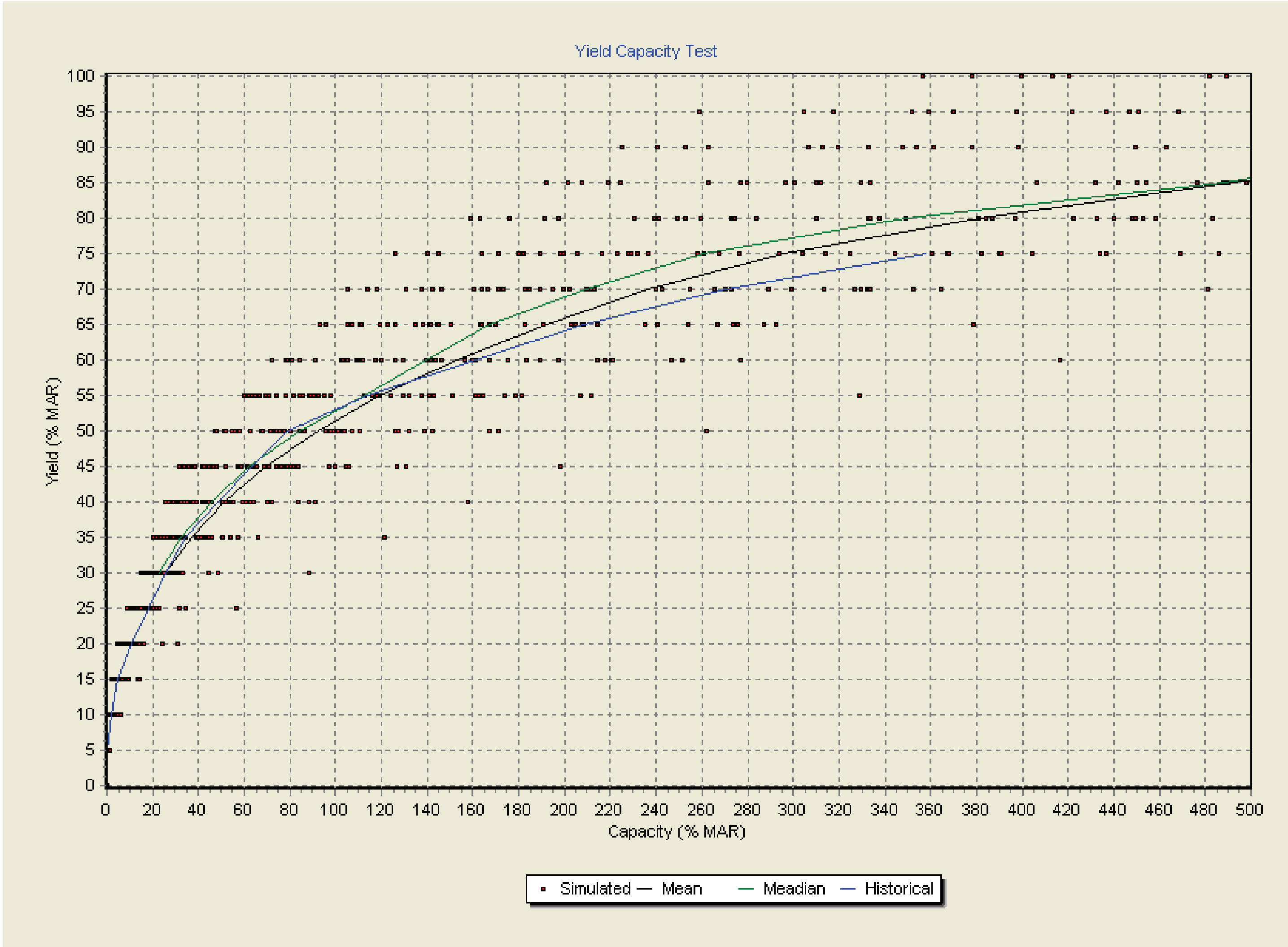
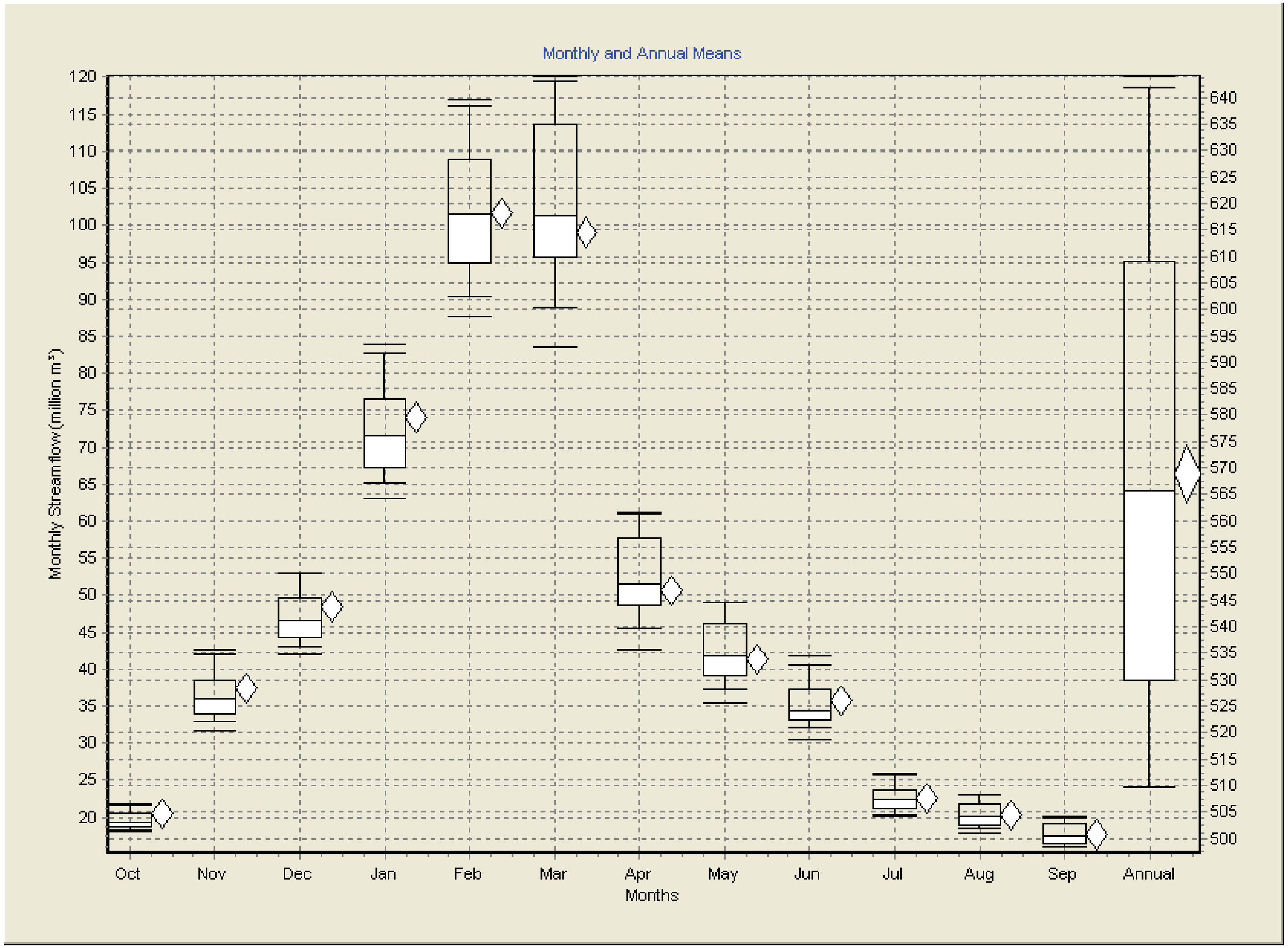
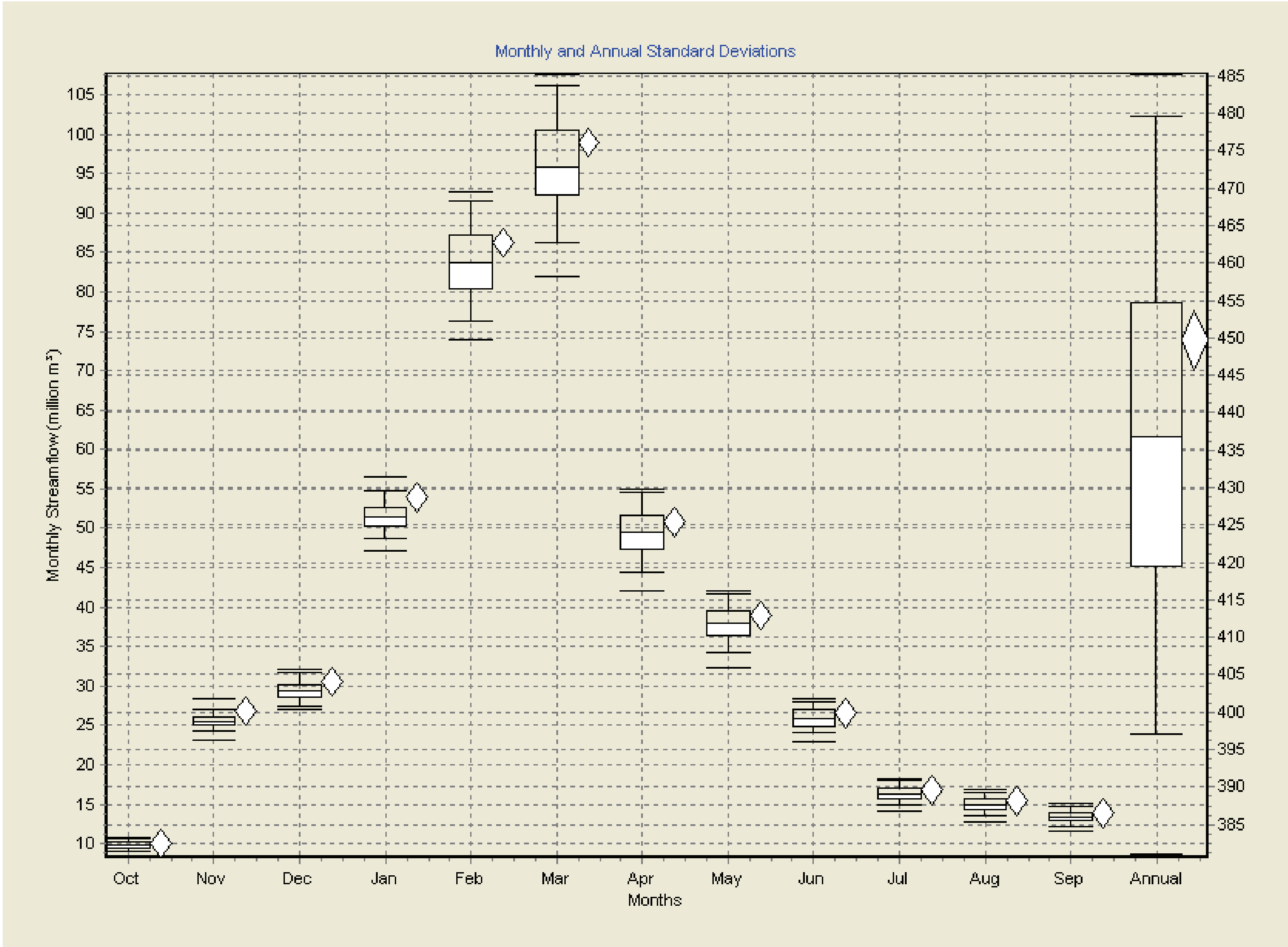


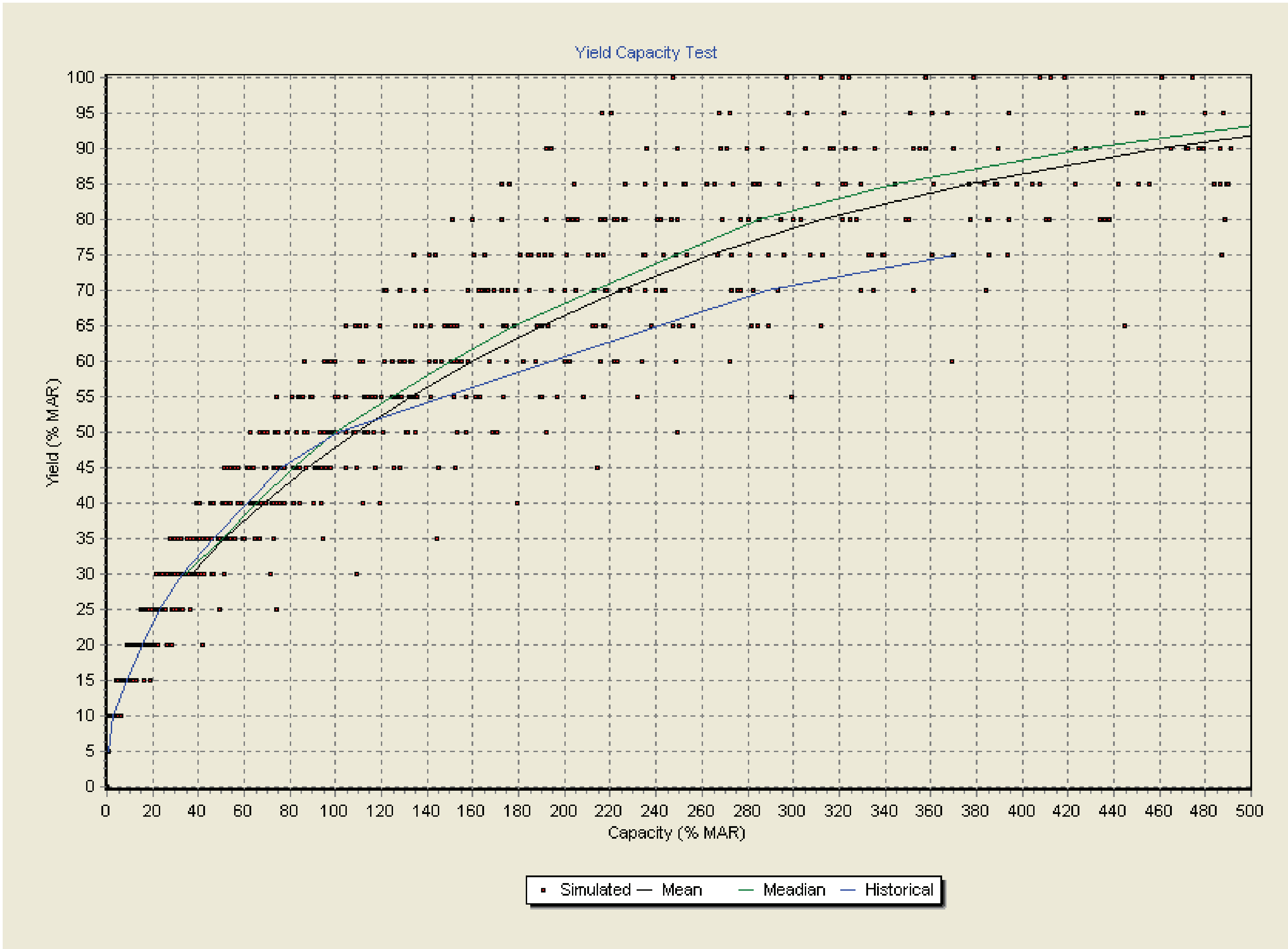
GROOTDRAAI DAM: GISS-ER: Intermediate Future



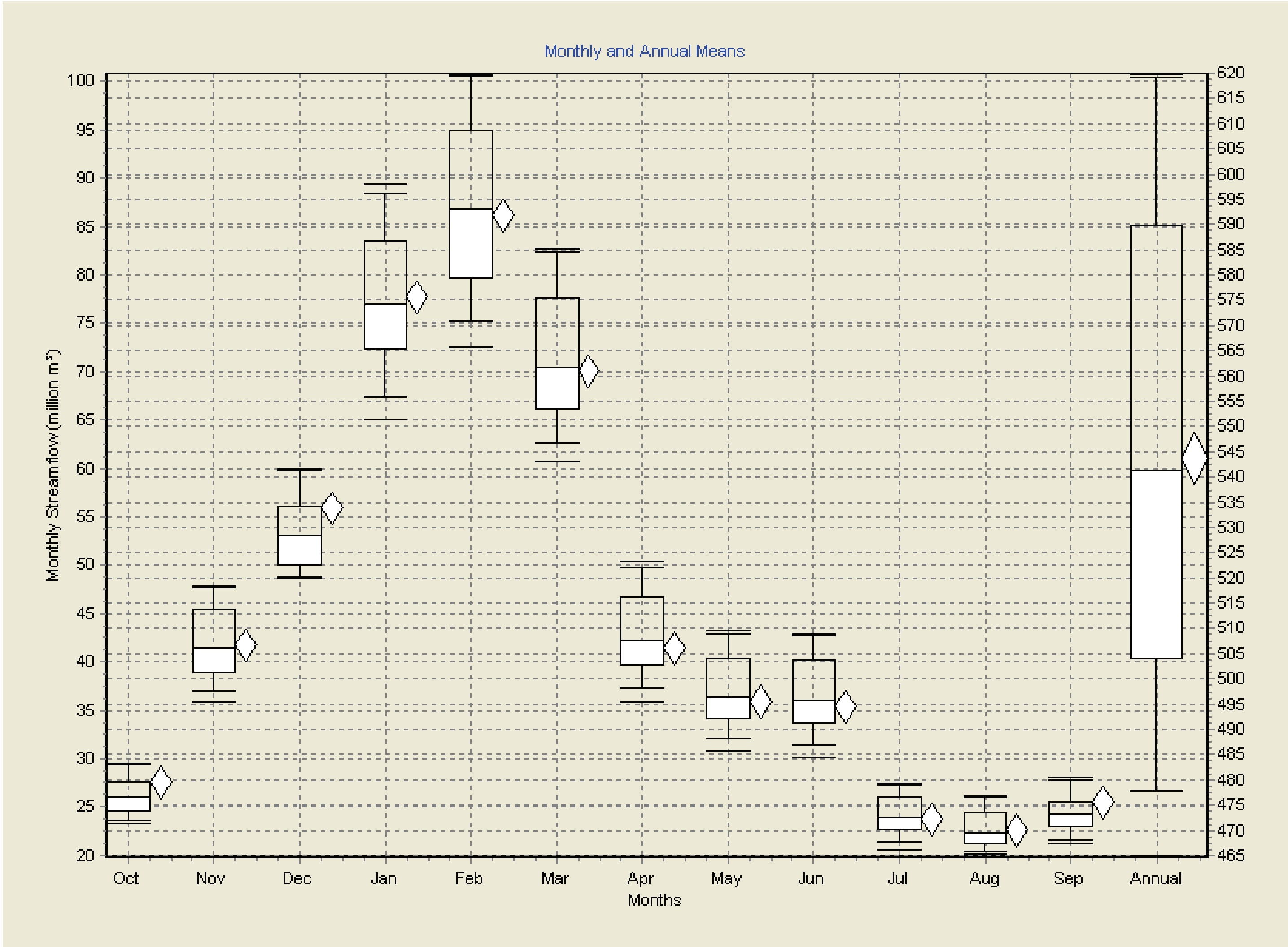
GROOTDRAAI DAM: GISS-ER: Intermediate Future



GROOTDRAAI DAM: GISS-ER: Intermediate Future



GROOTDRAAI DAM: GISS-ER: Distant Future



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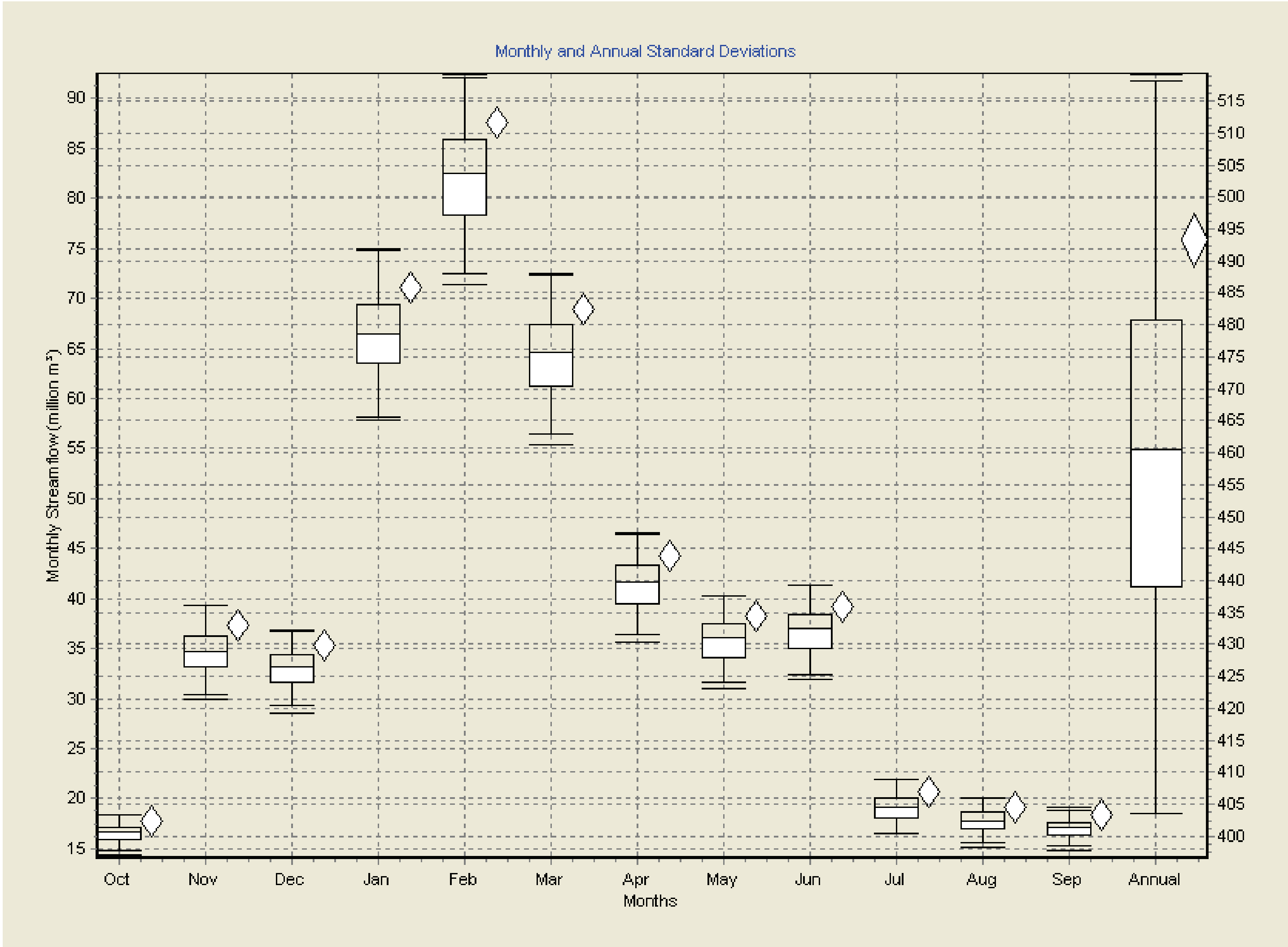
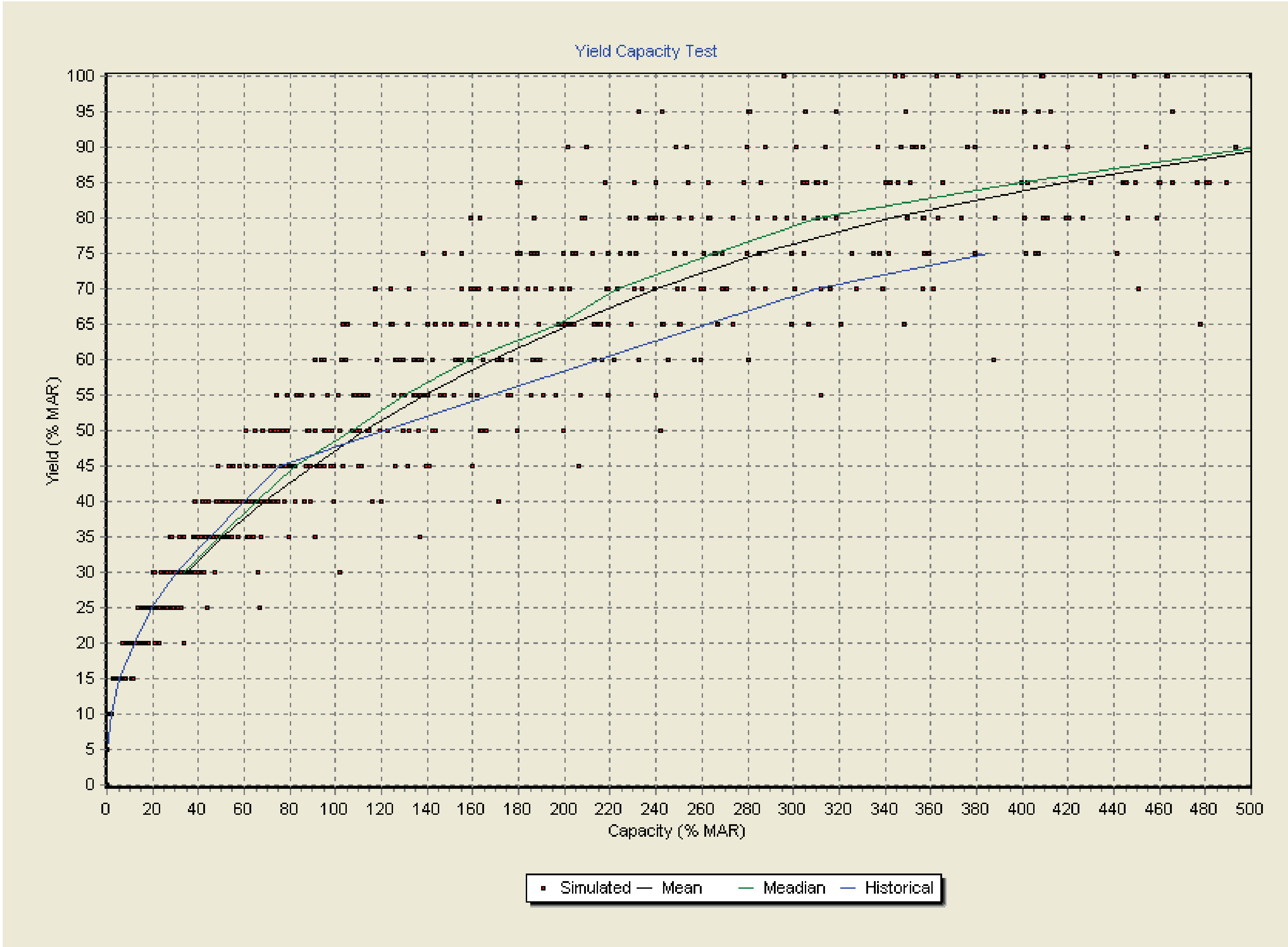
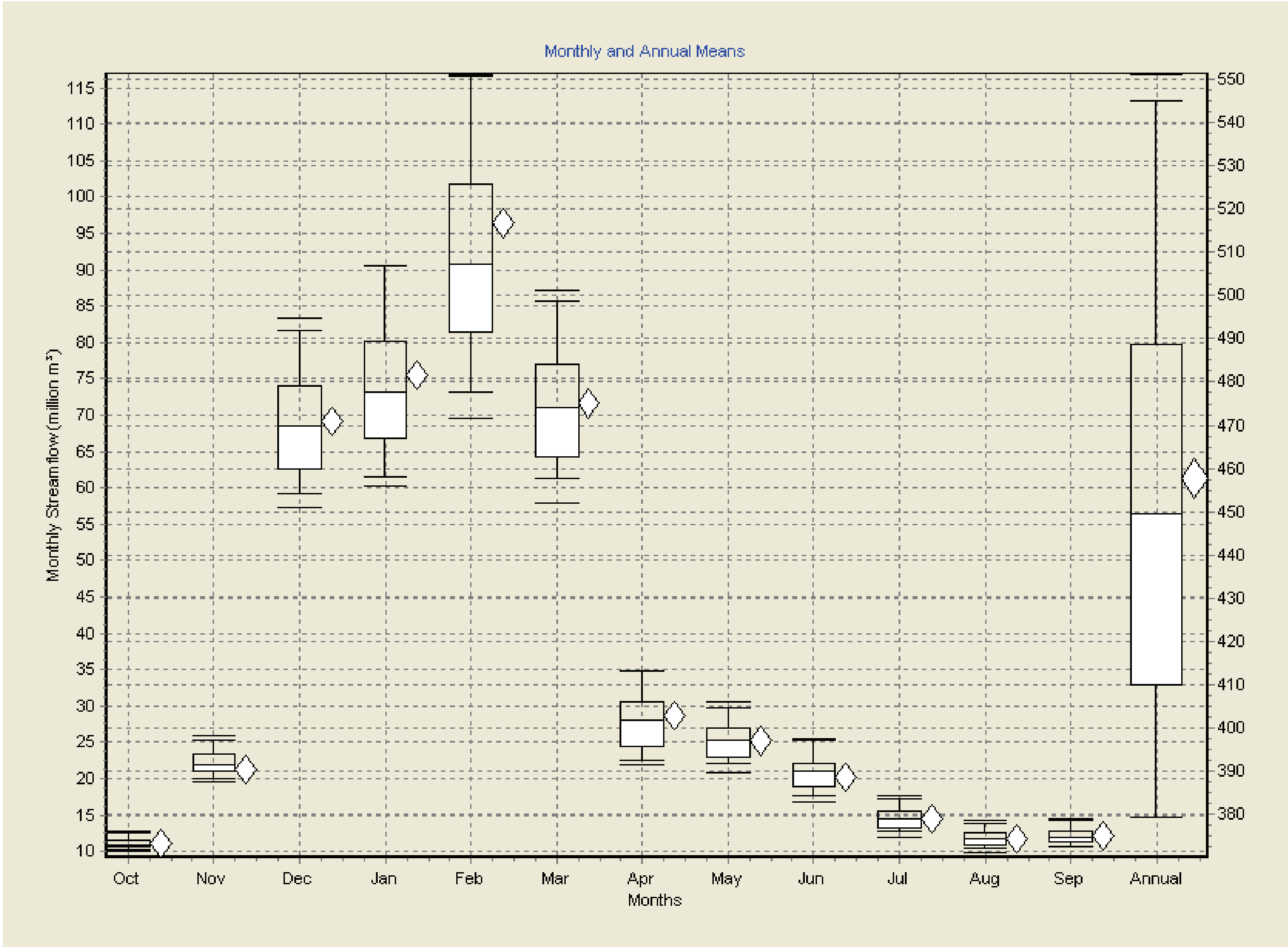


GROOTDRAAI DAM: GISS-ER: Distant Future



GROOTDRAAI DAM: IPSL-CM4: Present



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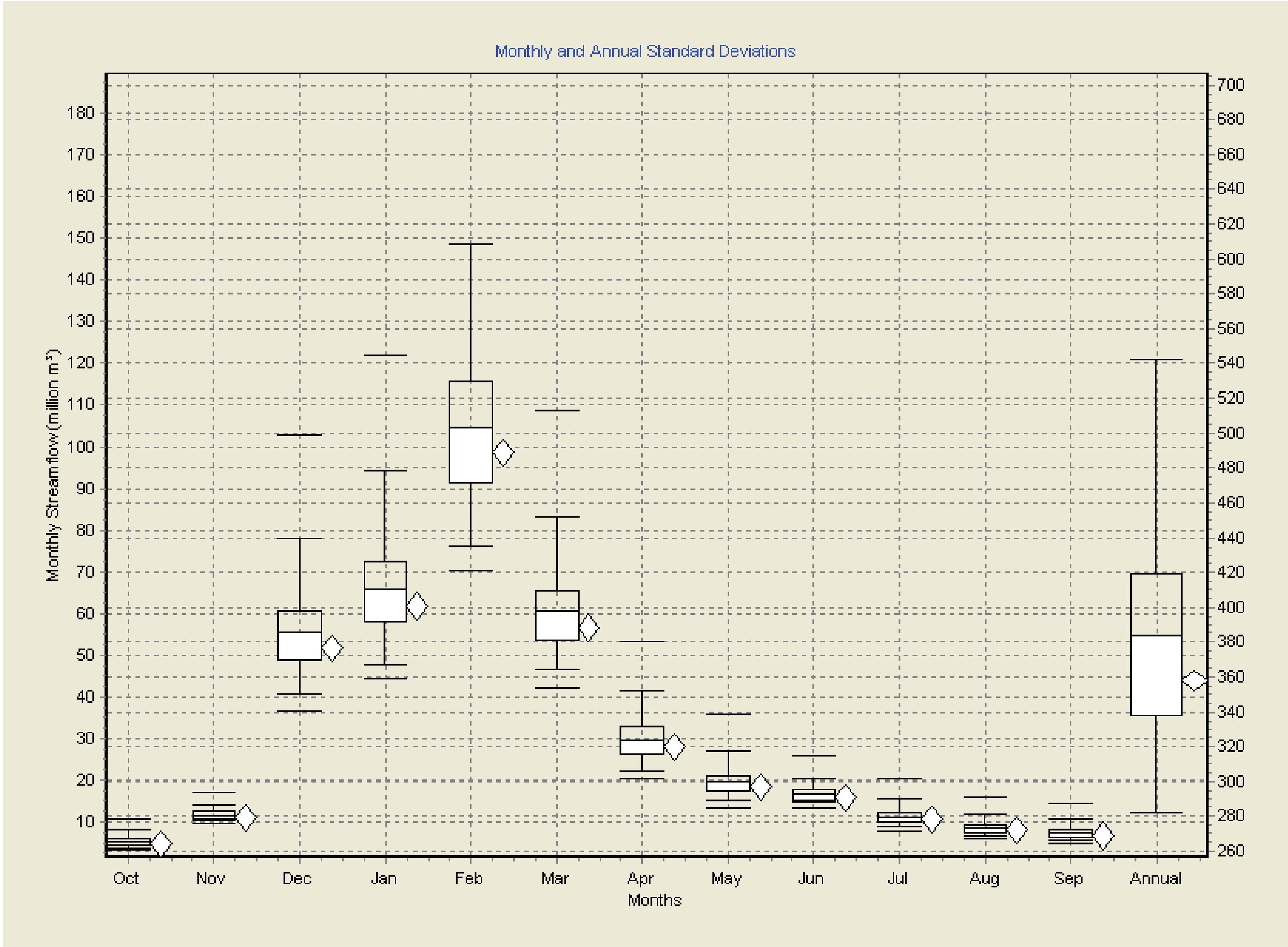
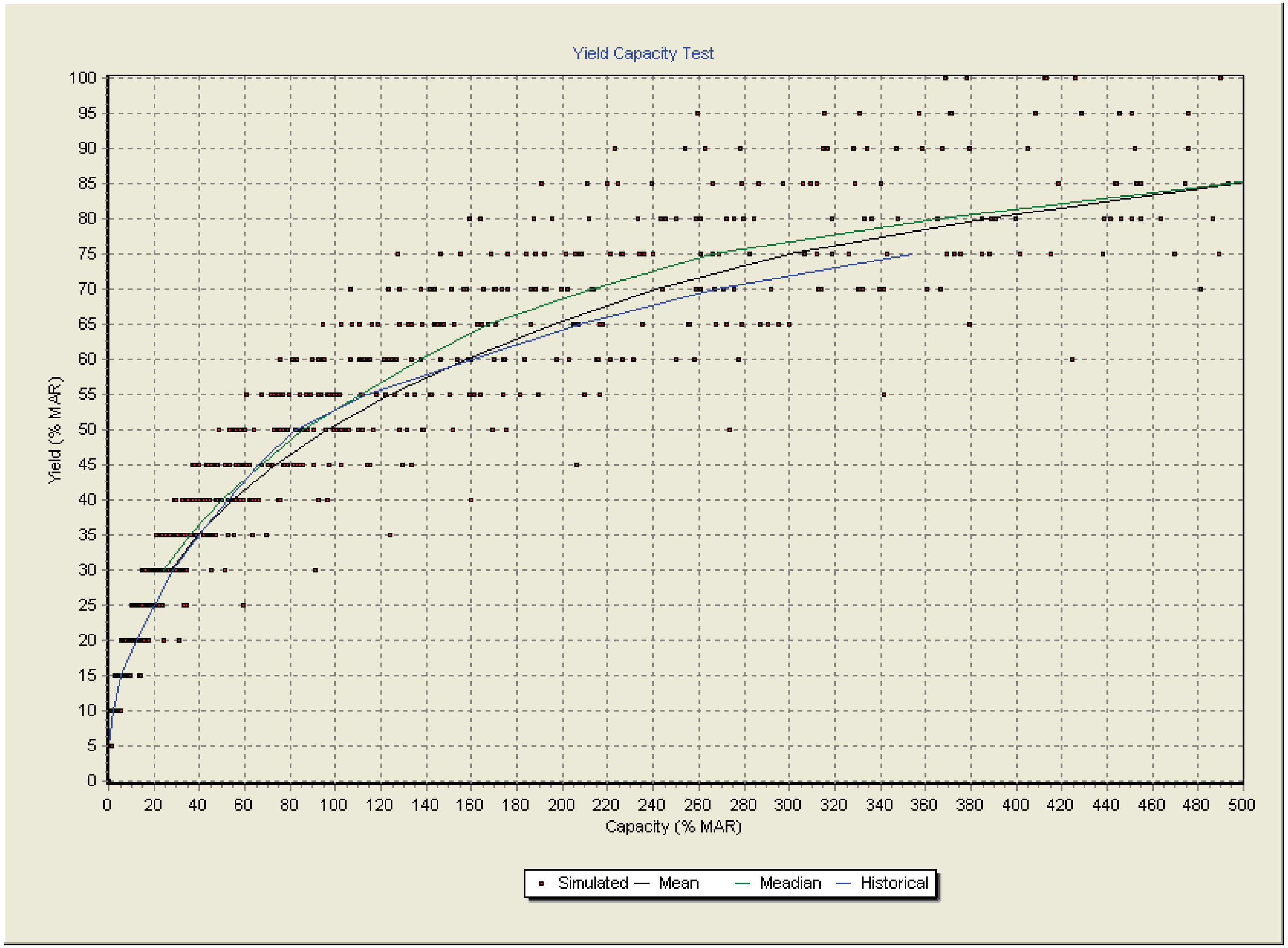
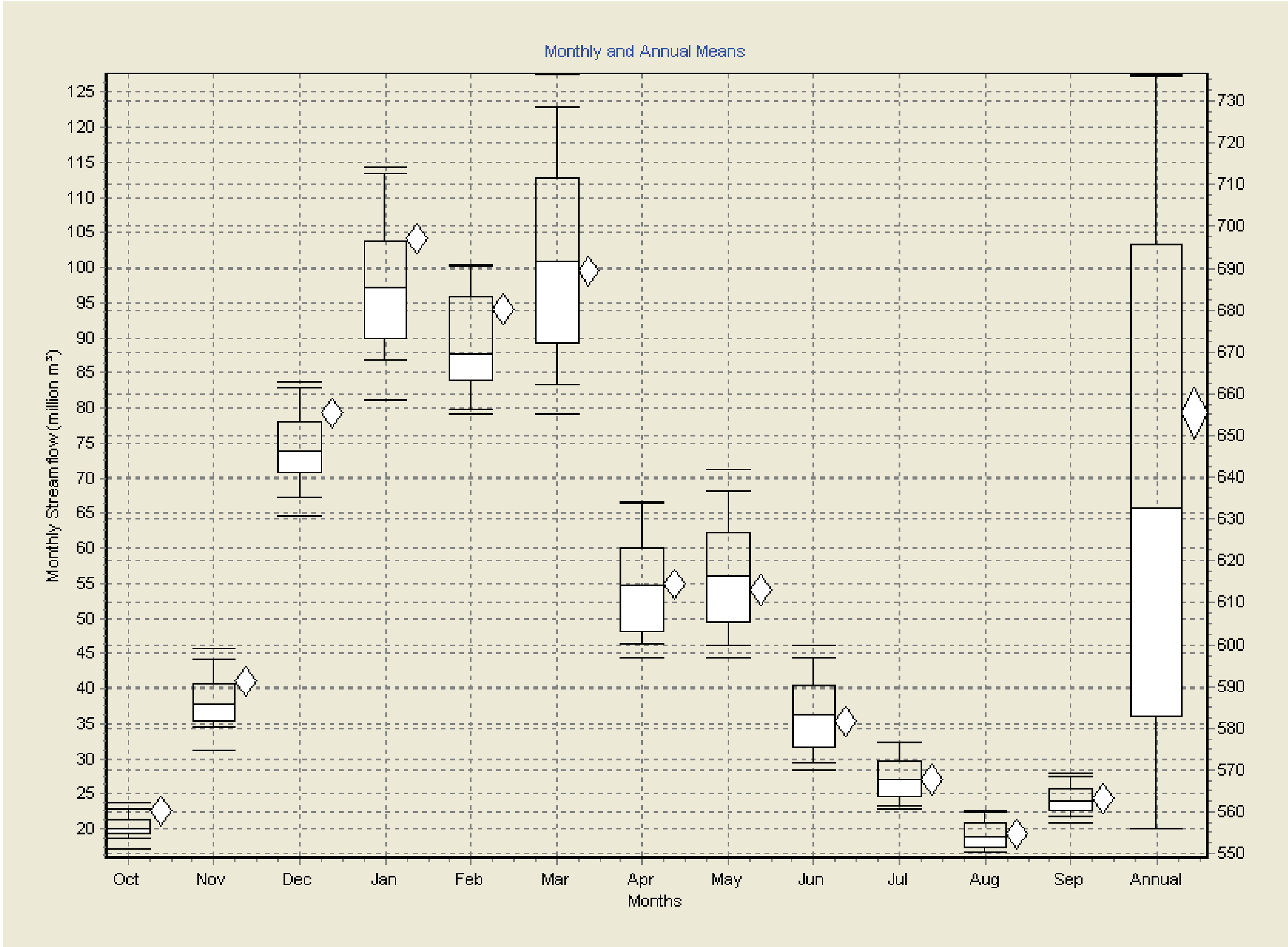


GROOTDRAAI DAM: IPSL-CM4: Present



GROOTDRAAI DAM: IPSL-CM4: Intermediate Future



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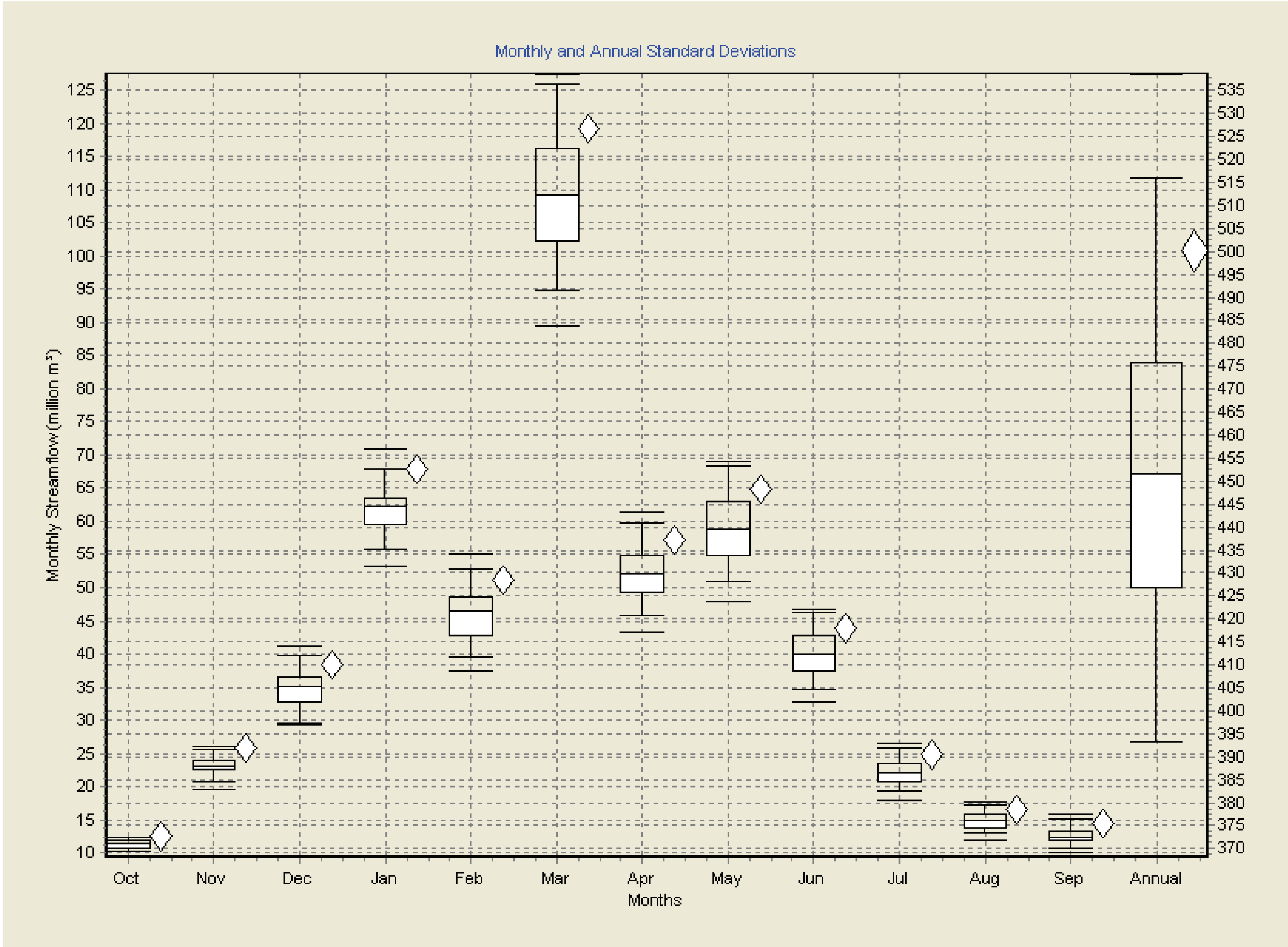

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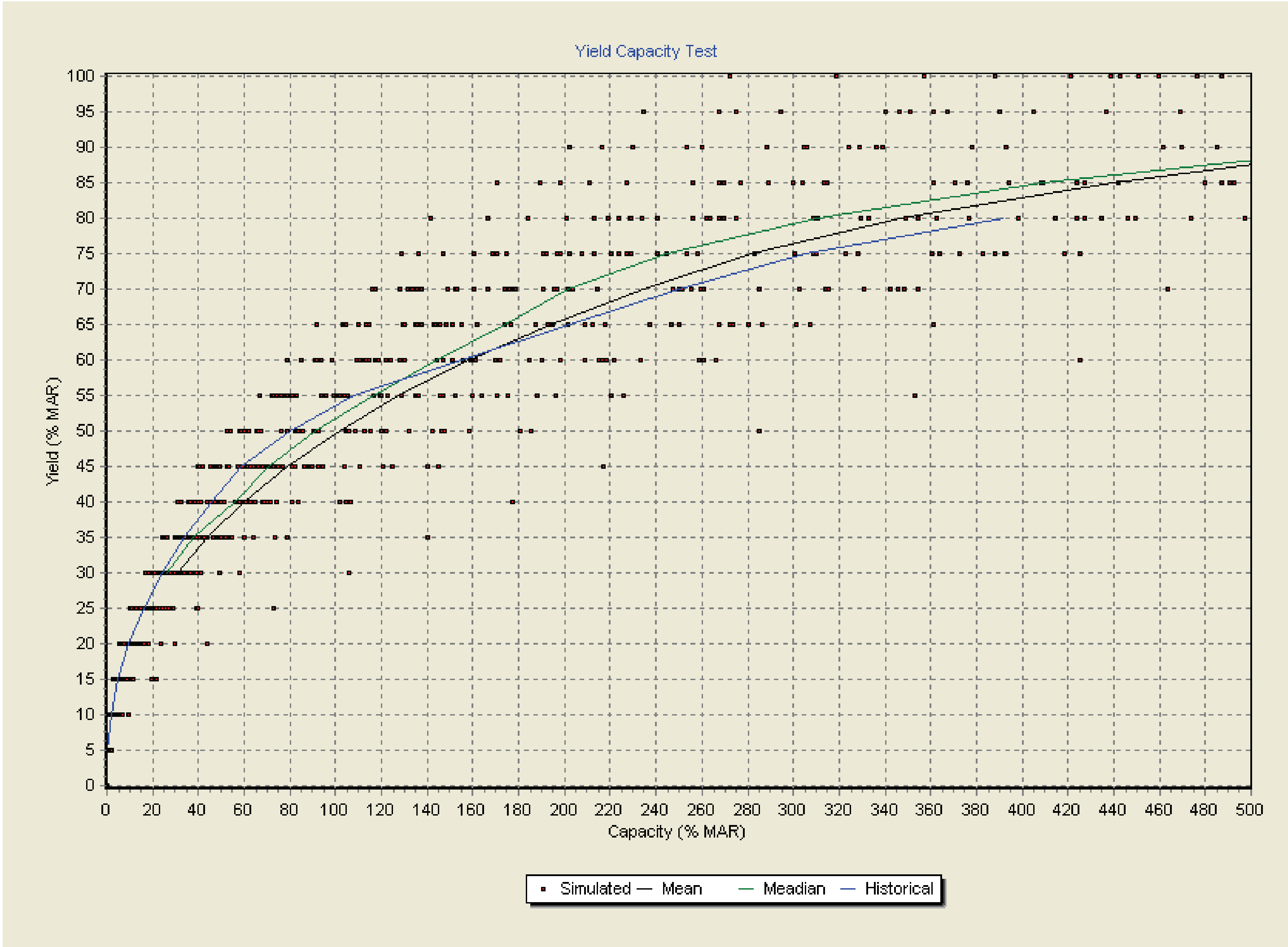

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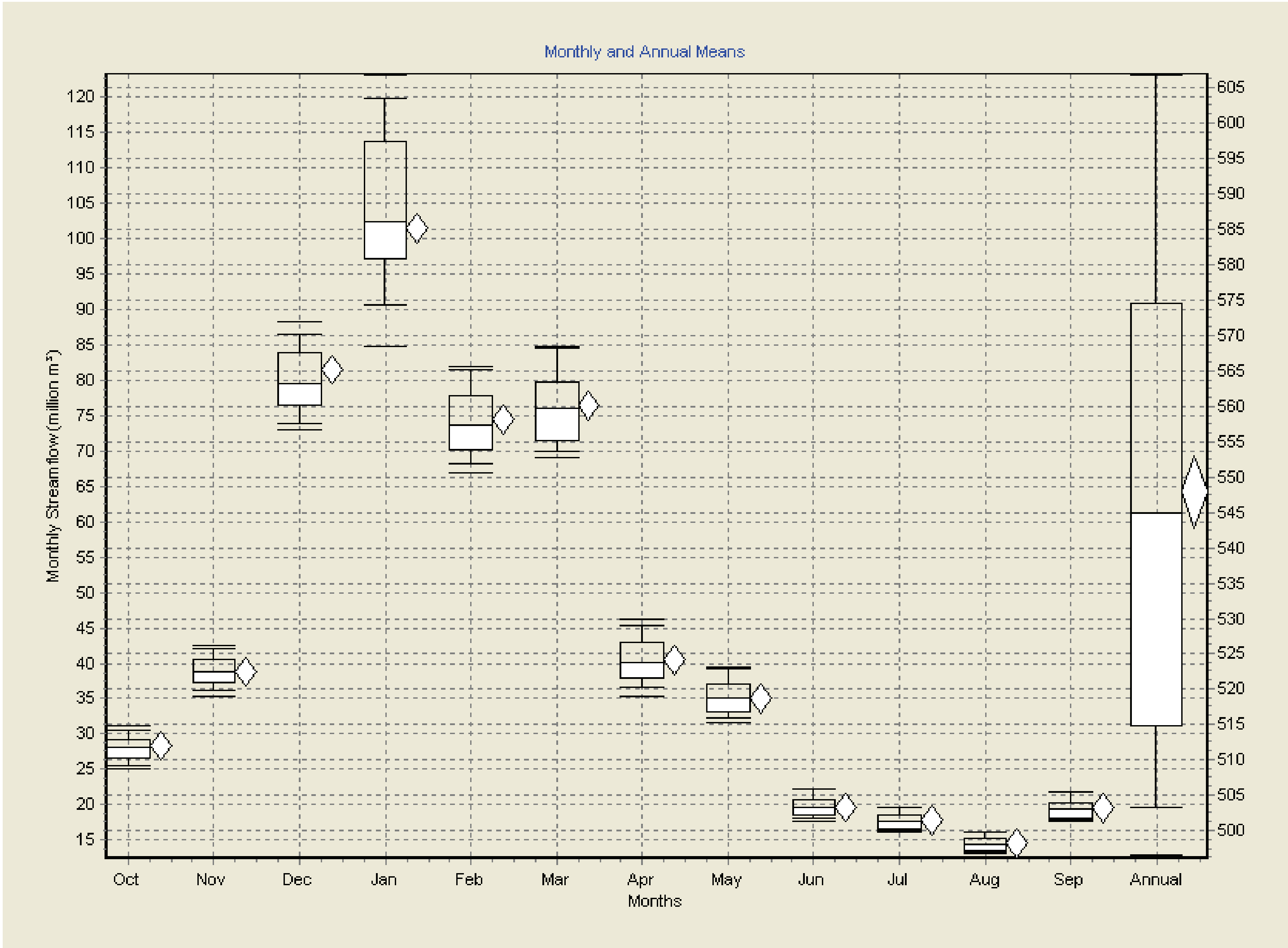

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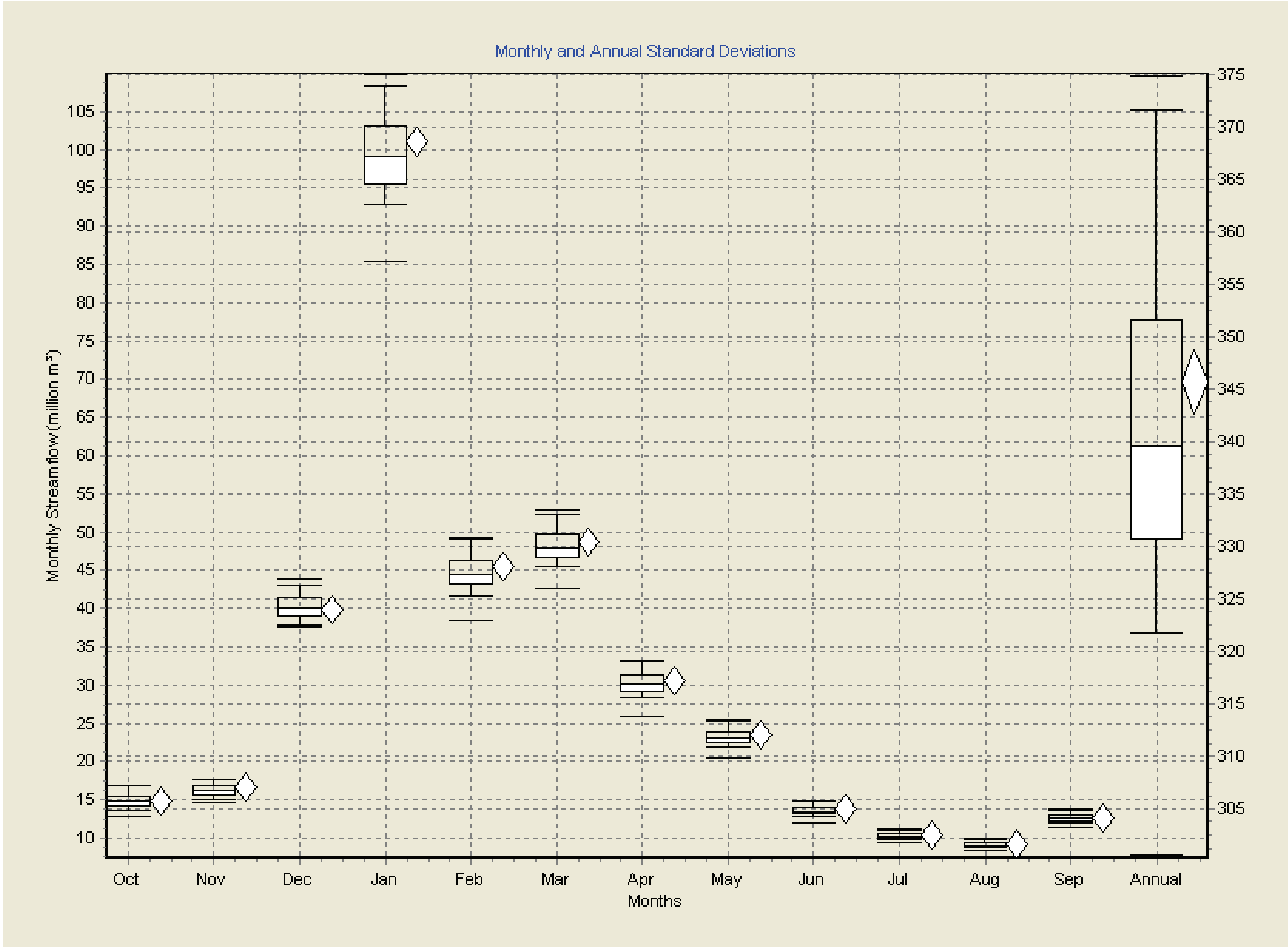

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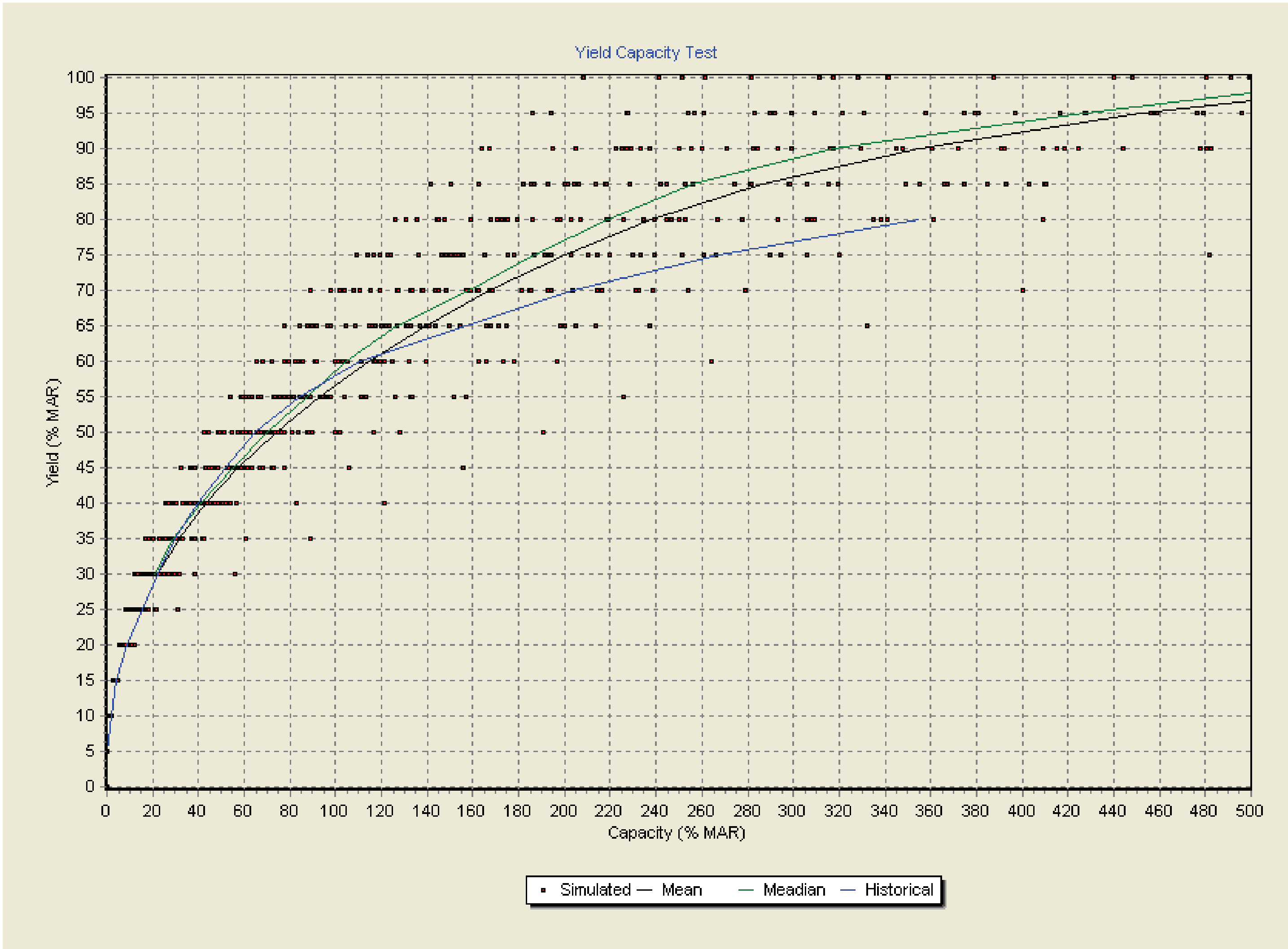
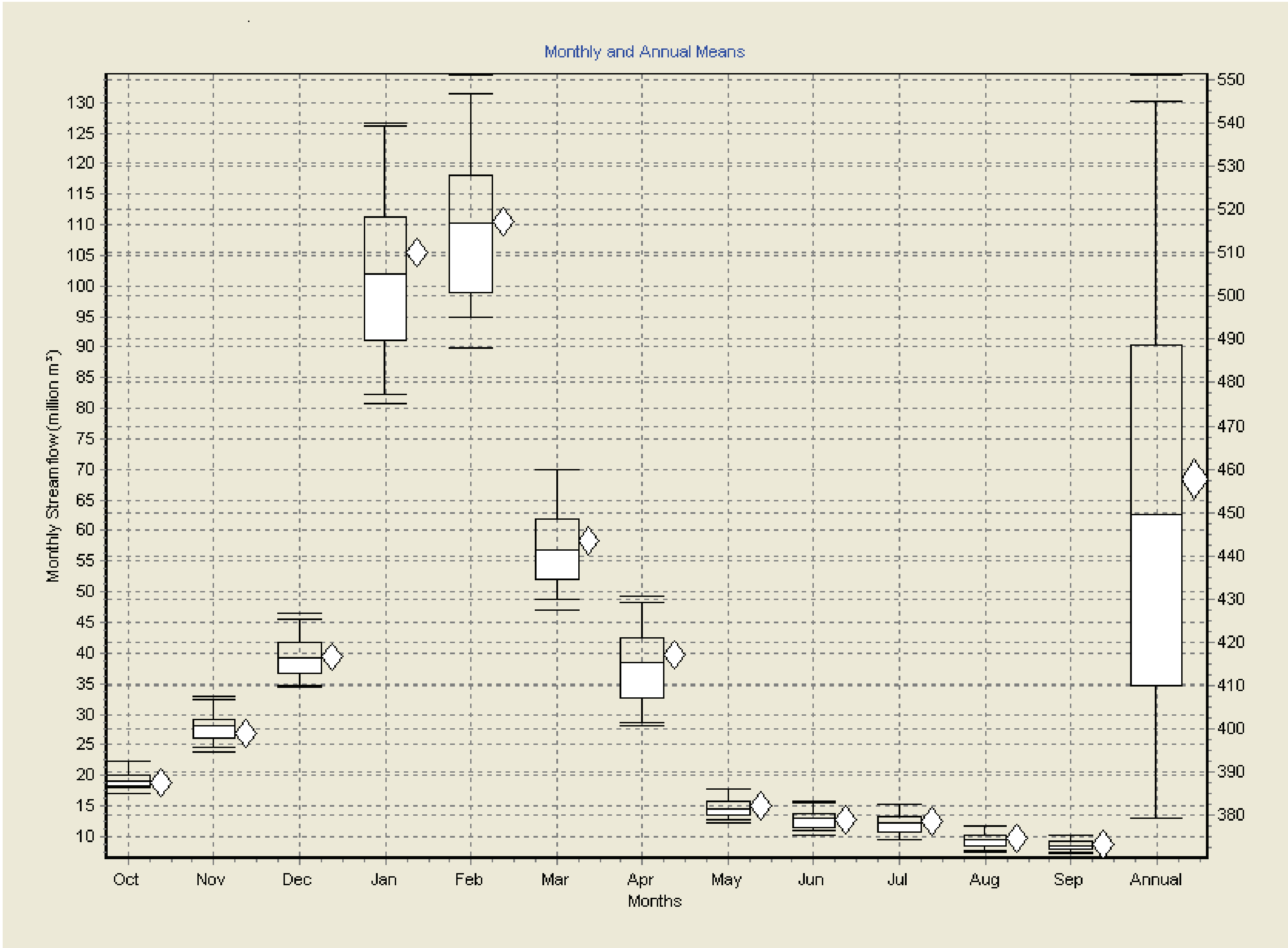


GROOTDRAAI DAM: CGCM3.1: PRESENT



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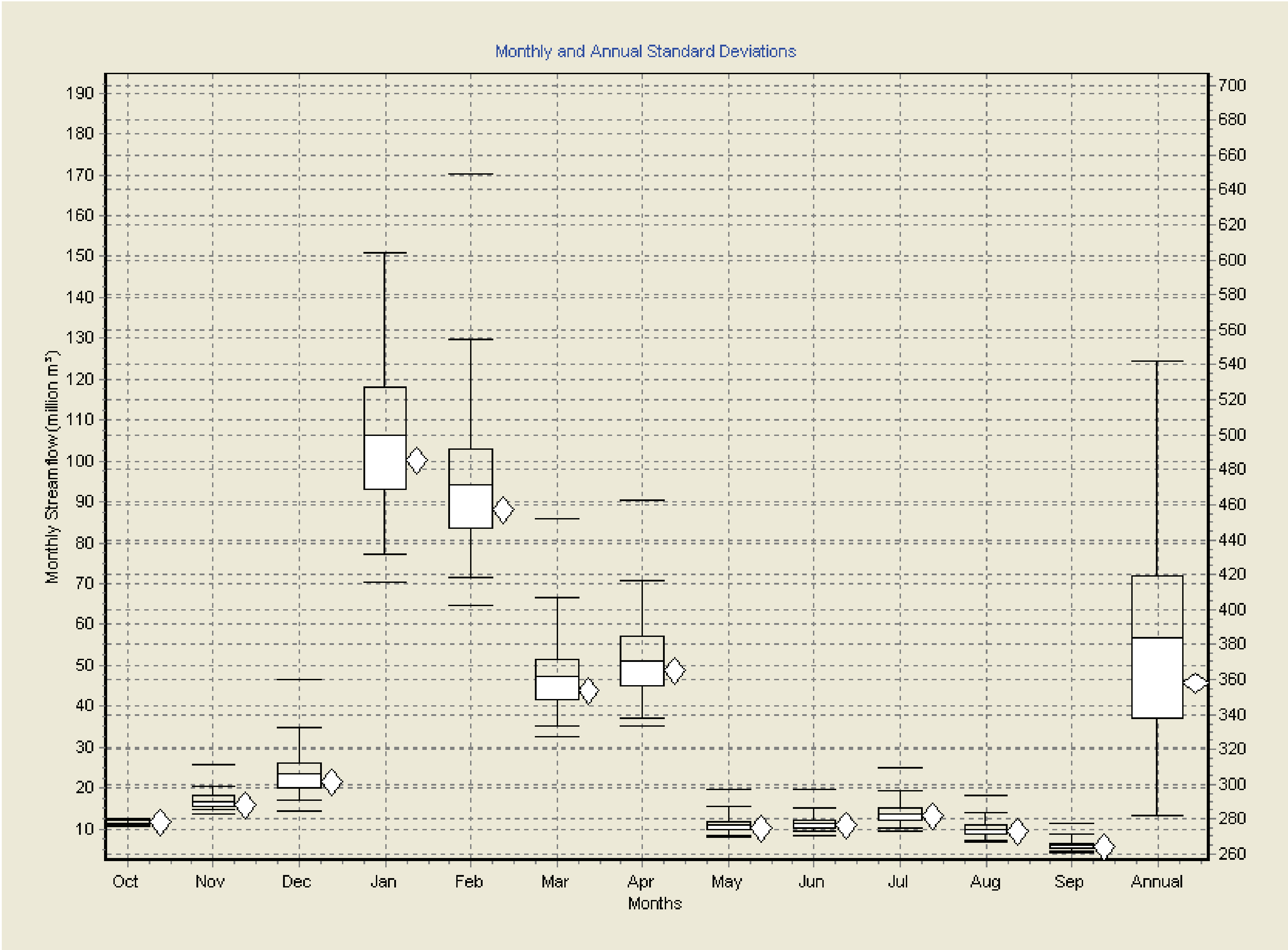

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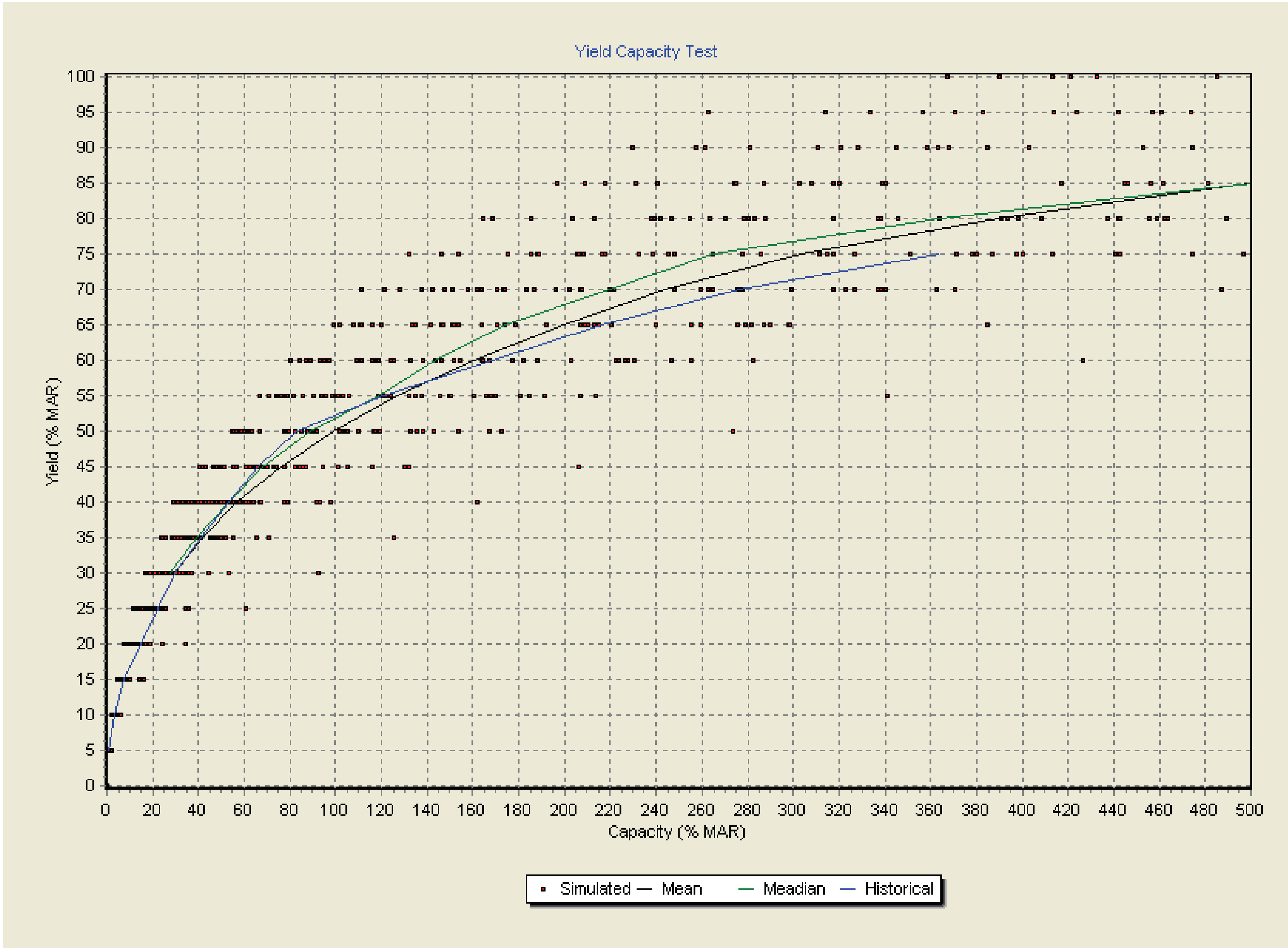
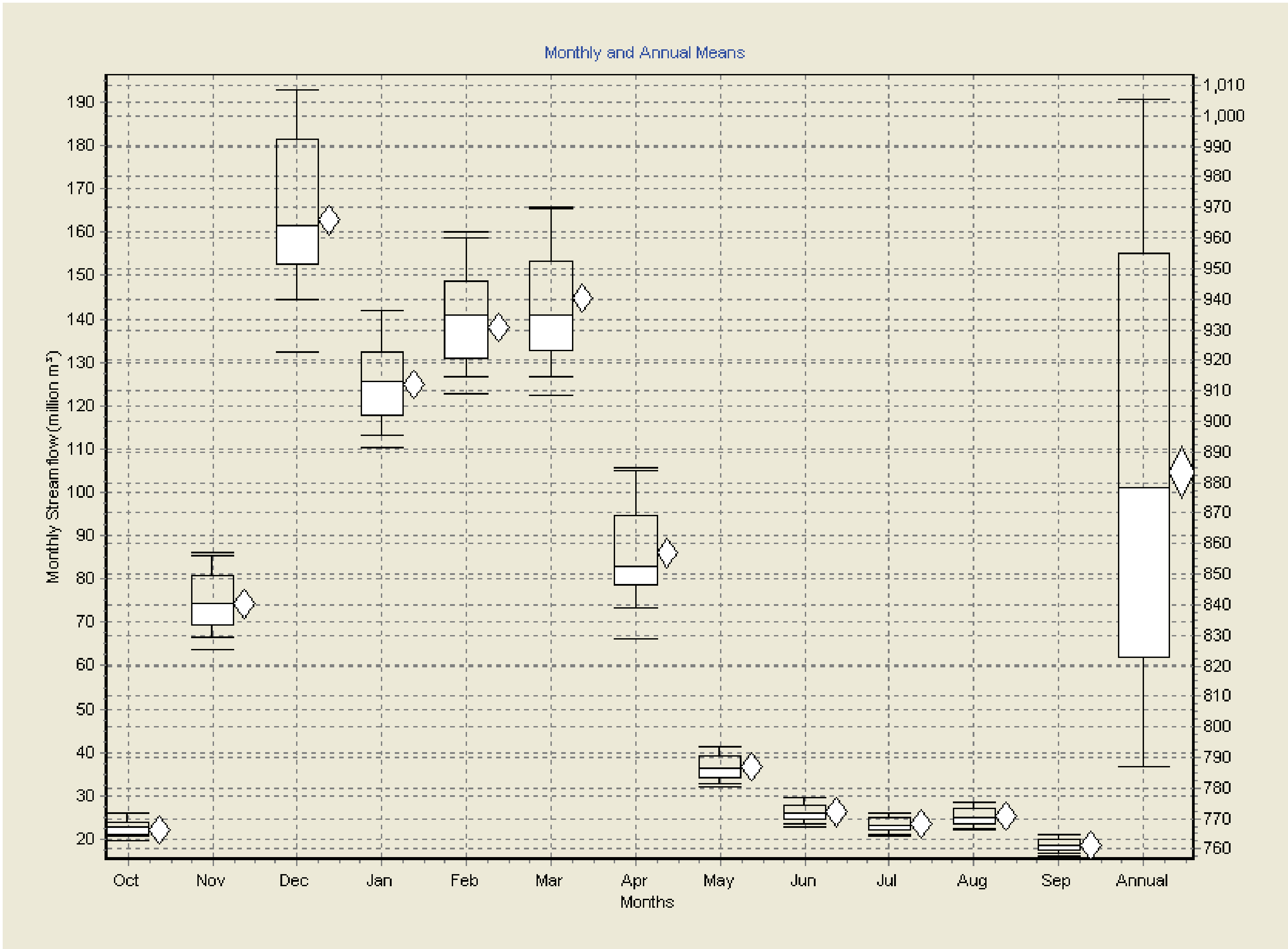


GROOTDRAAI DAM: CGCM3.1: INTERMEDIATE FUTURE



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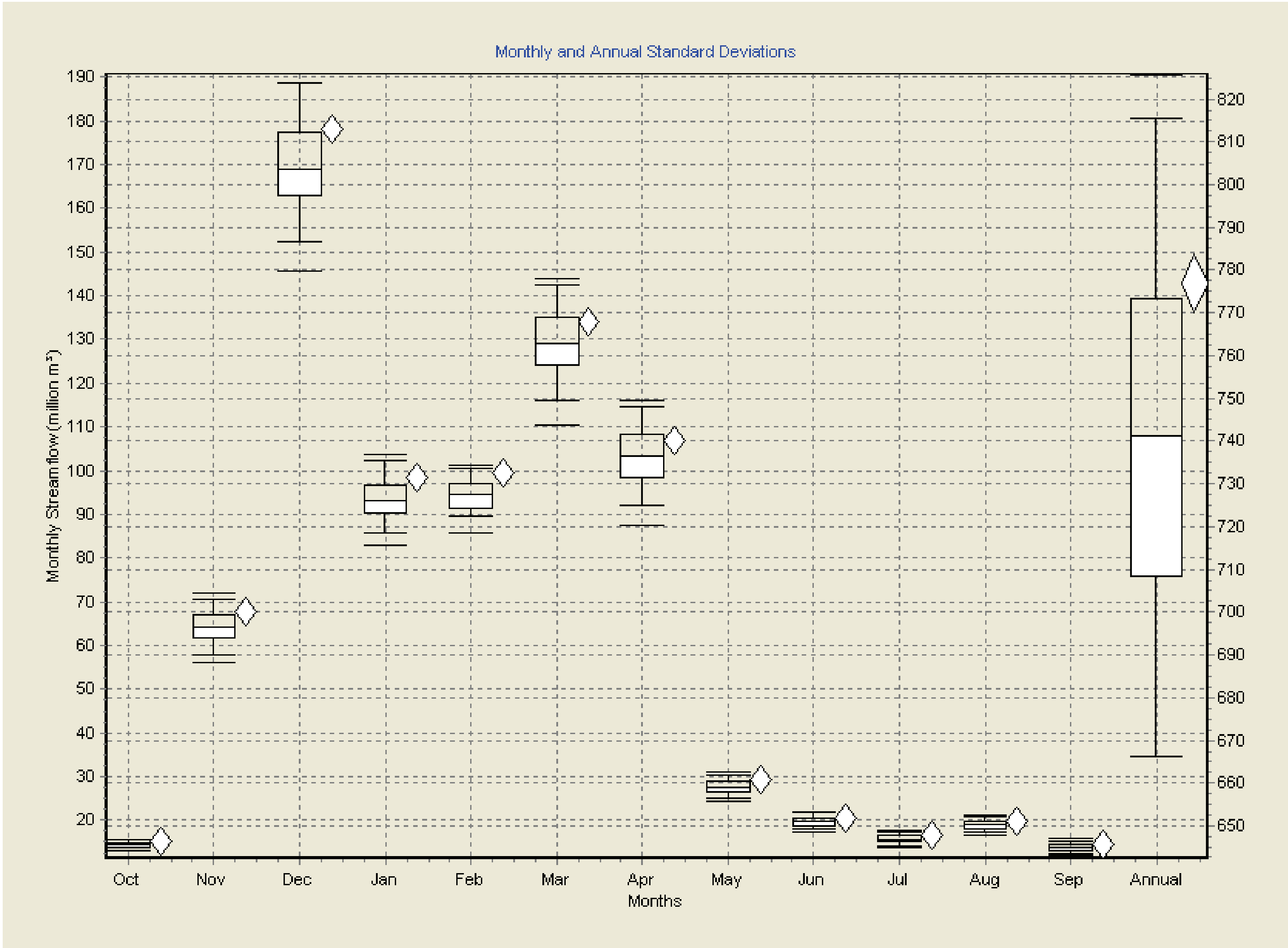

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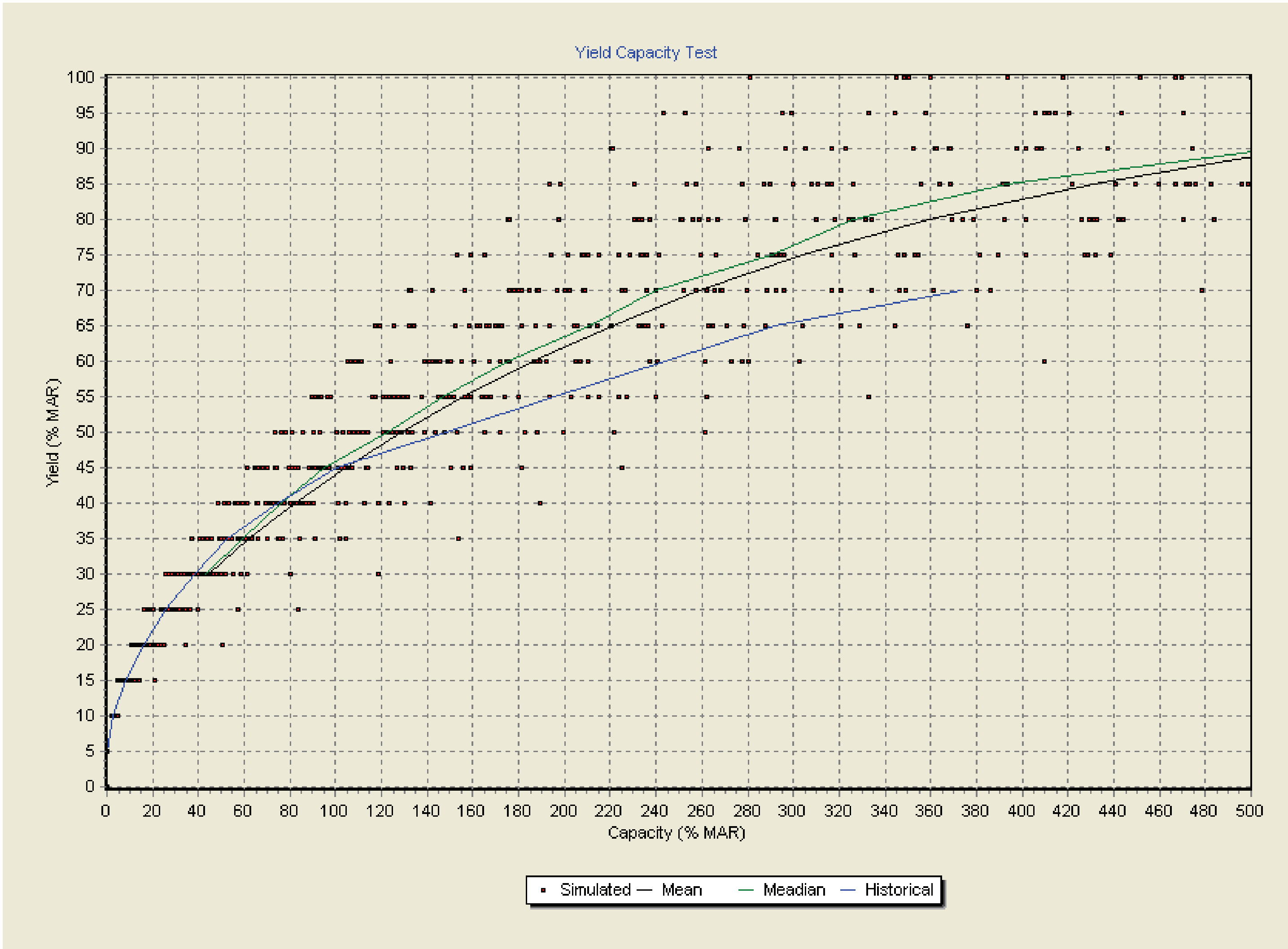
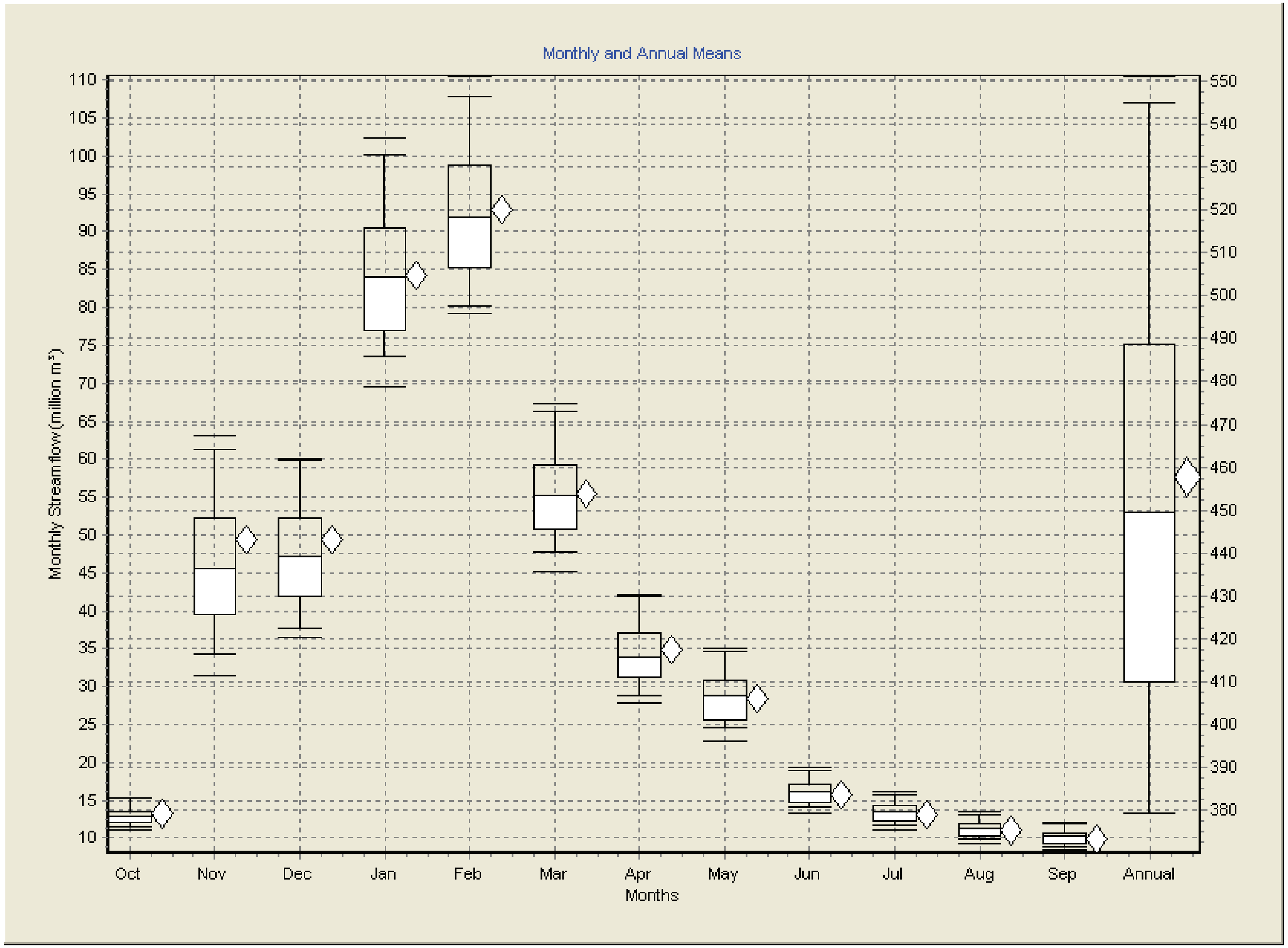
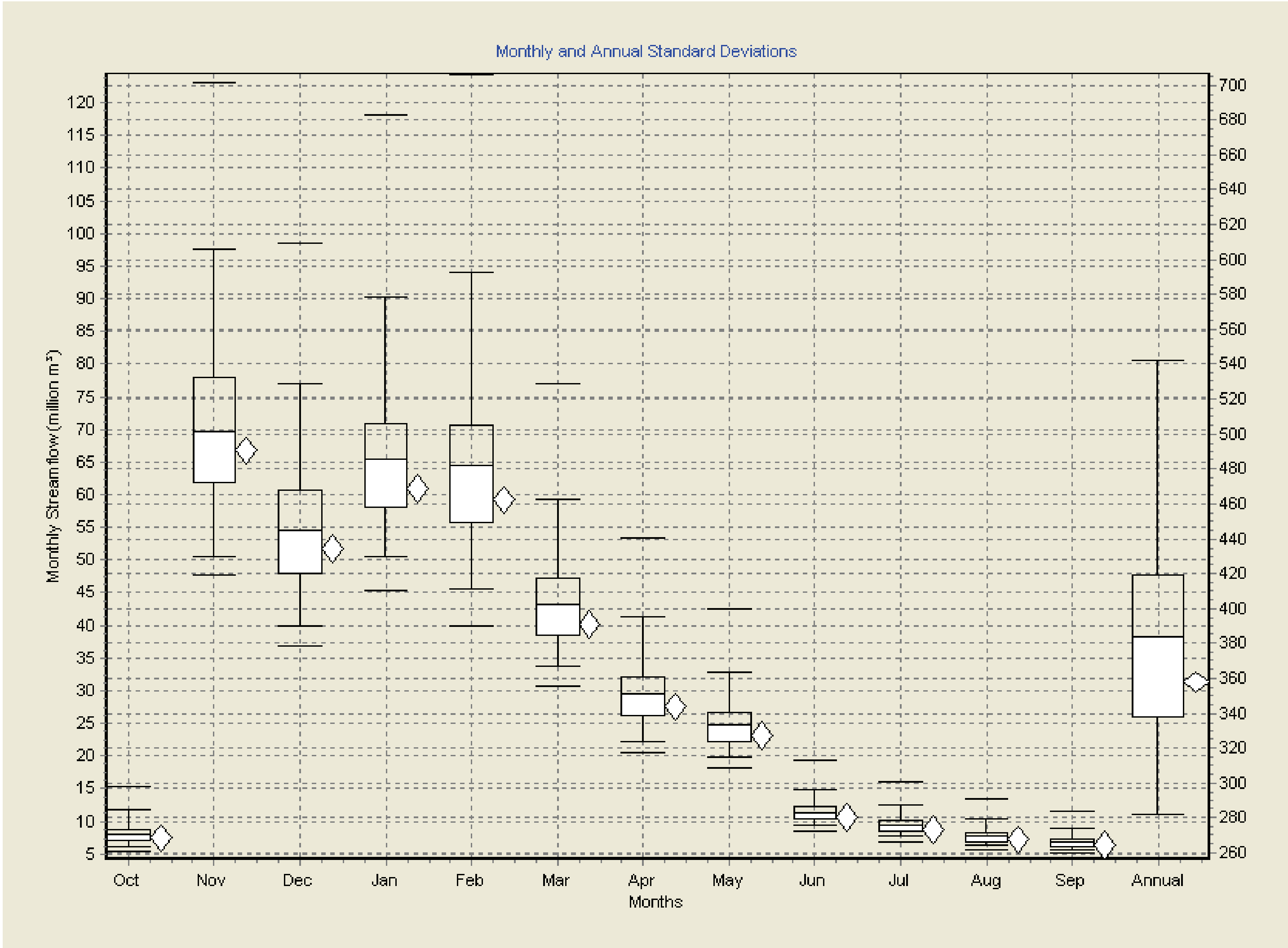


GROOTDRAAI DAM: CNRM-CM3: PRESENT



GROOTDRAAI DAM: CNRM-CM3: PRESENT



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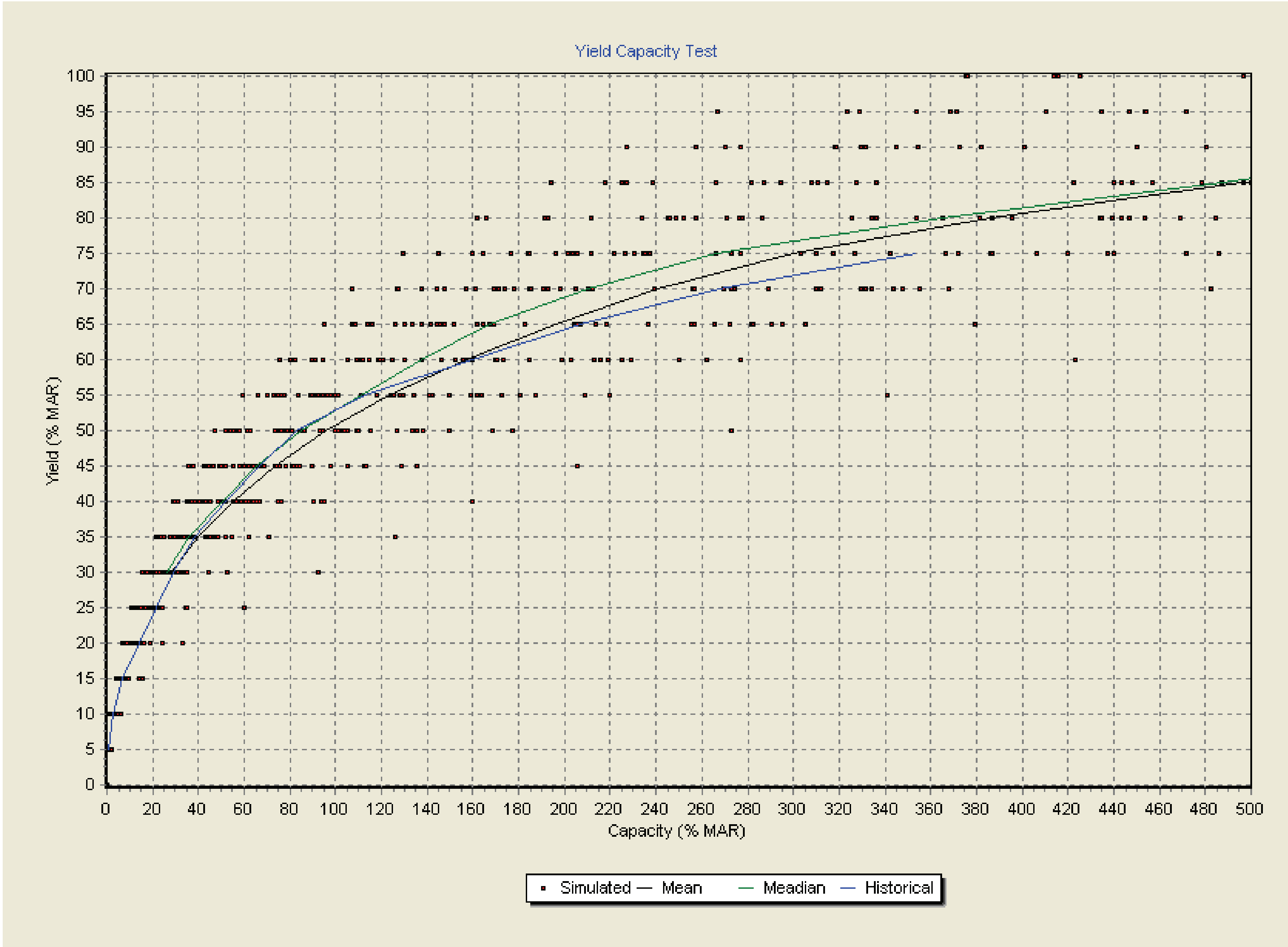

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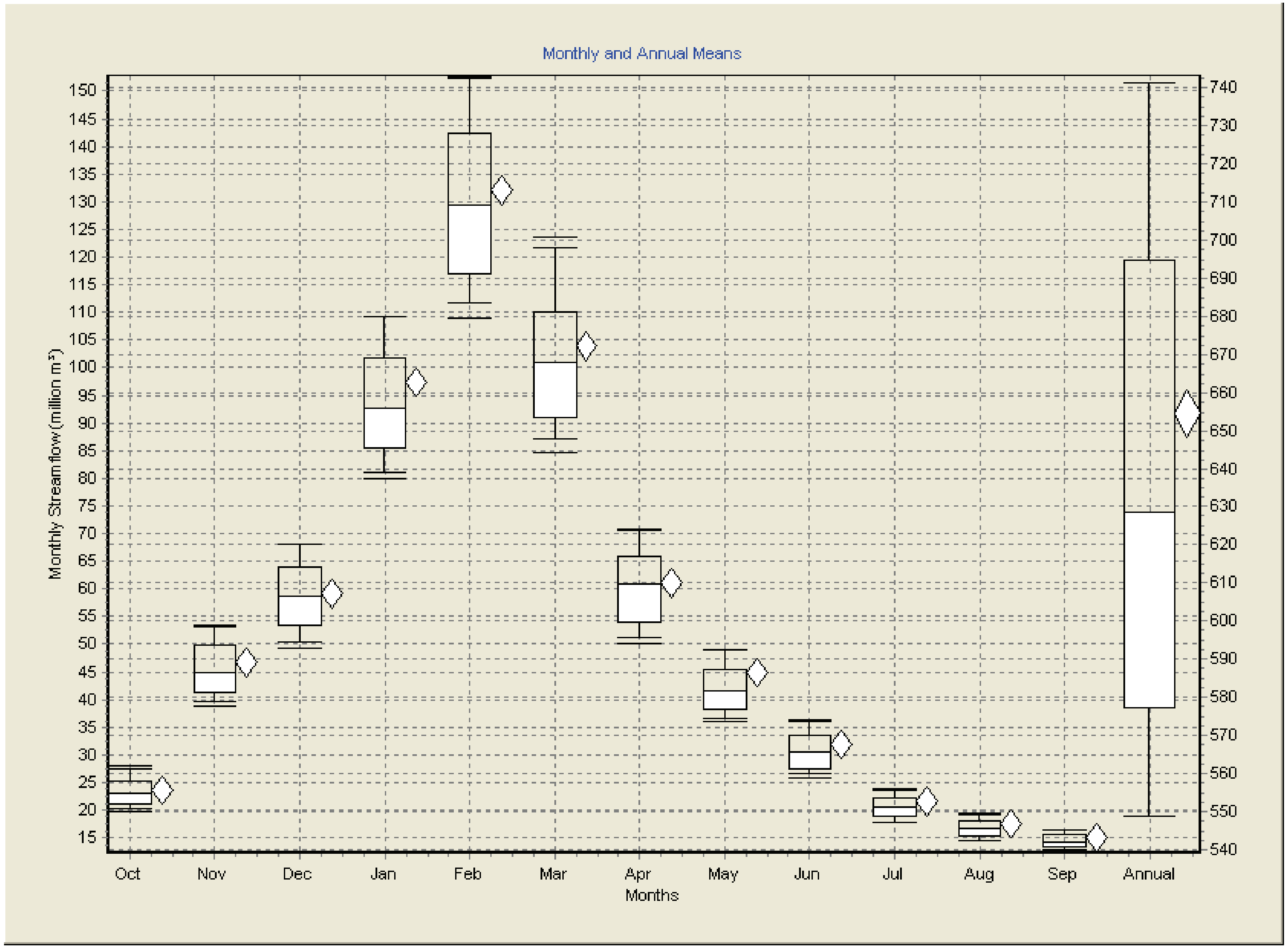

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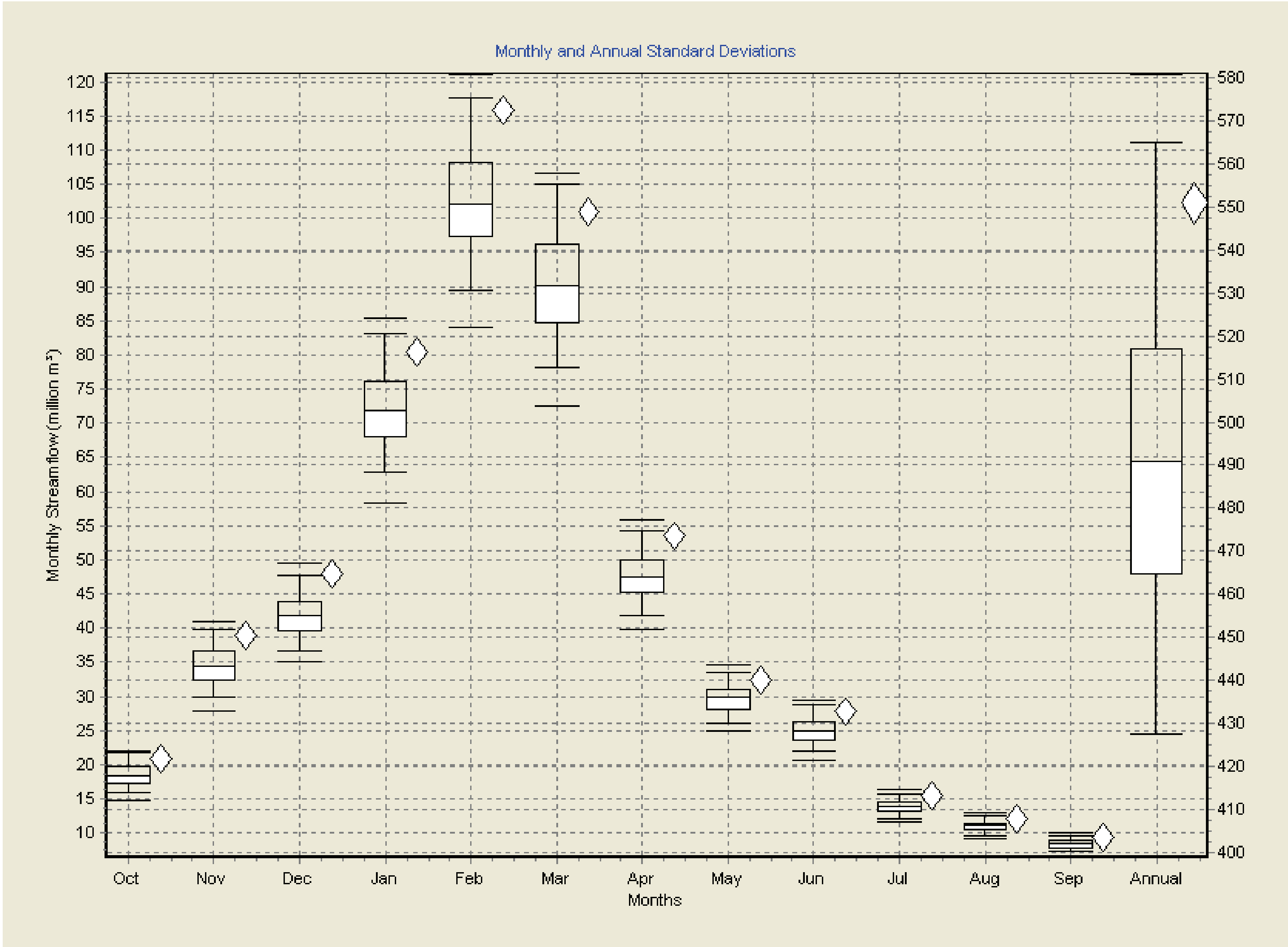

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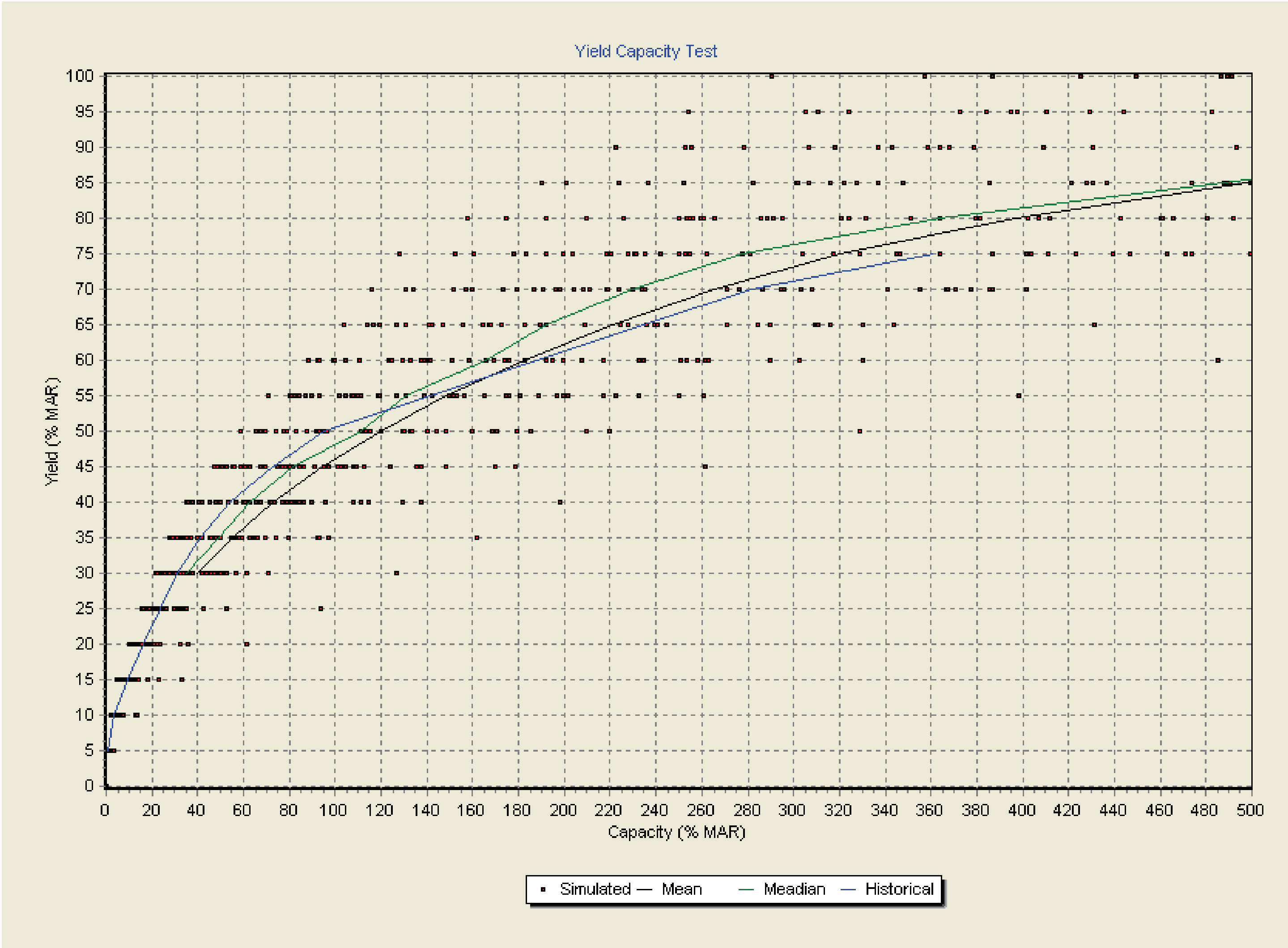
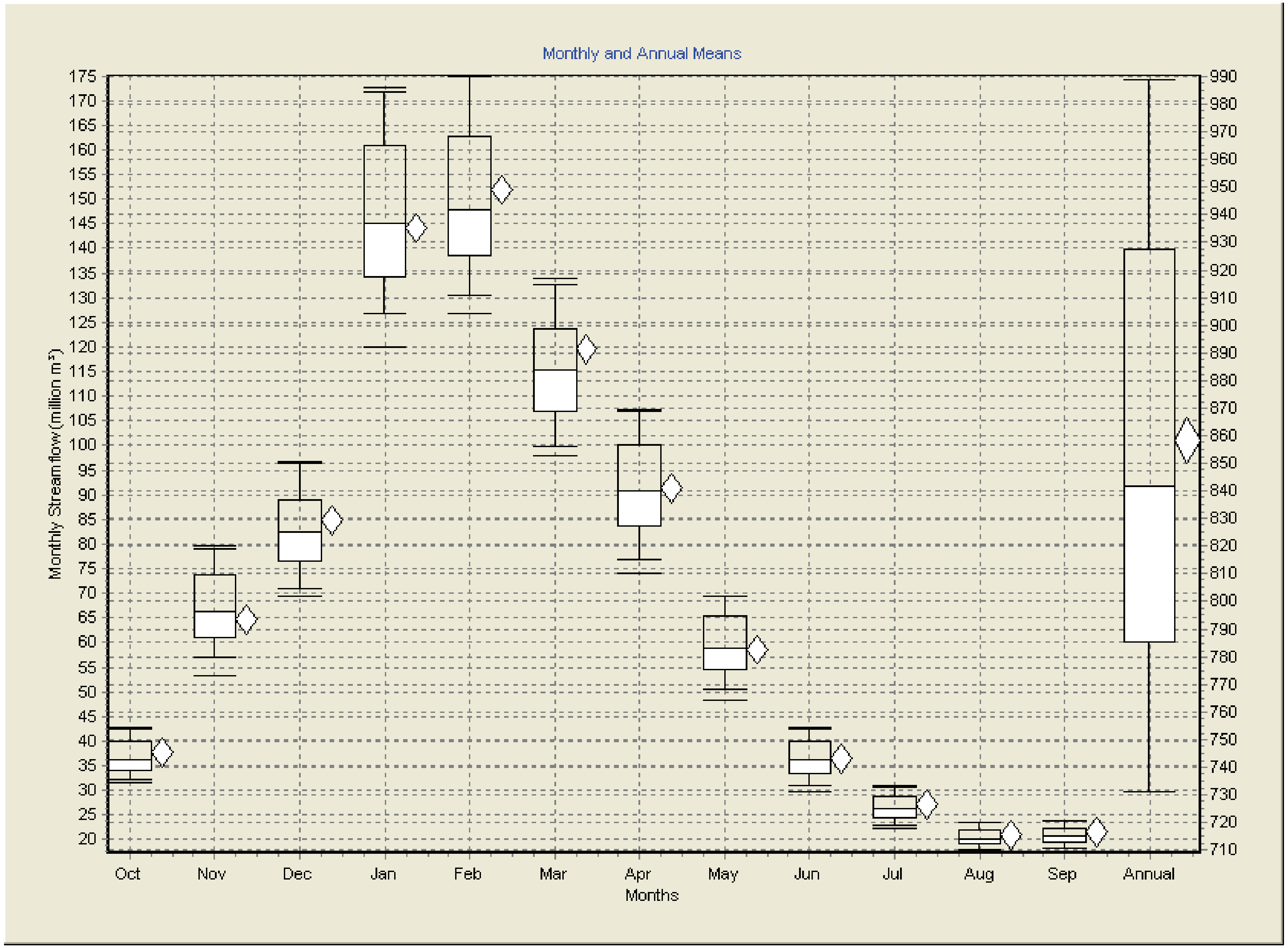
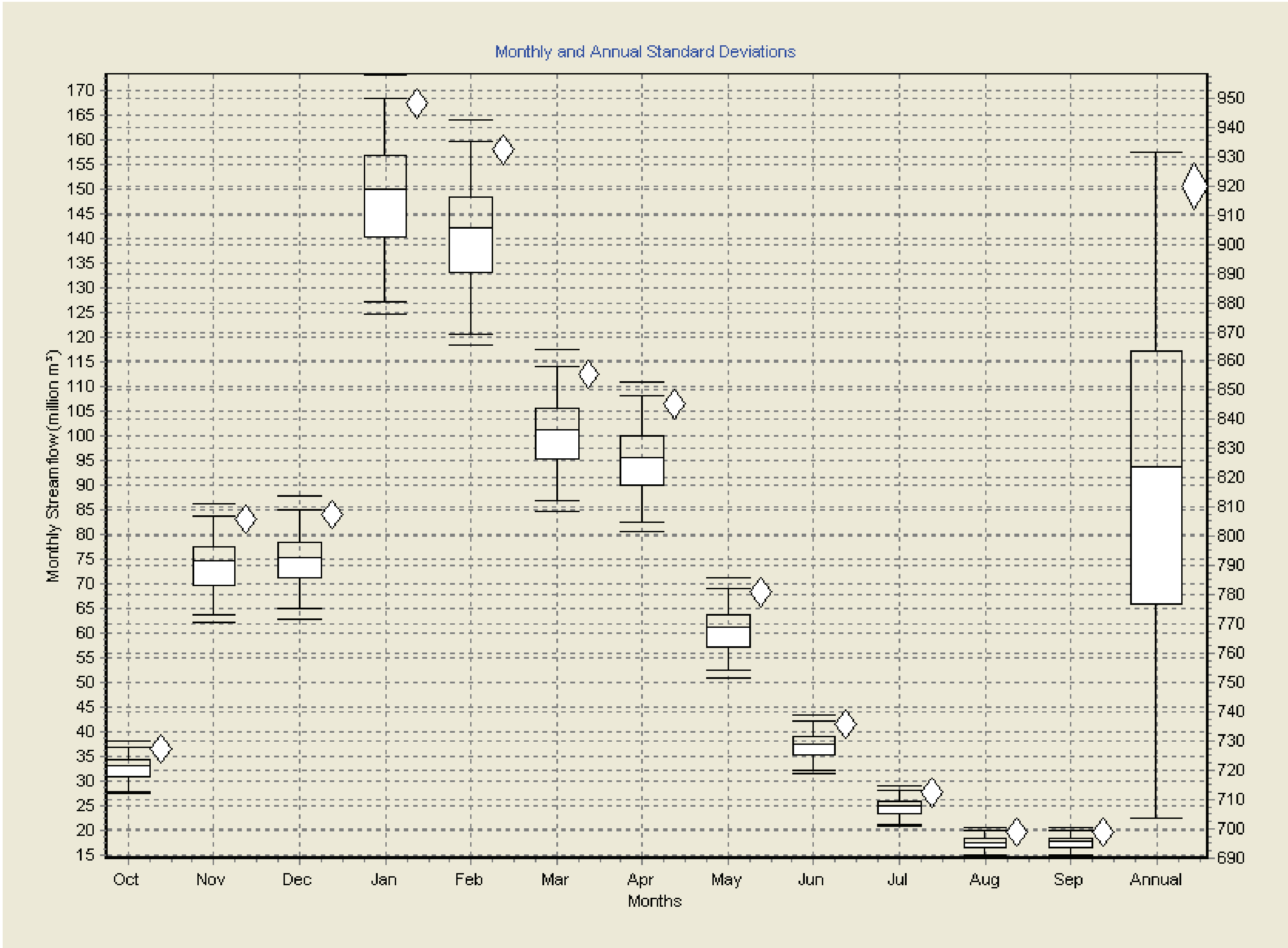


GROOTDRAAI DAM: CNRM-CM3: DISTANT FUTURE



GROOTDRAAI DAM: CNRM-CM3: DISTANT FUTURE



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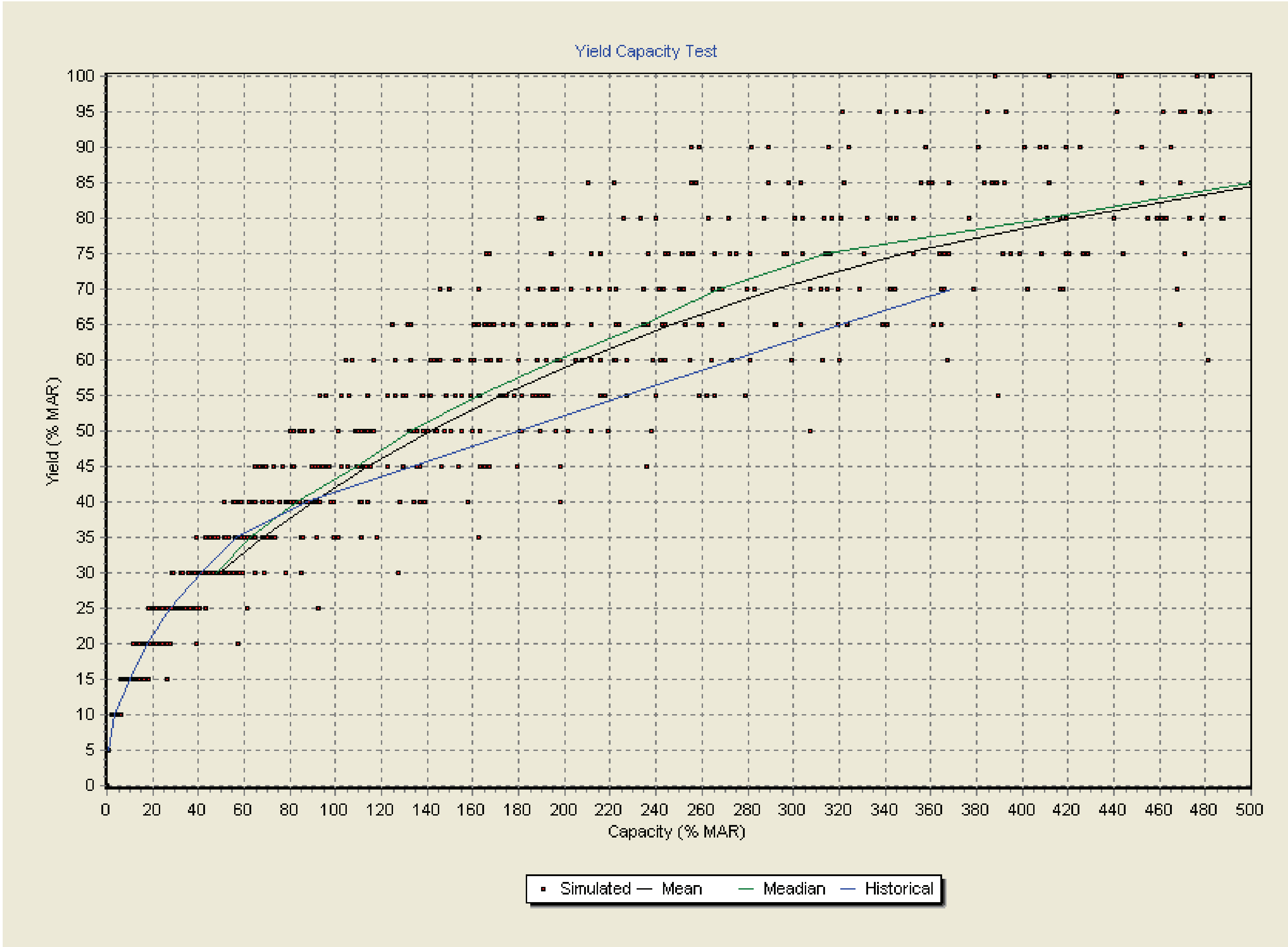
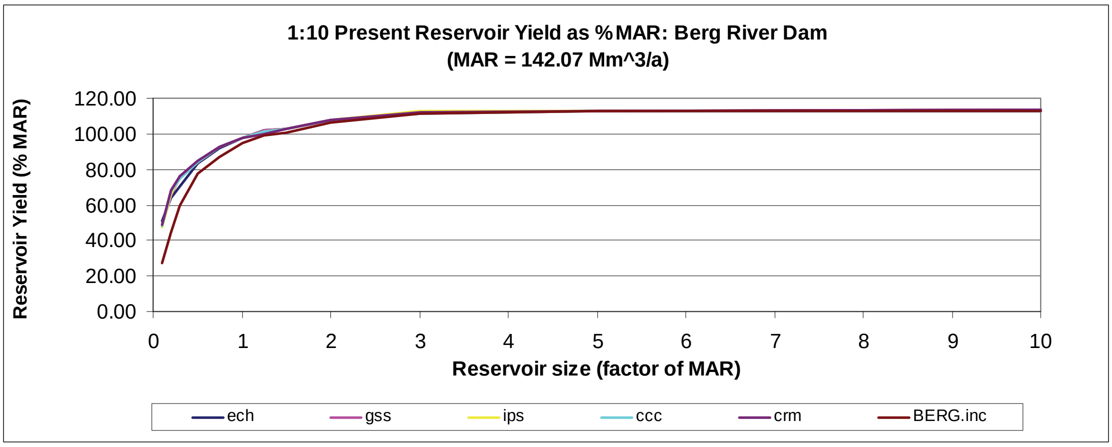
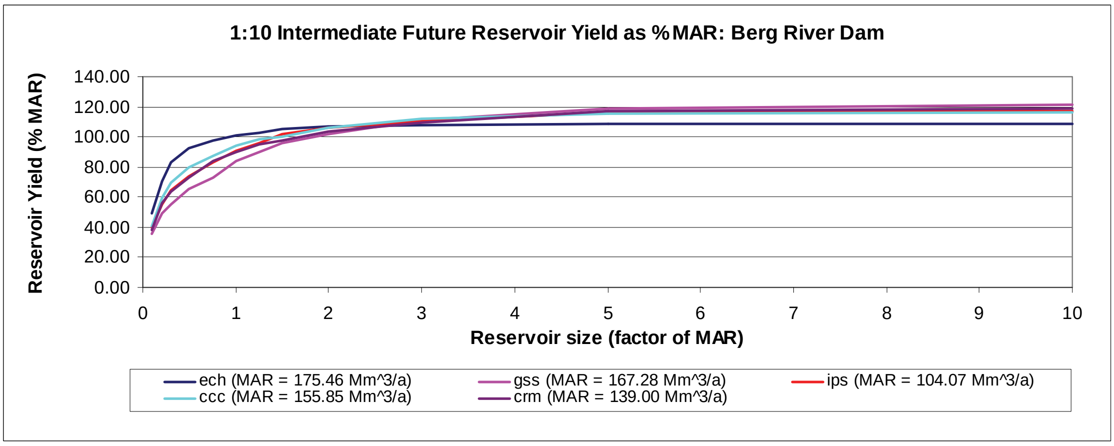


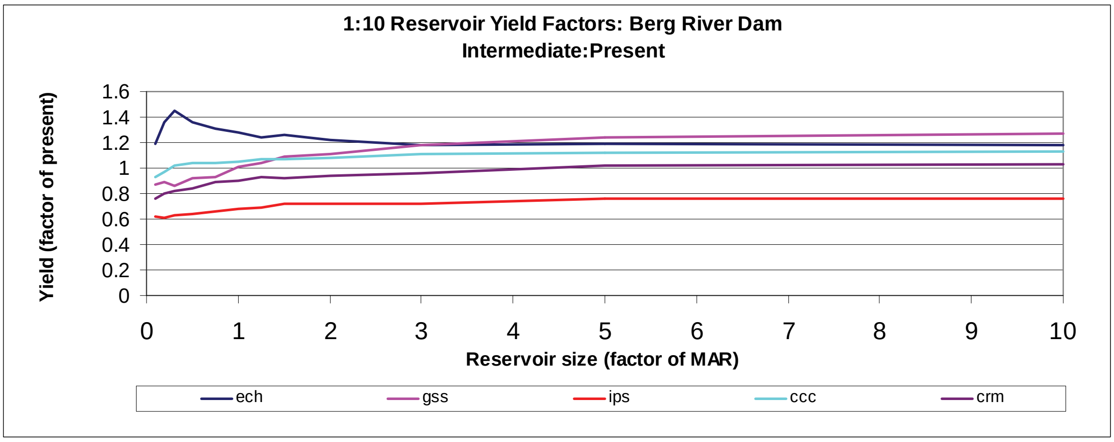
APPENDIX C: Yield-Capacity analysis results for assurances other than 98% (1:50 risk of failure)

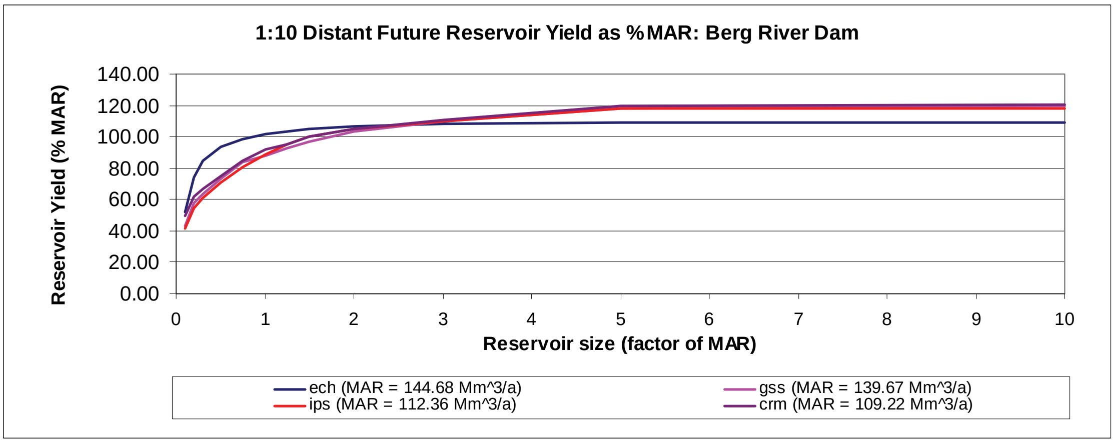
Appendix C.1: BERG RIVER DAM

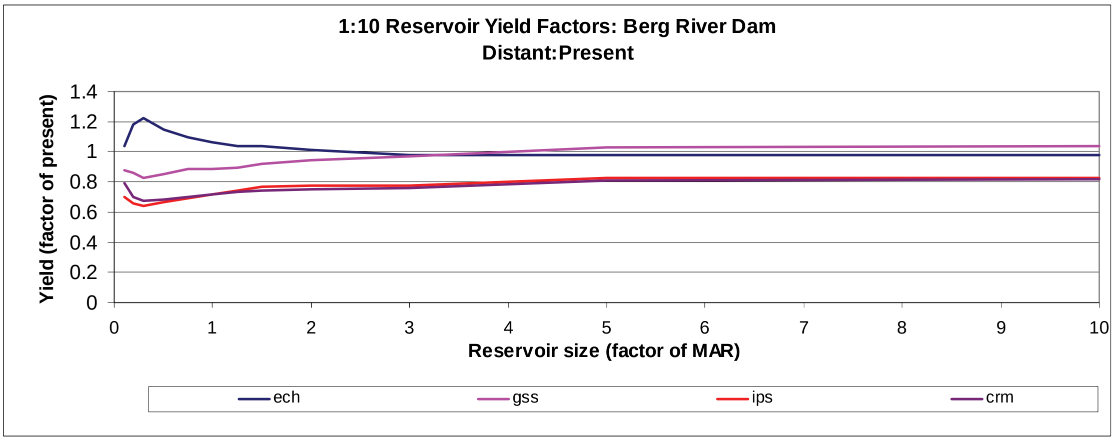
1:10



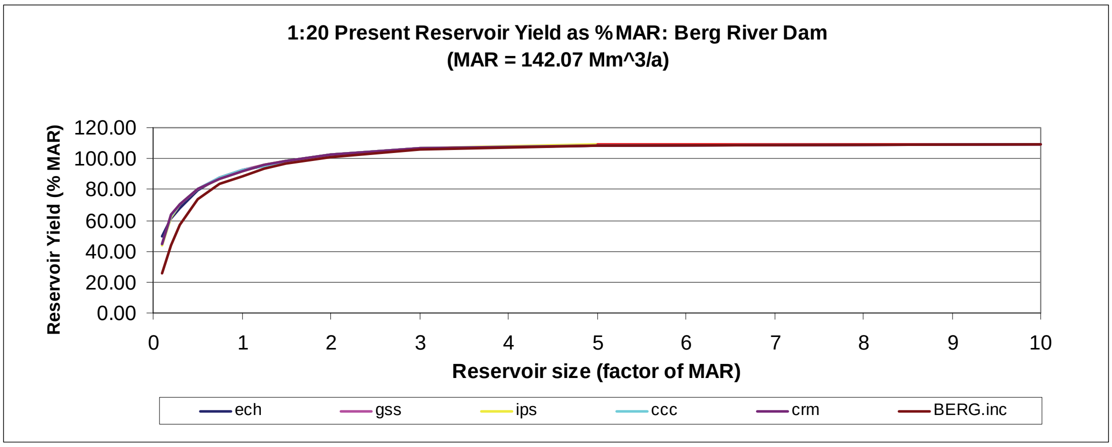


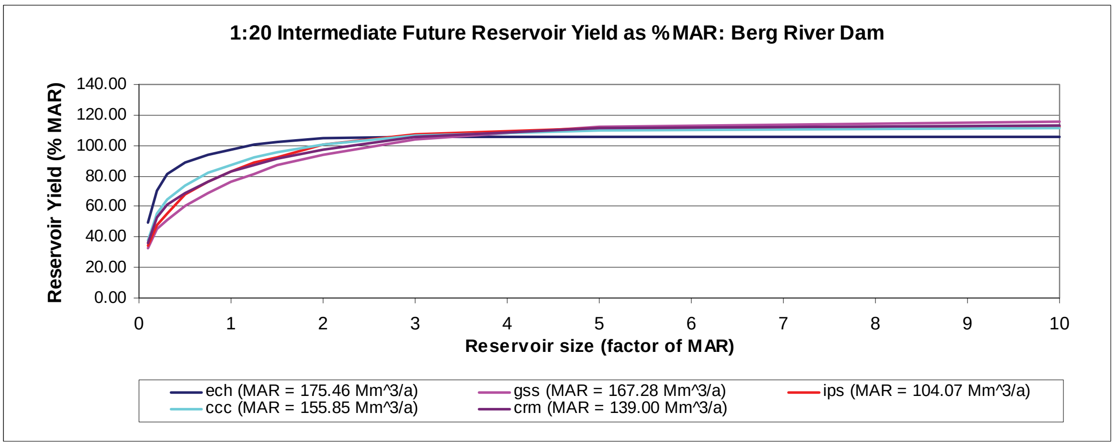


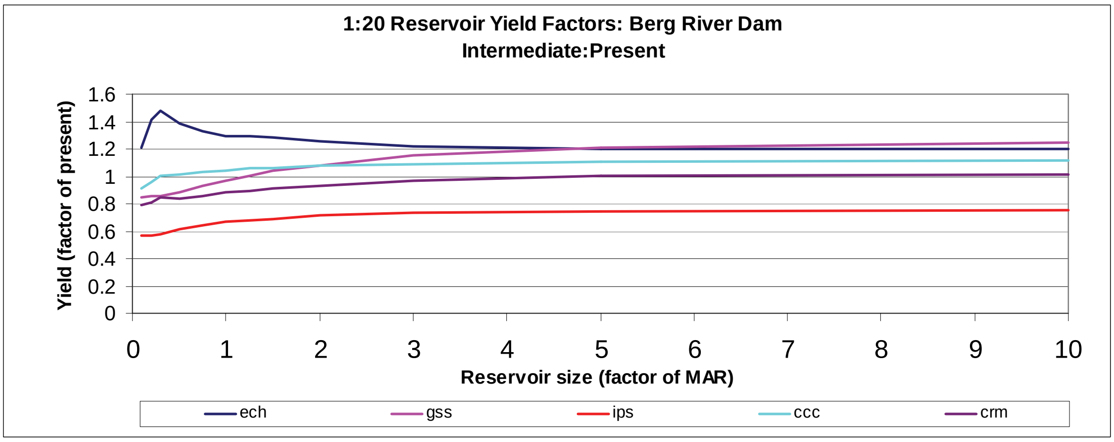

1:10 Distant Future Reservoir Yield as %MAR: Berg River Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 144.68 Mm^3/a)
ips (MAR = 112.36 Mm^3/a)
gss (MAR = 139.67 Mm^3/a)
crm (MAR = 109.22 Mm^3/a)

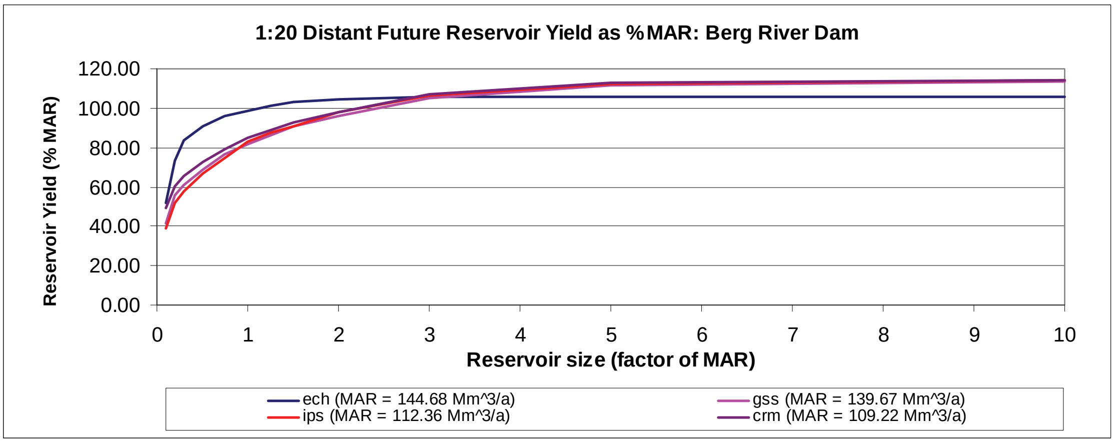

1:10 Reservoir Yield Factors: Berg River Dam
Distant:Present
Yield (factor of present)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

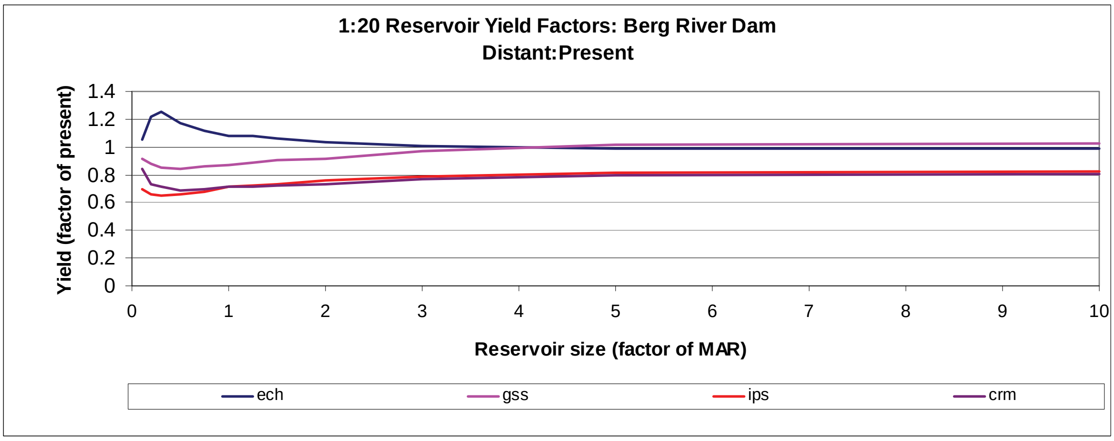
1:20


1:20 Present Reservoir Yield as %MAR: Berg River Dam
(MAR = 142.07 Mm^3/a)
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
BERG.inc

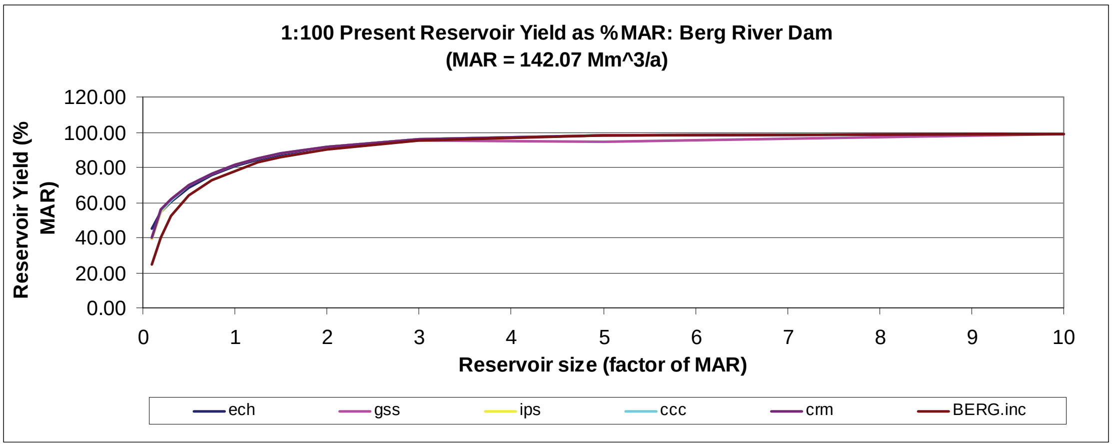

1:20 Intermediate Future Reservoir Yield as %MAR: Berg River Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 175.46 Mm^3/a)
gss (MAR = 167.28 Mm^3/a)
ips (MAR = 104.07 Mm^3/a)
ccc (MAR = 155.85 Mm^3/a)
crm (MAR = 139.00 Mm^3/a)


1:20 Reservoir Yield Factors: Berg River Dam
Intermediate:Present
Yield (factor of present)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

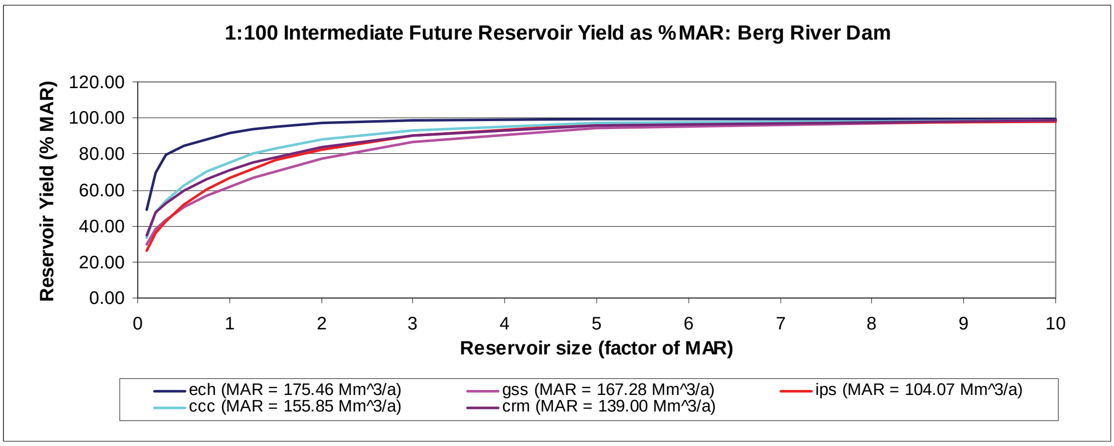

1:20 Distant Future Reservoir Yield as %MAR: Berg River Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 144.68 Mm^3/a)
gss (MAR = 139.67 Mm^3/a)
ips (MAR = 112.36 Mm^3/a)
crm (MAR = 109.22 Mm^3/a)


1:20 Reservoir Yield Factors: Berg River Dam
Distant:Present
Yield (factor of present)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

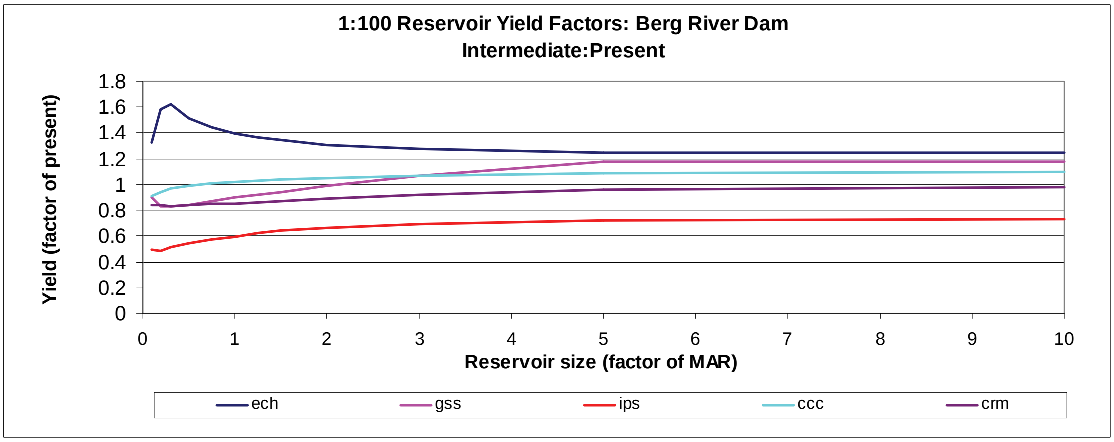
1:100



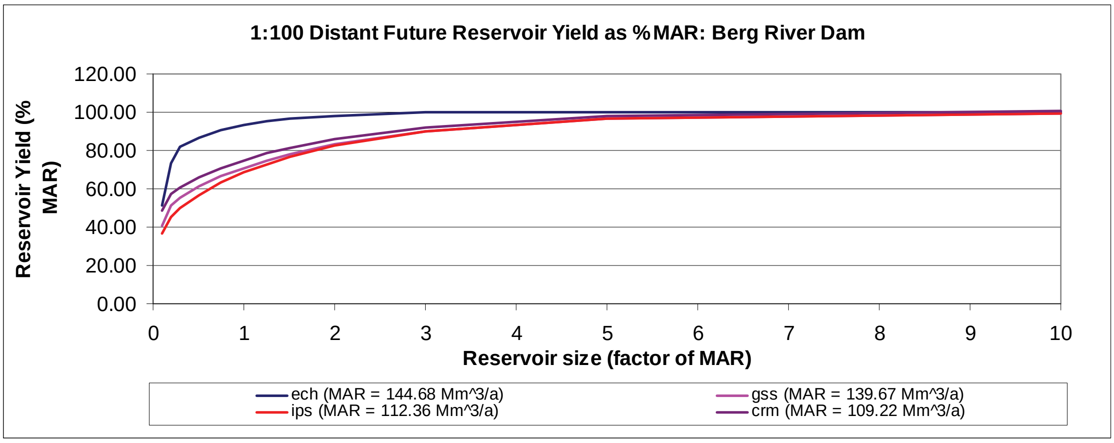
1:100 Present Reservoir Yield as %MAR: Berg River Dam
(MAR = 142.07 Mm^3/a)
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
BERG.inc

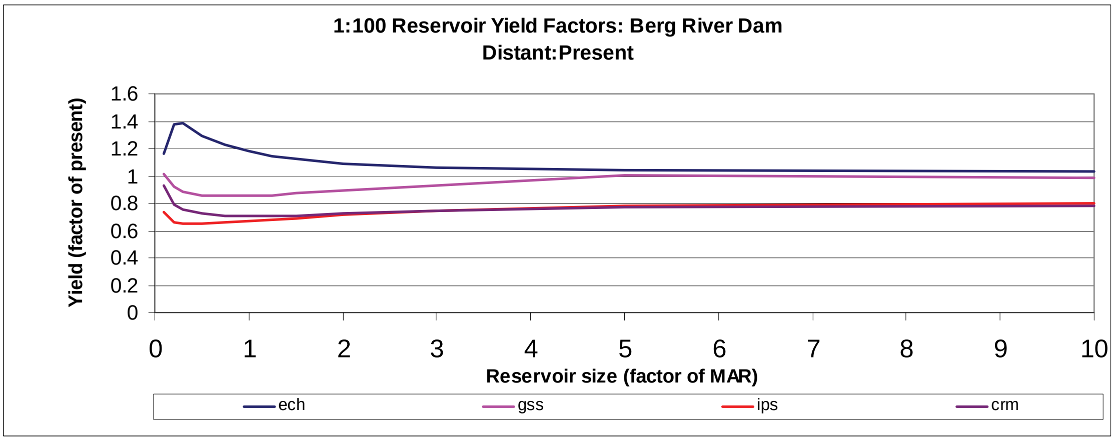


1:100 Intermediate Future Reservoir Yield as %MAR: Berg River Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 175.46 Mm^3/a)
gss (MAR = 167.28 Mm^3/a)
ips (MAR = 104.07 Mm^3/a)
ccc (MAR = 155.85 Mm^3/a)
crm (MAR = 139.00 Mm^3/a)

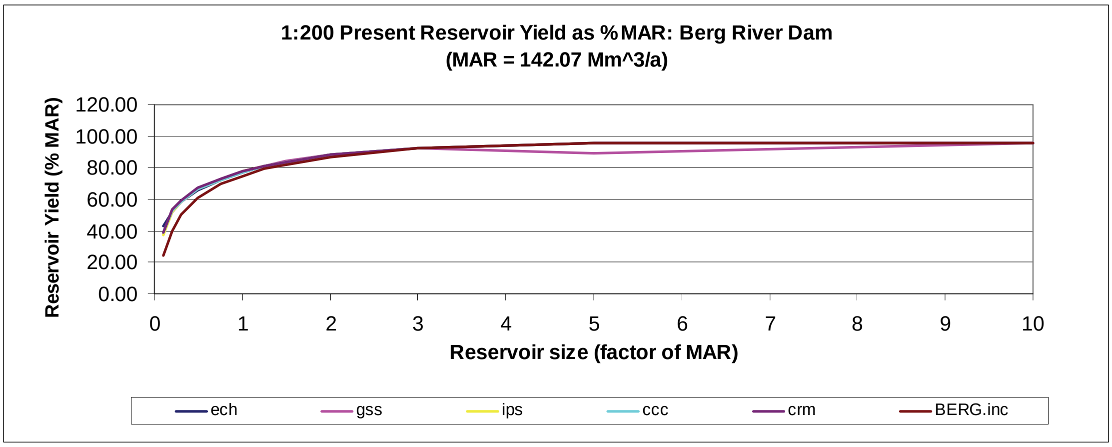


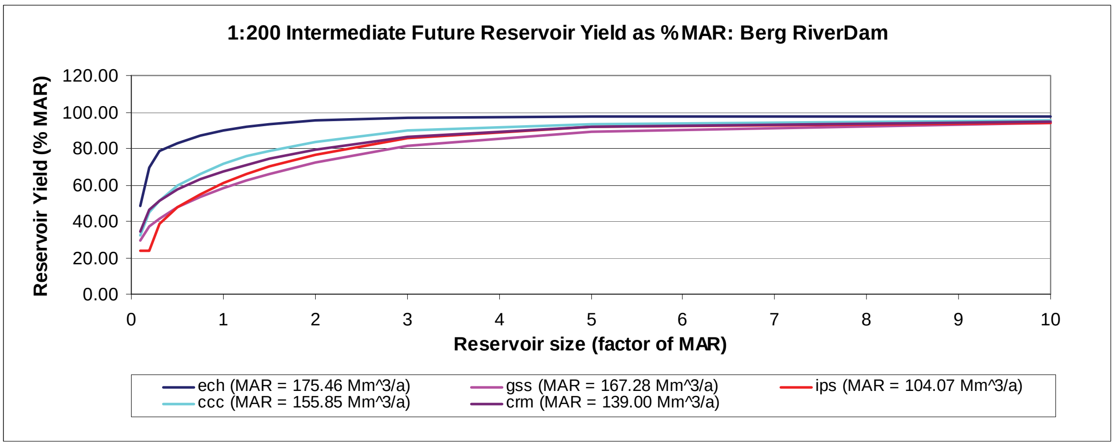
1:100 Reservoir Yield Factors: Berg River Dam
Intermediate:Present
Yield (factor of present)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

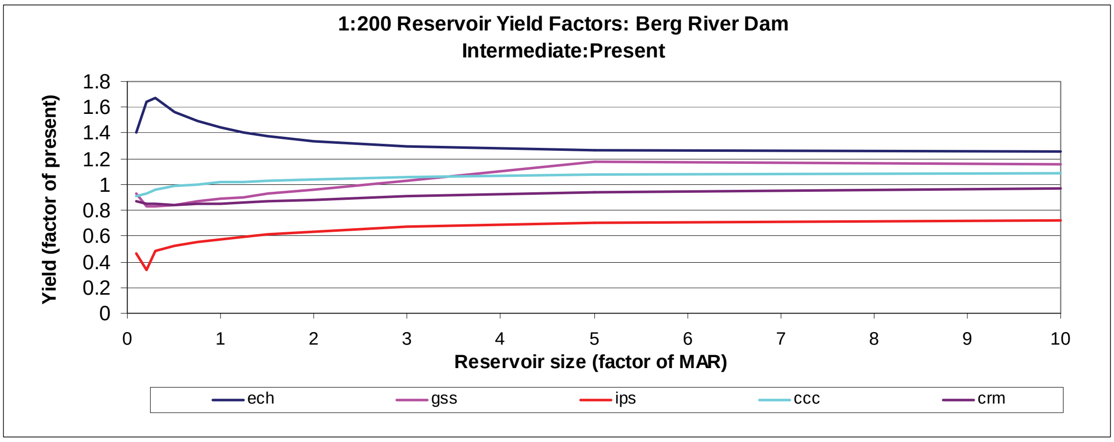

1:100 Distant Future Reservoir Yield as %MAR: Berg River Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 144.68 Mm^3/a)
gss (MAR = 139.67 Mm^3/a)
ips (MAR = 112.36 Mm^3/a)
crm (MAR = 109.22 Mm^3/a)

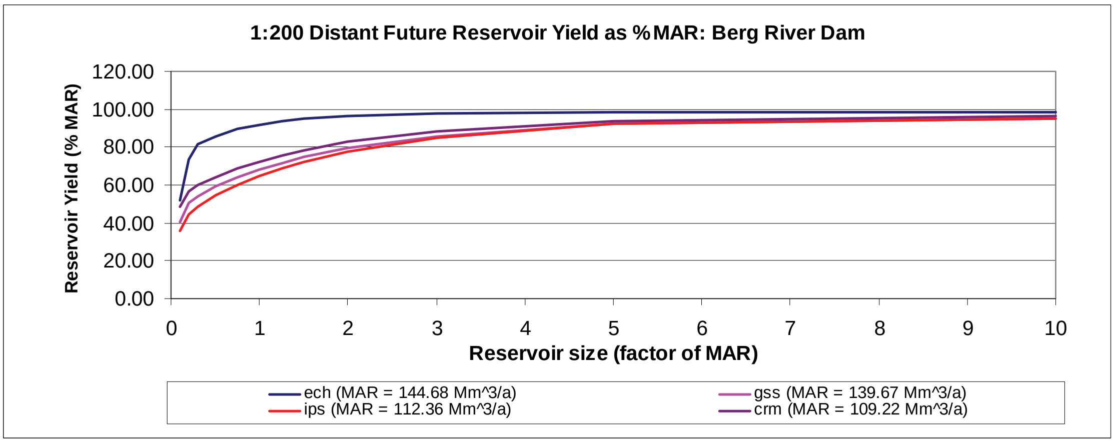

1:100 Reservoir Yield Factors: Berg River Dam
Distant:Present
Yield (factor of present)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
crm

1:200

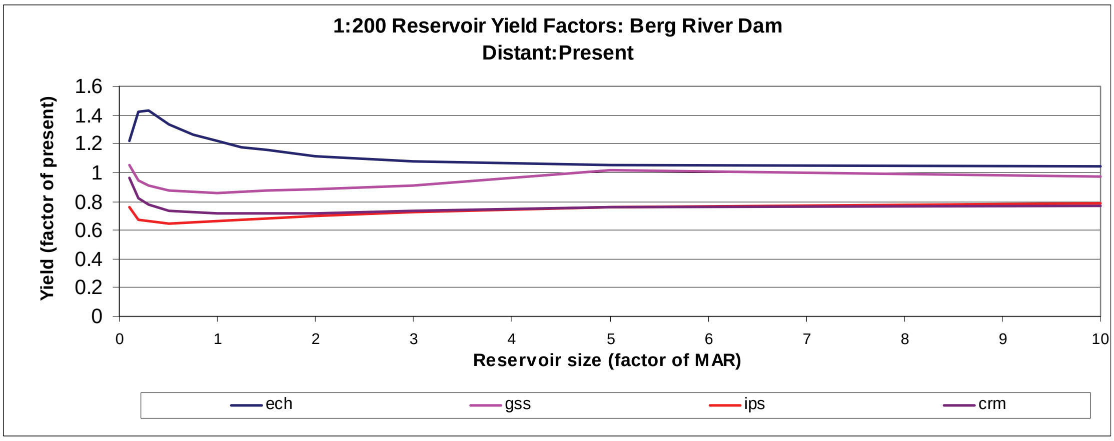

1:200 Present Reservoir Yield as %MAR: Berg River Dam
(MAR = 142.07 Mm^3/a)
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
BERG.inc


1:200 Intermediate Future Reservoir Yield as %MAR: Berg RiverDam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 175.46 Mm^3/a)
gss (MAR = 167.28 Mm^3/a)
ips (MAR = 104.07 Mm^3/a)
ccc (MAR = 155.85 Mm^3/a)
crm (MAR = 139.00 Mm^3/a)


1:200 Reservoir Yield Factors: Berg River Dam
Intermediate:Present
Yield (factor of present)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm



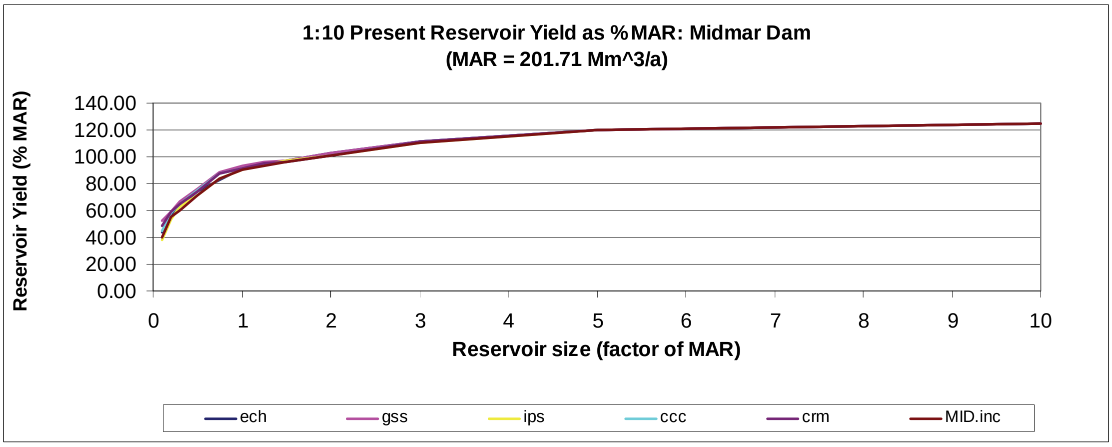
1:200 Distant Future Reservoir Yield as %MAR: Berg River Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 144.68 Mm^3/a)
gss (MAR = 139.67 Mm^3/a)
ips (MAR = 112.36 Mm^3/a)
crm (MAR = 109.22 Mm^3/a)

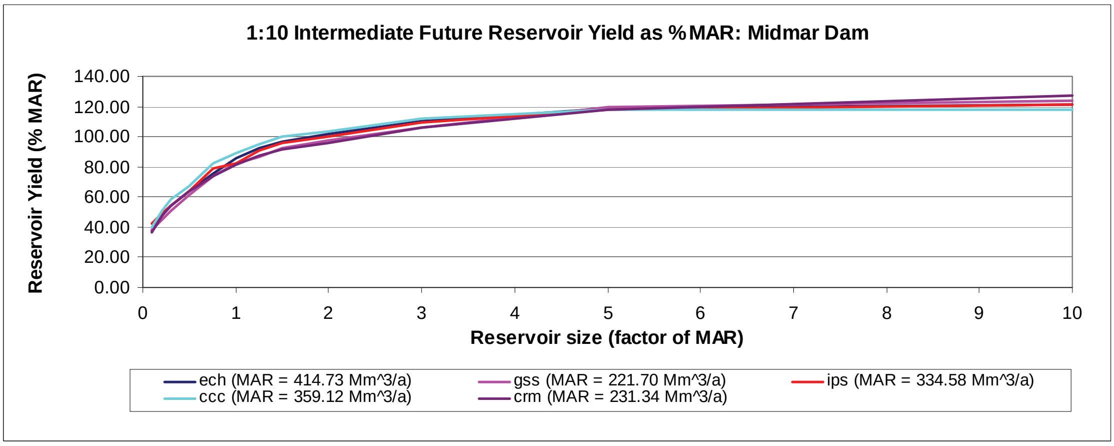


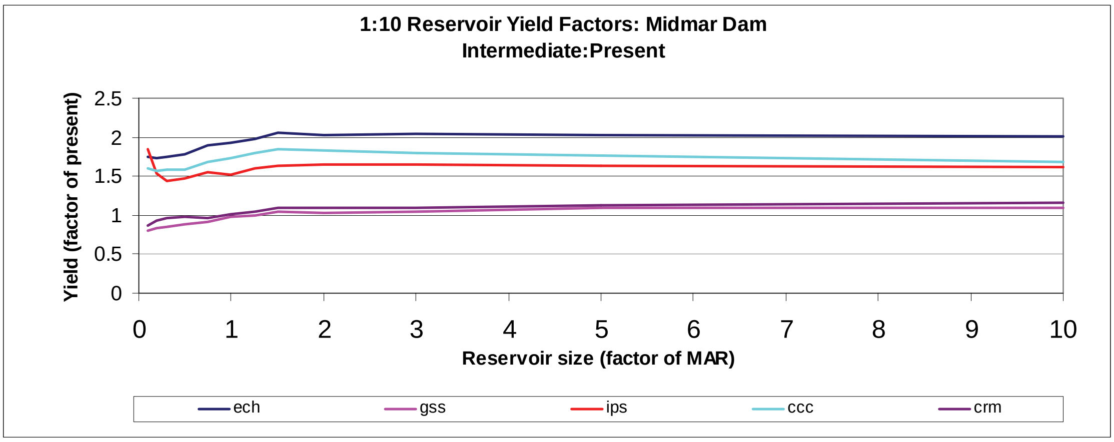
1:200 Reservoir Yield Factors: Berg River Dam
Distant:Present
Yield (factor of present)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
crm

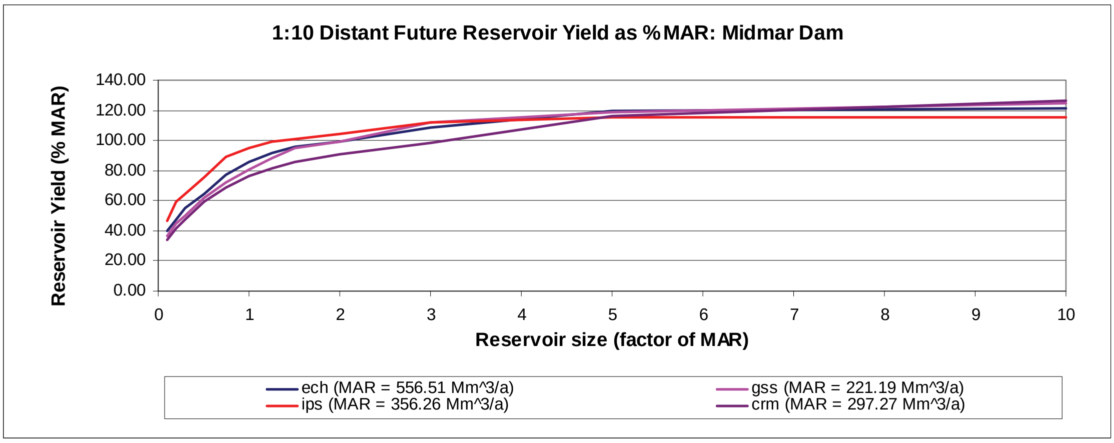
Appendix C.2: MIDMAR DAM

1:10

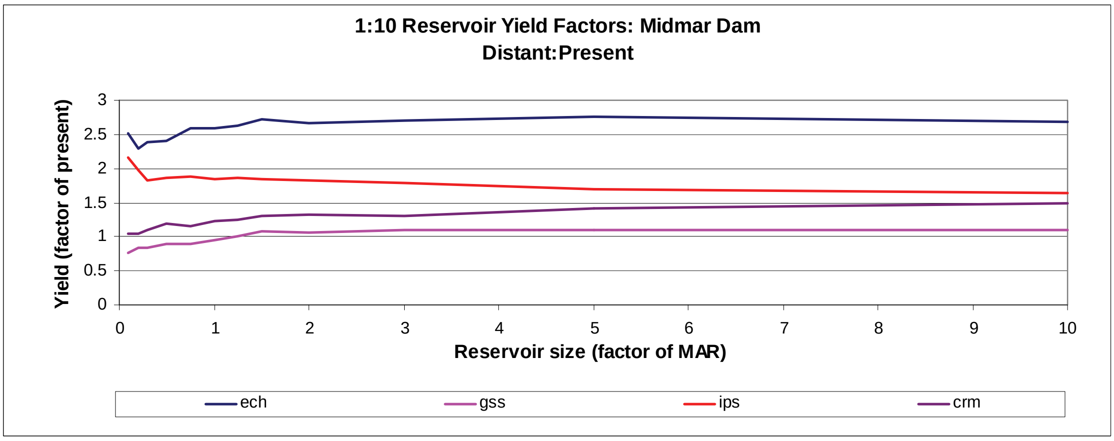






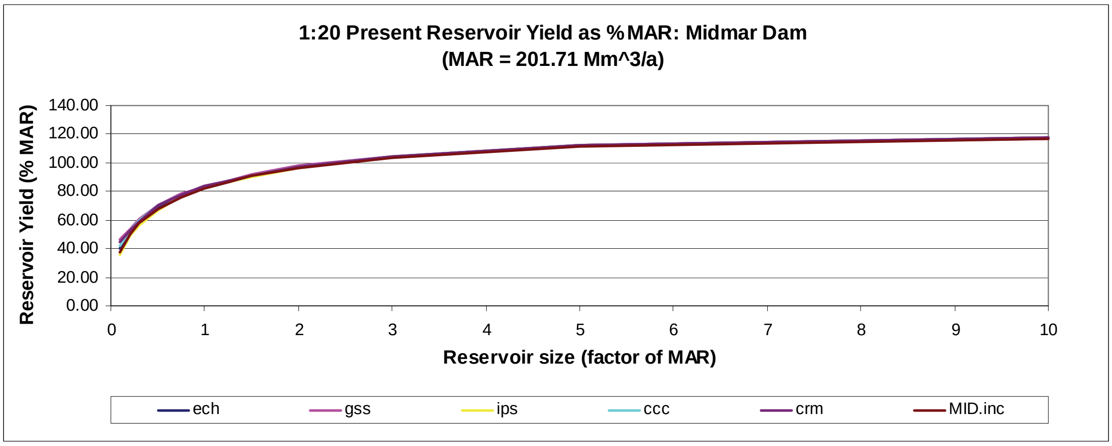


1:10 Distant Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 556.51 Mm^3/a)
gss (MAR = 221.19 Mm^3/a)
ips (MAR = 356.26 Mm^3/a)
crm (MAR = 297.27 Mm^3/a)

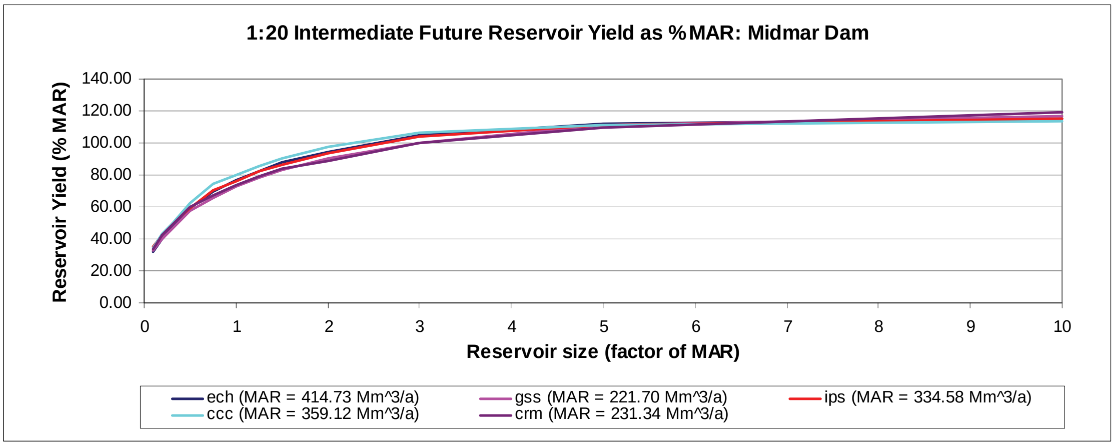


1:10 Reservoir Yield Factors: Midmar Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

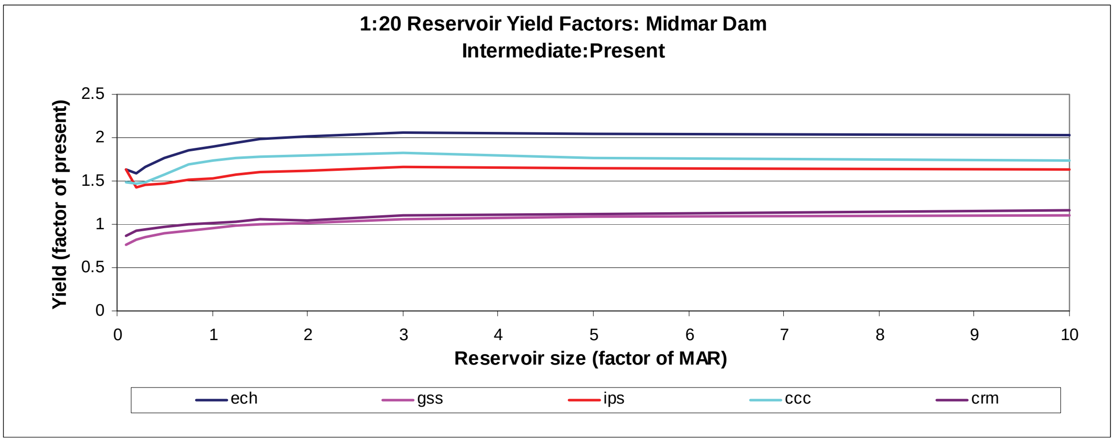
1:20



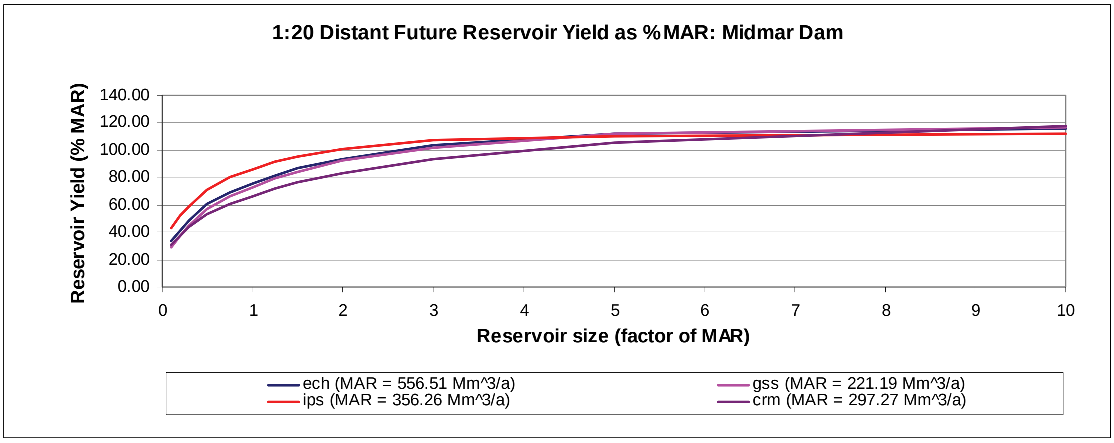
1:20 Present Reservoir Yield as %MAR: Midmar Dam
(MAR = 201.71 Mm^3/a)
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
MID.inc

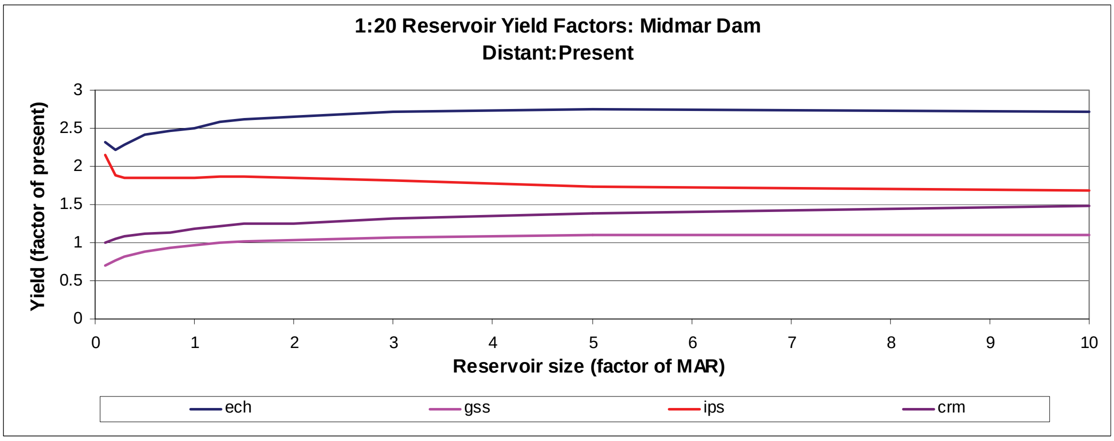


1:20 Intermediate Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 414.73 Mm^3/a)
gss (MAR = 221.70 Mm^3/a)
ips (MAR = 334.58 Mm^3/a)
ccc (MAR = 359.12 Mm^3/a)
crm (MAR = 231.34 Mm^3/a)

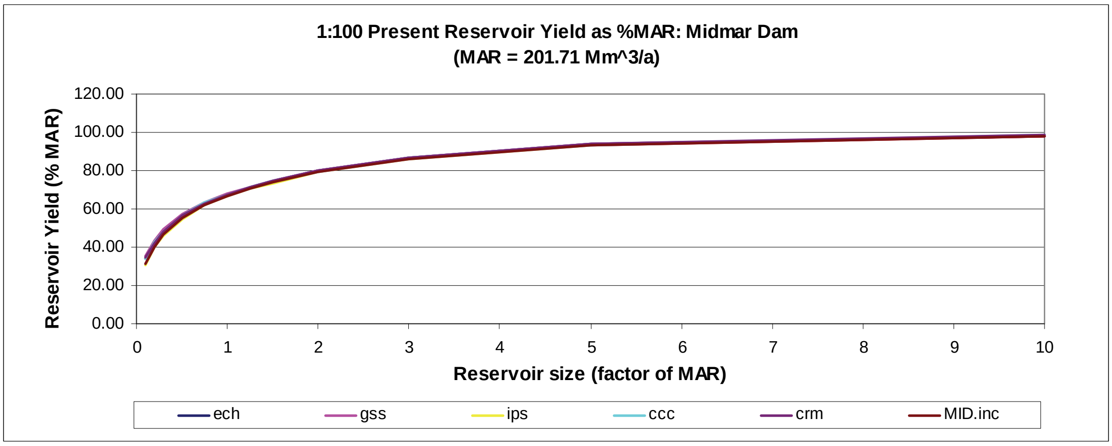


1:20 Reservoir Yield Factors: Midmar Dam
Intermediate:Present
Yield (factor of present)
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

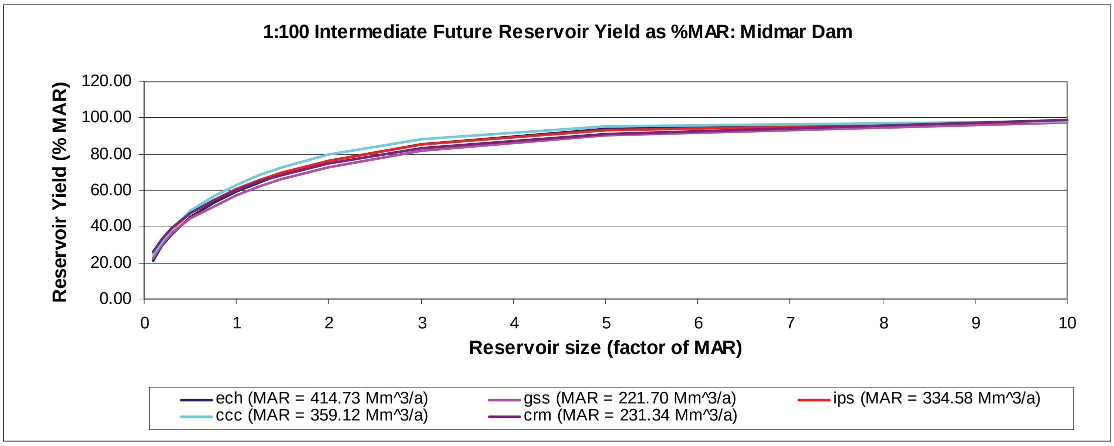

1:20 Distant Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 556.51 Mm^3/a)
ips (MAR = 356.26 Mm^3/a)
gss (MAR = 221.19 Mm^3/a)
crm (MAR = 297.27 Mm^3/a)


1:20 Reservoir Yield Factors: Midmar Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

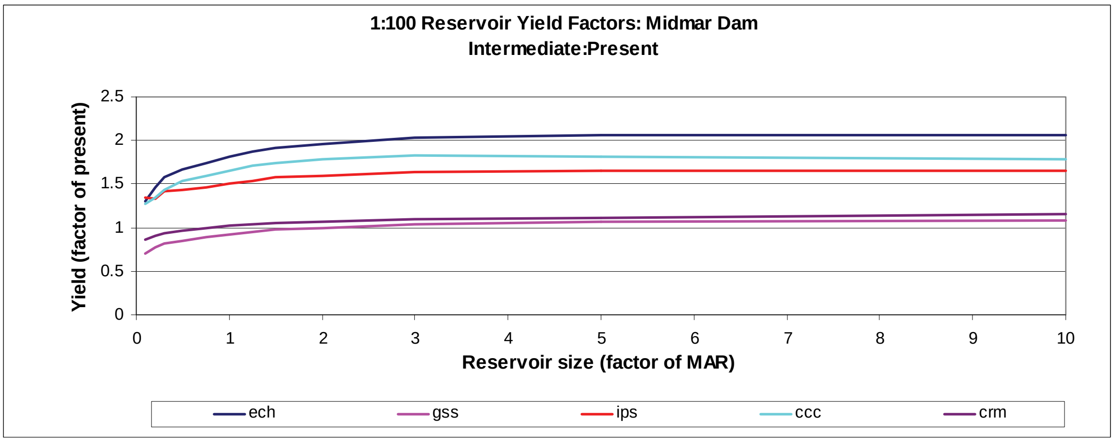
1:100



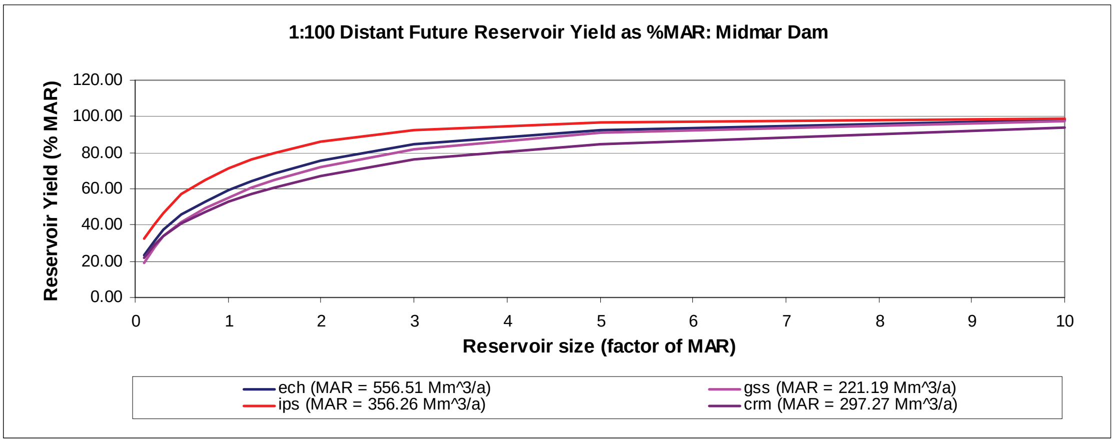
1:100 Present Reservoir Yield as %MAR: Midmar Dam
(MAR = 201.71 Mm^3/a)
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
MID.inc

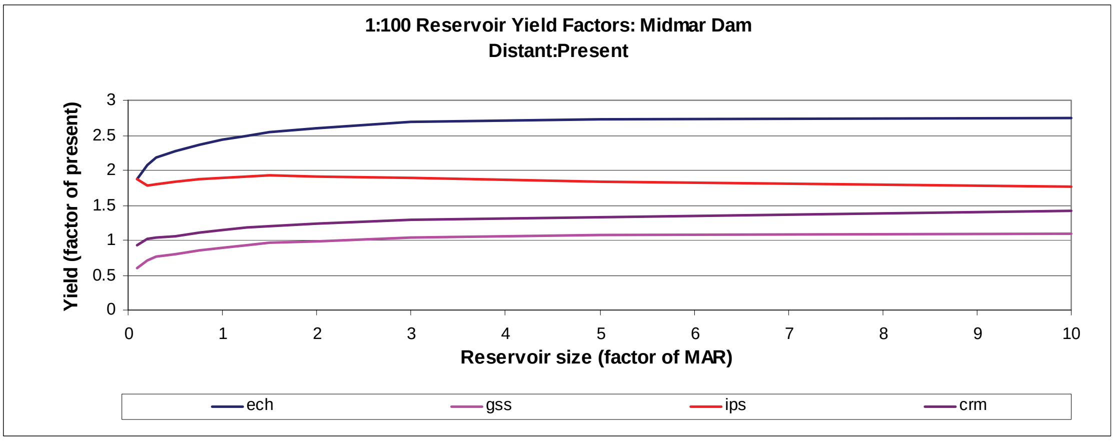


1:100 Intermediate Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 414.73 Mm^3/a)
gss (MAR = 221.70 Mm^3/a)
ips (MAR = 334.58 Mm^3/a)
ccc (MAR = 359.12 Mm^3/a)
crm (MAR = 231.34 Mm^3/a)

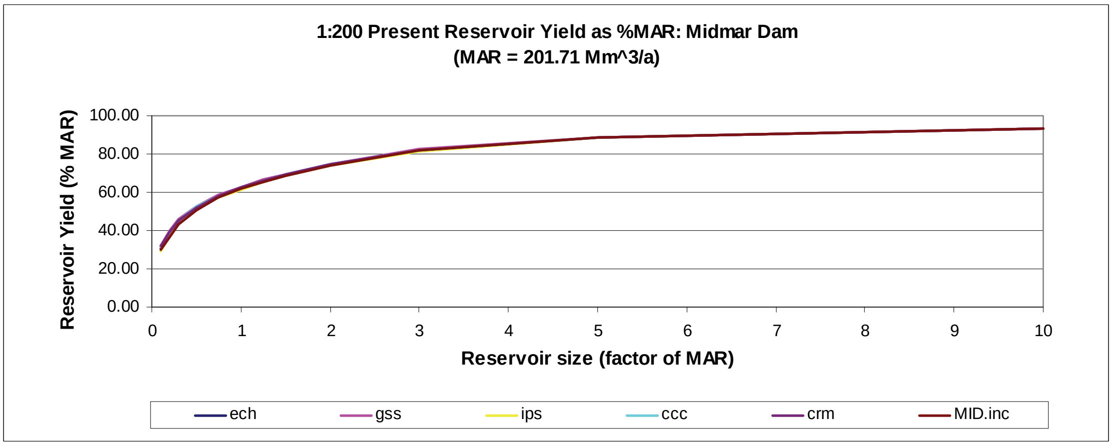


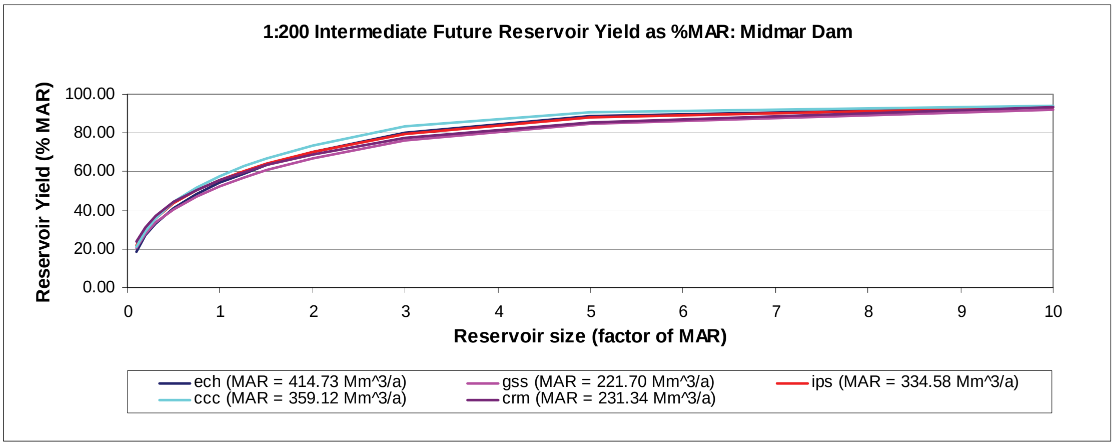
1:100 Reservoir Yield Factors: Midmar Dam
Intermediate:Present
Yield (factor of present)
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

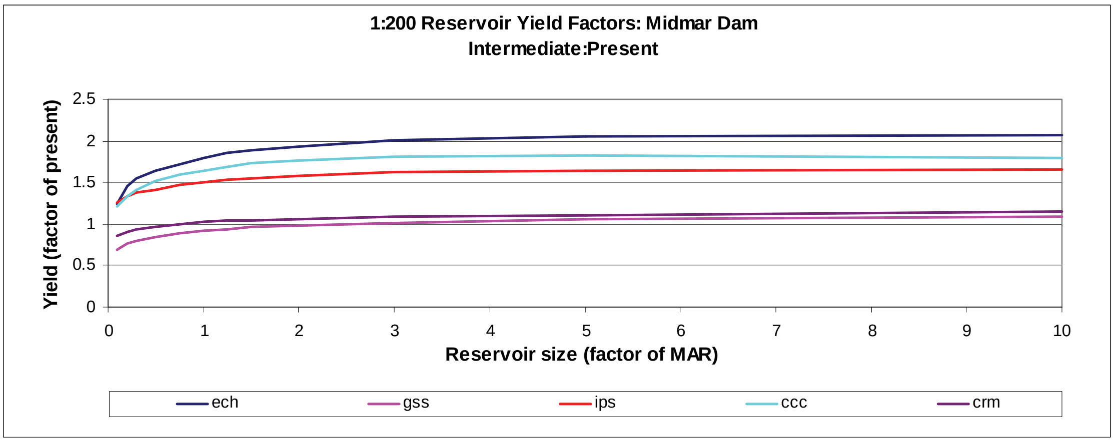

1:100 Distant Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 556.51 Mm^3/a)
ips (MAR = 356.26 Mm^3/a)
gss (MAR = 221.19 Mm^3/a)
crm (MAR = 297.27 Mm^3/a)

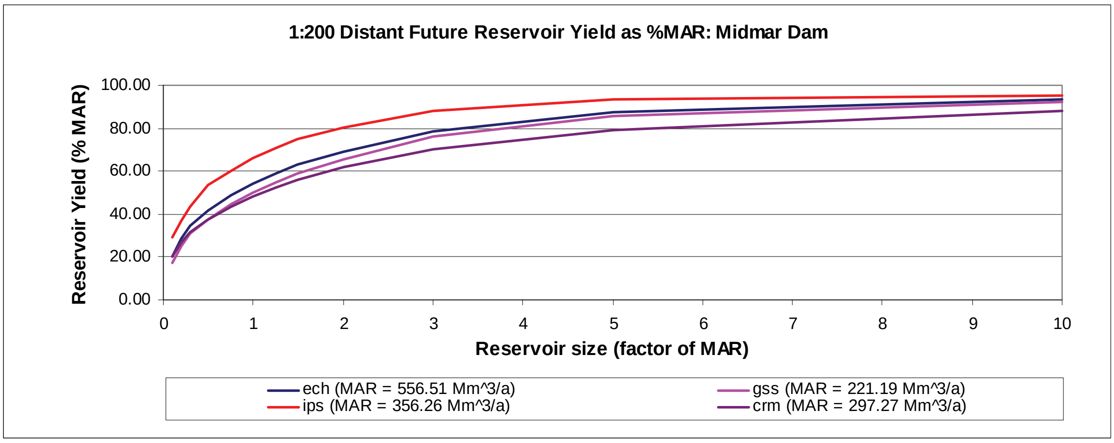

1:100 Reservoir Yield Factors: Midmar Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
crm

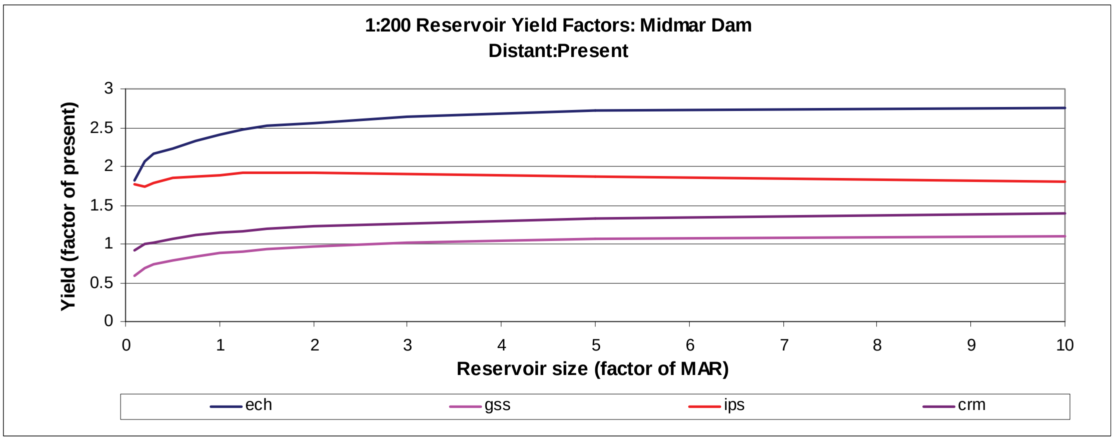
1:200


1:200 Present Reservoir Yield as %MAR: Midmar Dam
(MAR = 201.71 Mm^3/a)
Reservoir Yield (% MAR)
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
MID.inc


1:200 Intermediate Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 414.73 Mm^3/a)
gss (MAR = 221.70 Mm^3/a)
ips (MAR = 334.58 Mm^3/a)
ccc (MAR = 359.12 Mm^3/a)
crm (MAR = 231.34 Mm^3/a)

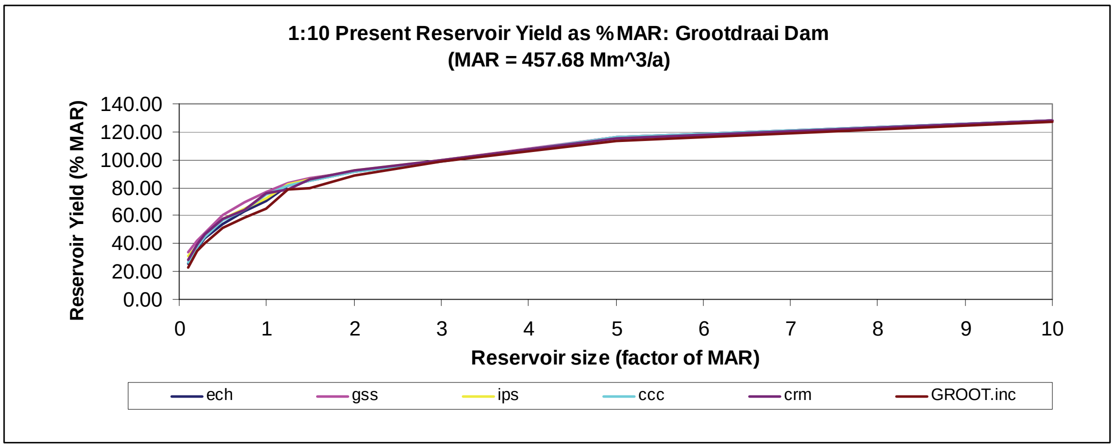

1:200 Reservoir Yield Factors: Midmar Dam
Intermediate:Present
Yield (factor of present)
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

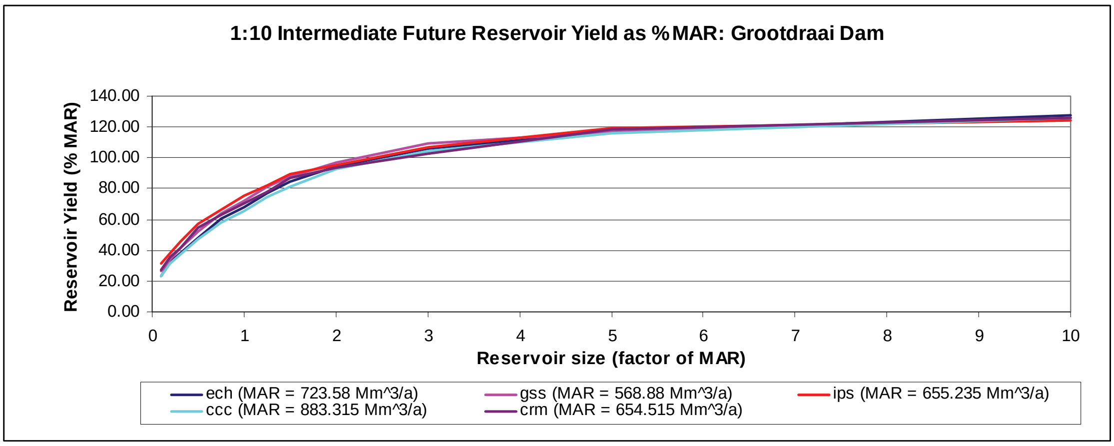

1:200 Distant Future Reservoir Yield as %MAR: Midmar Dam
Reservoir Yield (% MAR)
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 556.51 Mm^3/a)
ips (MAR = 356.26 Mm^3/a)
gss (MAR = 221.19 Mm^3/a)
crm (MAR = 297.27 Mm^3/a)

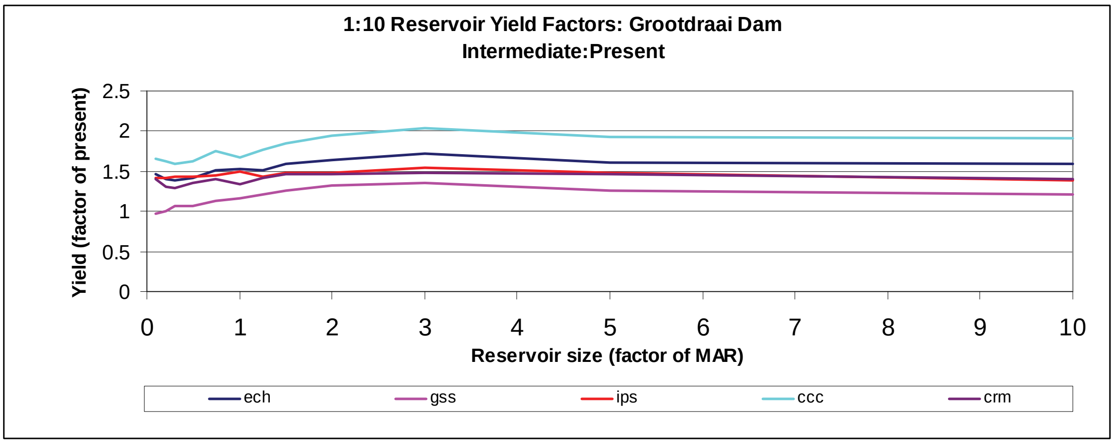

1:200 Reservoir Yield Factors: Midmar Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

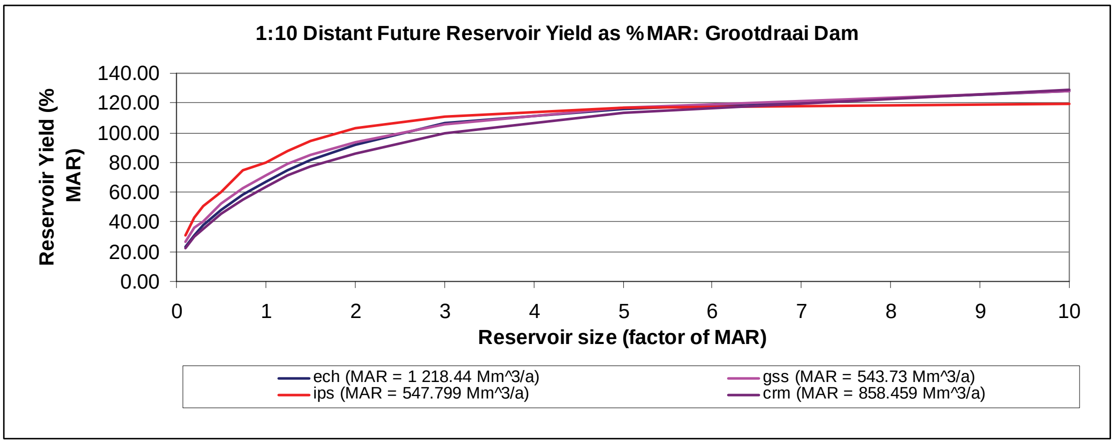
Appendix C.3: GROOTDRAAI DAM

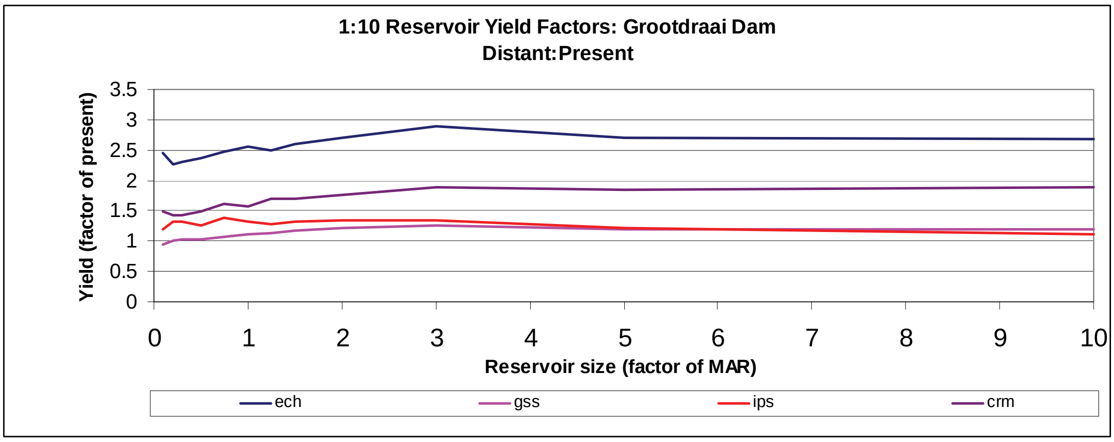
1:10



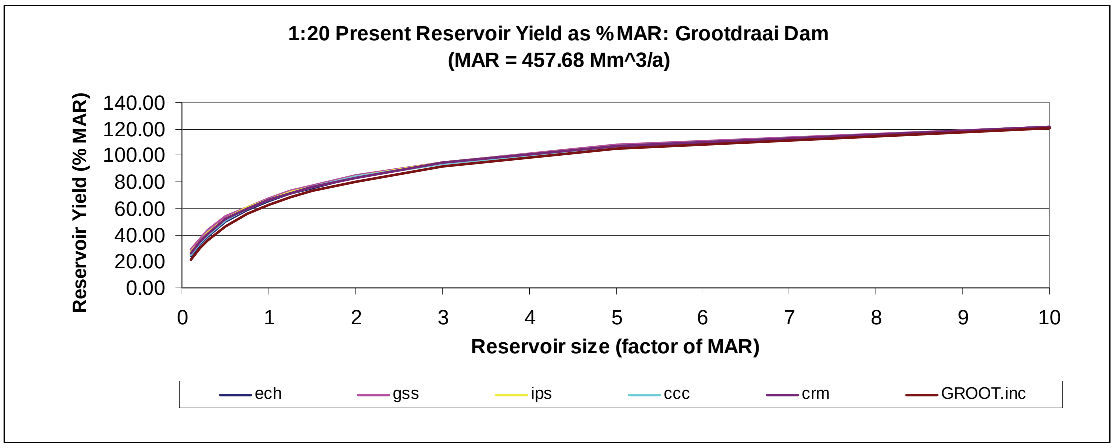


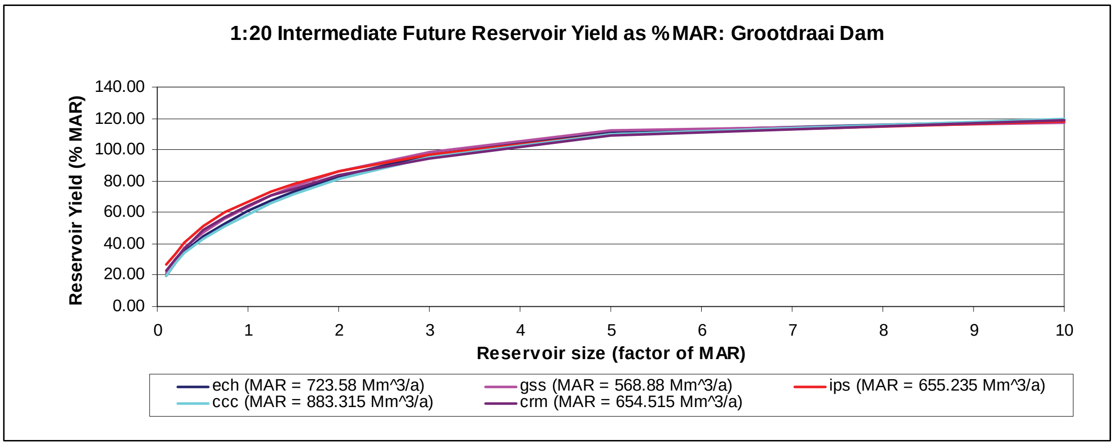


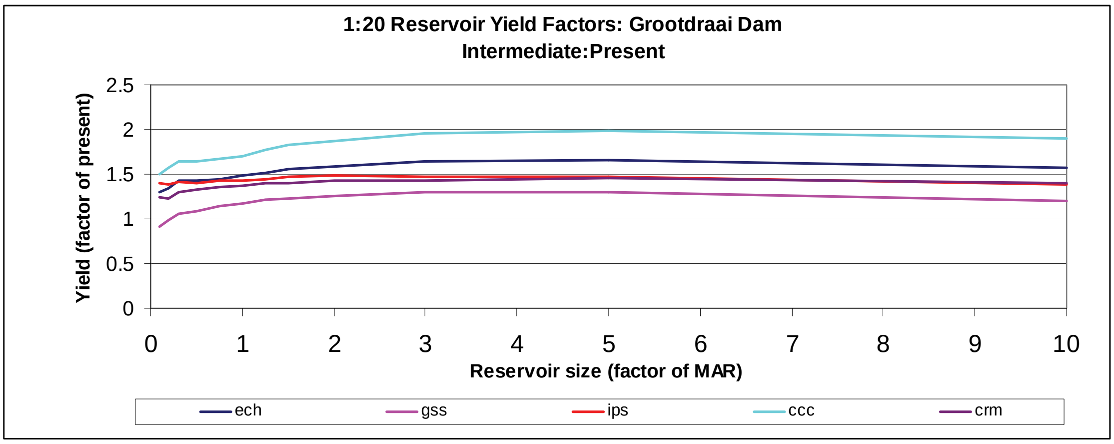

1:10 Distant Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 1 218.44 Mm^3/a)
gss (MAR = 543.73 Mm^3/a)
ips (MAR = 547.799 Mm^3/a)
crm (MAR = 858.459 Mm^3/a)

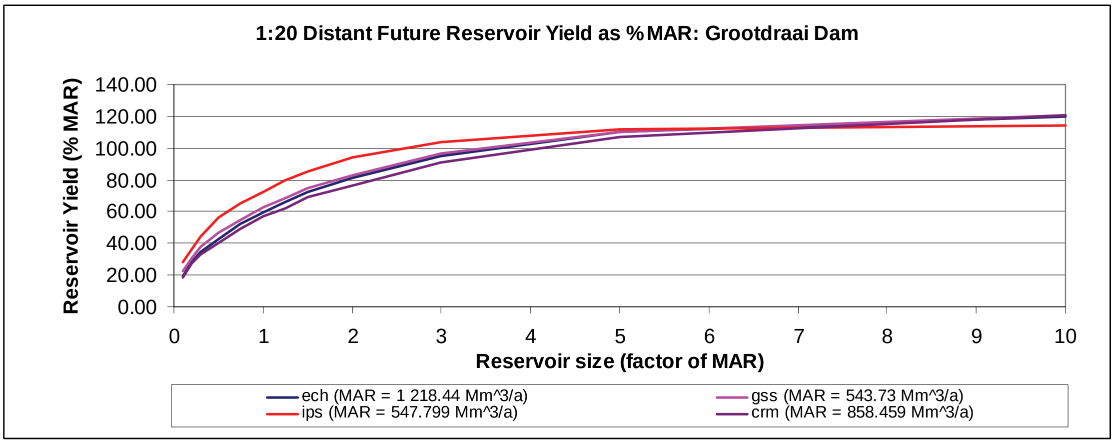

1:10 Reservoir Yield Factors: Grootdraai Dam
Distant:Present
Yield (factor of present)
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

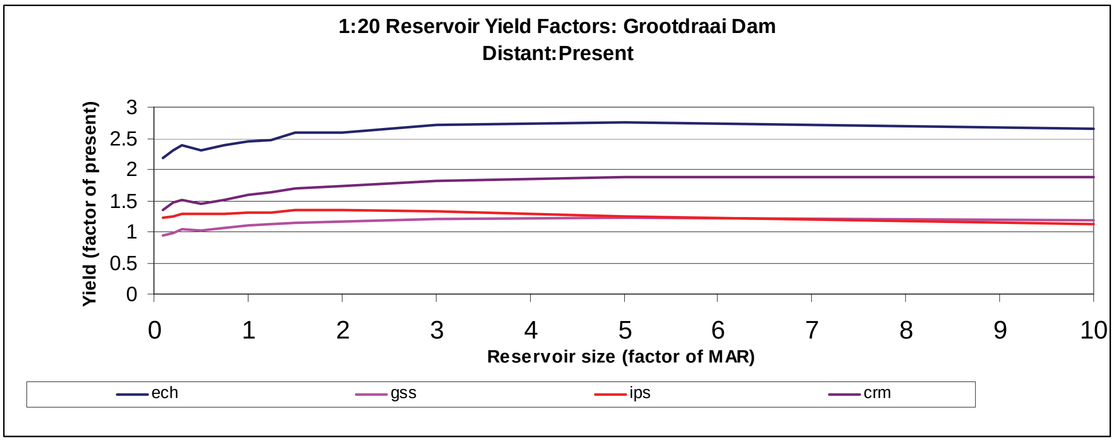
1:20


1:20 Present Reservoir Yield as %MAR: Grootdraai Dam
(MAR = 457.68 Mm^3/a)
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
GROOT.inc

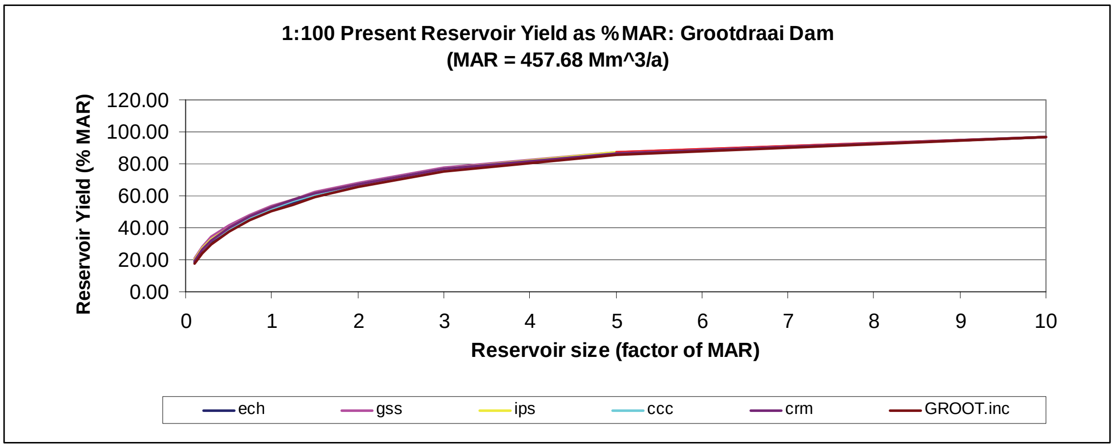

1:20 Intermediate Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 723.58 Mm^3/a)
gss (MAR = 568.88 Mm^3/a)
ips (MAR = 655.235 Mm^3/a)
ccc (MAR = 883.315 Mm^3/a)
crm (MAR = 654.515 Mm^3/a)

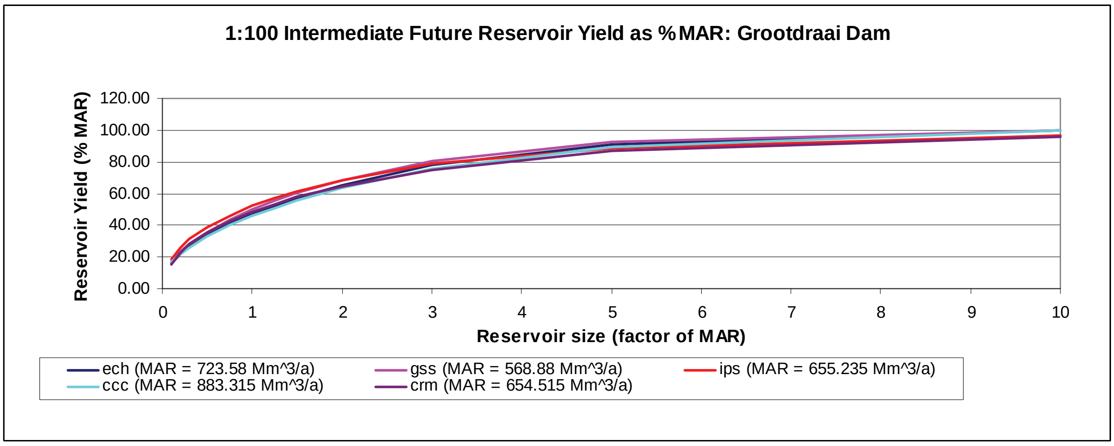

1:20 Reservoir Yield Factors: Grootdraai Dam
Intermediate:Present
Yield (factor of present)
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

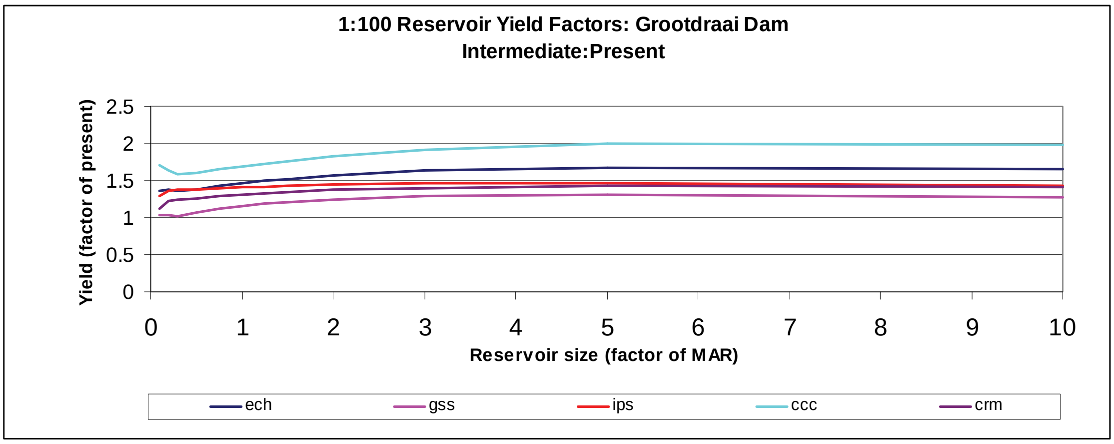

1:20 Distant Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 1 218.44 Mm^3/a)
ips (MAR = 547.799 Mm^3/a)
gss (MAR = 543.73 Mm^3/a)
crm (MAR = 858.459 Mm^3/a)

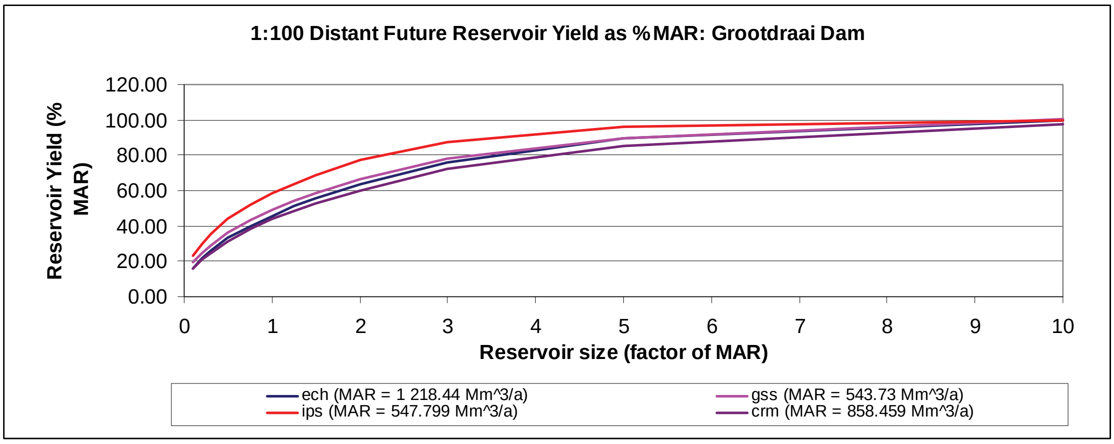

1:20 Reservoir Yield Factors: Grootdraai Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

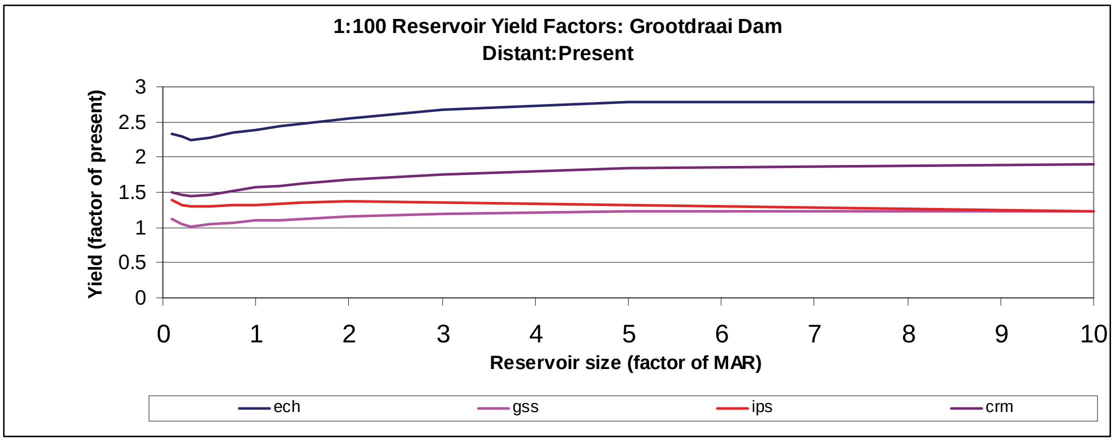
1:100


1:100 Present Reservoir Yield as %MAR: Grootdraai Dam
(MAR = 457.68 Mm^3/a)
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
GROOT.inc

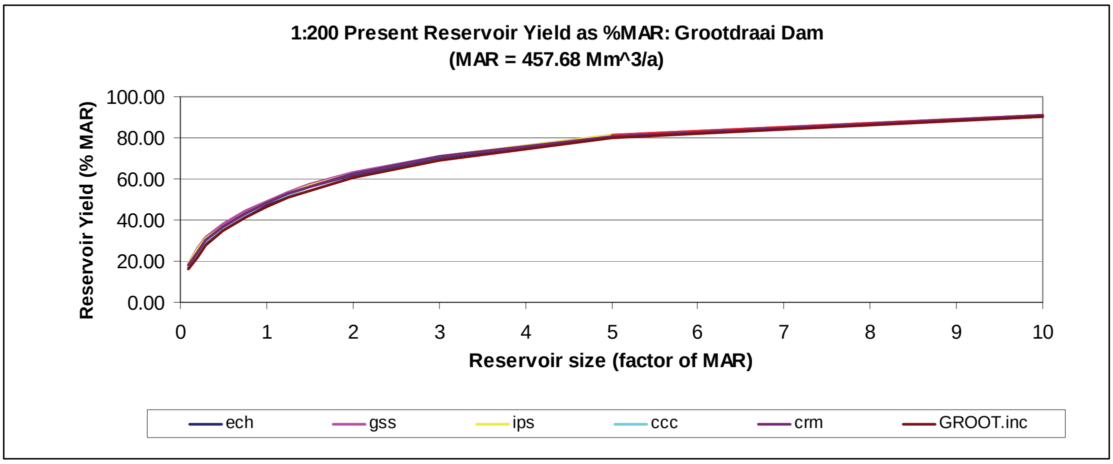

1:100 Intermediate Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 723.58 Mm^3/a)
gss (MAR = 568.88 Mm^3/a)
ips (MAR = 655.235 Mm^3/a)
ccc (MAR = 883.315 Mm^3/a)
crm (MAR = 654.515 Mm^3/a)

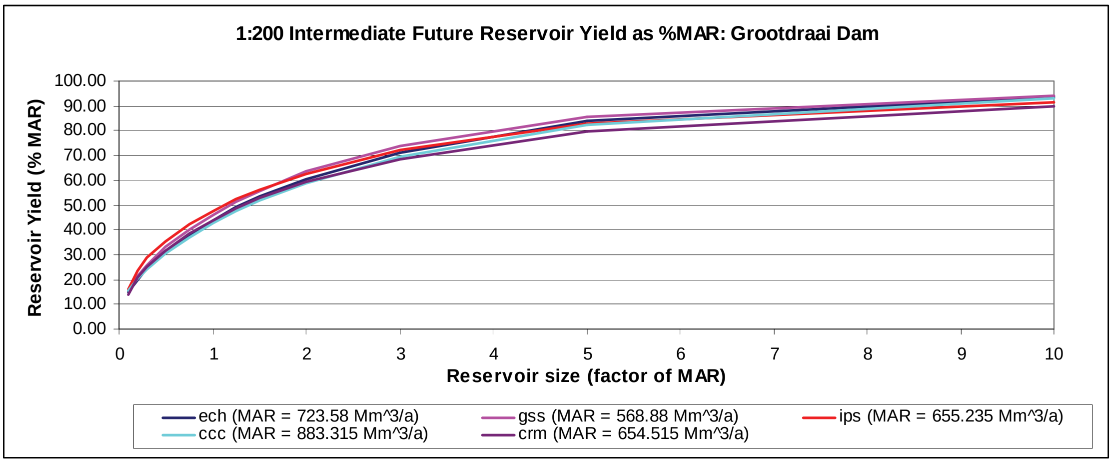

1:100 Reservoir Yield Factors: Grootdraai Dam
Intermediate:Present
Yield (factor of present)
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm

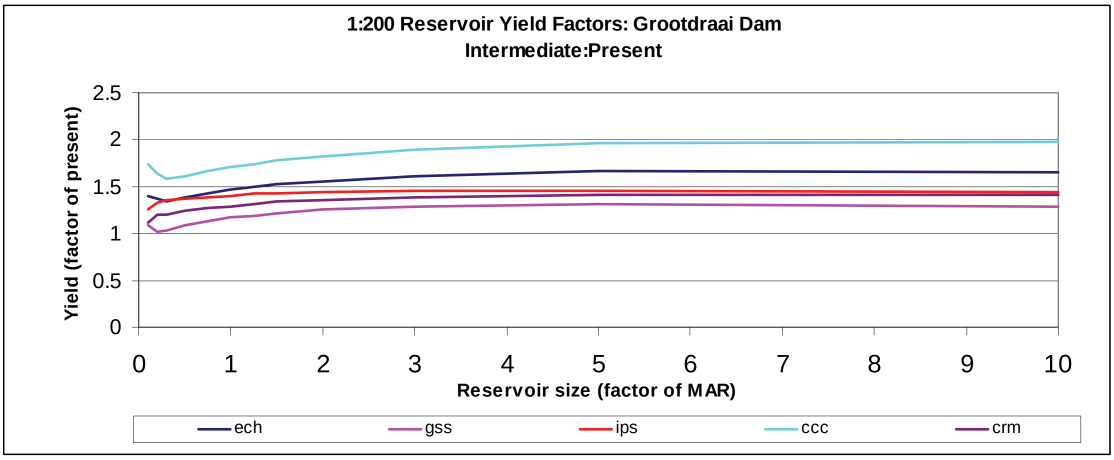

1:100 Distant Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech (MAR = 1 218.44 Mm^3/a)
ips (MAR = 547.799 Mm^3/a)
gss (MAR = 543.73 Mm^3/a)
crm (MAR = 858.459 Mm^3/a)

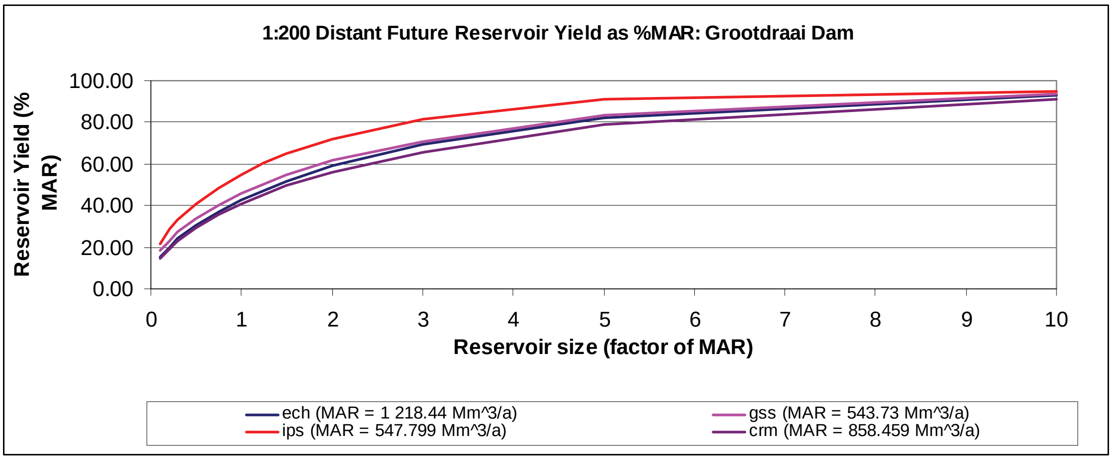

1:100 Reservoir Yield Factors: Grootdraai Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Reservoir size (factor of MAR)
ech
gss
ips
crm

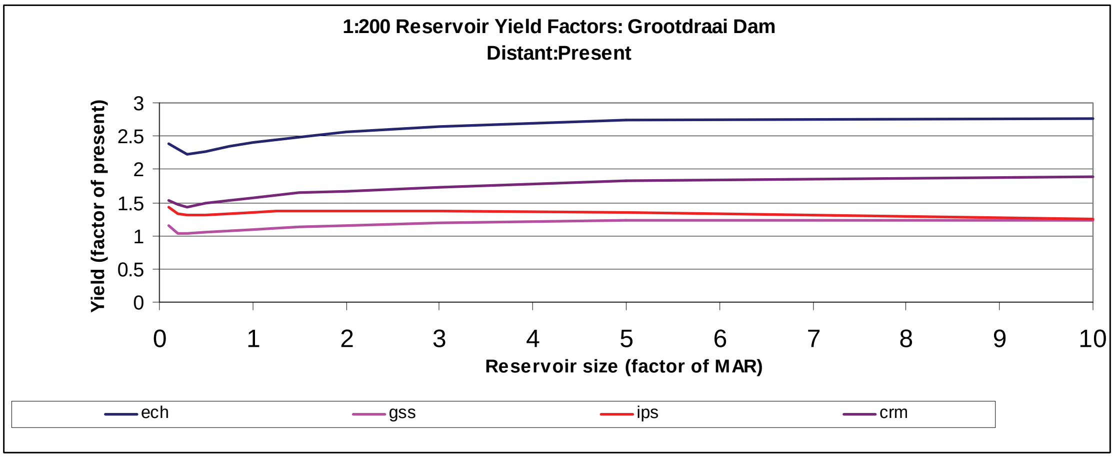
1:200


1:200 Present Reservoir Yield as %MAR: Grootdraai Dam
(MAR = 457.68 Mm^3/a)
Reservoir Yield (% MAR)
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm
GROOT.inc


1:200 Intermediate Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
Reservoir size (factor of MAR)
ech (MAR = 723.58 Mm^3/a)
gss (MAR = 568.88 Mm^3/a)
ips (MAR = 655.235 Mm^3/a)
ccc (MAR = 883.315 Mm^3/a)
crm (MAR = 654.515 Mm^3/a)


1:200 Reservoir Yield Factors: Grootdraai Dam
Intermediate:Present
Yield (factor of present)
Reservoir size (factor of MAR)
ech
gss
ips
ccc
crm


1:200 Distant Future Reservoir Yield as %MAR: Grootdraai Dam
Reservoir Yield (% MAR)
100.00
80.00
60.00
40.00
20.00
0.00
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech (MAR = 1 218.44 Mm^3/a)
gss (MAR = 543.73 Mm^3/a)
ips (MAR = 547.799 Mm^3/a)
crm (MAR = 858.459 Mm^3/a)


1:200 Reservoir Yield Factors: Grootdraai Dam
Distant:Present
Yield (factor of present)
3
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10
Reservoir size (factor of MAR)
ech
gss
ips
crm